UPDATING DRINKING WATER DATA FOR UNUSUALLY SENSITIVE AREAS STANDARDS AND BEST PRACTICES
GIS TECHNICAL REPORT

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LIST OF ACRONYMS

AADWS	Adequate Alternative Drinking Water Source
ALLU	Alluvial Aquifer
AML	Arc Macro Language
BGEO	Bedrock Geology
CWS	Community Water System
DRIFT	Glacial Drift
DW	Drinking Water
DW USA	Drinking Water Unusually Sensitive Area
EPA	U.S. Environmental Protection Agency
ESRI	Environmental Systems Research Institute
ft	feet
FOIA	Freedom of Information Act
GIS	Geographical Information System
gpm	gallons per minute
GWSI	Groundwater Site Inventory
HCA	High Consequence Areas
NAPA	Not a Principal Aquifer
NHD	National Hydrography Dataset
NPMS	National Pipeline Mapping System Repository
NTNCWS	Non-Transient Non-Community Water System
PHMSA	Pipeline and Hazardous Material Safety Administration
PWS	Public Water System
PWS ID	Public Water System Identifier
QA/QC	Quality Assurance and Quality Control
RPI	Research Planning, Inc.
SEDTHICK	Sediment Thickness
SDWA	Safe Drinking Water Act
SDWIS	Safe Drinking Water Information System
SGEO	Surficial Geology
sq mi	square mile

SSA	Sole Source Aquifer
SWAP	Source Water Assessment Program
SWI	Surface Water Intake
SWPA	Source Water Protection Area
TNCWS	Transient Non-Community Water System
USA	Unusually Sensitive Area
USDOT	U.S. Department of Transportation
USGS	U.S. Geological Survey
WHPA	Wellhead Protection Area

UPDATING DRINKING WATER UNUSUALLY SENSITIVE AREAS
EXECUTIVE SUMMARY

In 2016, the U.S. Department of Transportation (USDOT), Pipeline and Hazardous Materials Safety Administration (PHMSA) began updating unusually sensitive areas (USA) for drinking water (DW USA) resources across the United States (U.S.). In accordance with pipeline safety laws (49 U.S.C. § 60109), PHMSA is required to identify areas unusually sensitive to environmental damage in the event of a hazardous liquid pipeline accident. DW USA data were updated for the entire U.S. including Washington, D.C. and Puerto Rico between 2016 and 2019.

To identify each DW USA, candidate drinking water resources were subjected to the appropriate filter criteria (per 49 CFR Part 195.6) to identify those resources that are more susceptible to permanent or long-term environmental damage from a hazardous liquid pipeline accident. Work included collecting and preprocessing required and known optional data layers needed to run the DW USA model; subjecting the preprocessed data layers to the filter criteria in the DW USA model; and delivering standardized geospatial data layers with detailed metadata documents.

PHMSA collected the required data layers from federal and state resource agencies that are responsible for managing and protecting the nation's drinking water resources. Required data layers included public water system (PWS) data (surface water intakes, springs, and groundwater wells), aquifer boundaries, and hydrography. Additionally, useful optional data layers were acquired when available. Optional data layers consisted of geology (bedrock, surficial, glacial, and basin geologic features), sole source aquifers, and source water and wellhead protection areas along with relational tables linking the protection areas to the PWS data.

The required and optional data layers collected from national or state sources were preprocessed to fit the requirements of the DW USA model following the detailed guidelines found in this report. Processed data were then projected to the standard DW USA map projection before inclusion into the DW USA model.

The DW USA model required geospatial data. The model also required a set of aquifer vulnerability guidelines that considered all available and relevant groundwater well information (e.g., location, depth, screened intervals, pump rate) and aquifer/geologic information. The guidelines were used to identify vulnerable groundwater wells and are based on a modified version of the Pettyjohn aquifer classification scheme. Once the model was run for a state and the final data (ESRI shapefile format) were reviewed, a detailed Federal Geographic Data Committee formatted metadata document was prepared. The metadata contained federal and state resource information by state in the Lineage Section as well as PWS input counts and the final number of DW USA by count and area (in square miles). Adequate alternative data were not available due to heightened data security.

The final DW USA data and metadata documents were delivered to PHMSA and will be made available to vetted pipeline operators via online request to PHMSA through the National Pipeline Mapping System program.

UPDATING DRINKING WATER UNUSUALLY SENSITIVE AREAS
GIS TECHNICAL REPORT

1.0 INTRODUCTION

Research Planning, Inc.’s (RPI) integrated team of scientists and geospatial experts worked closely with the Pipeline and Hazardous Materials Safety Administration (PHMSA) to update the Unusually Sensitive Areas (USA) for drinking water (DW USA) resources across the United States. In accordance with pipeline safety laws (49 U.S.C. § 60109), PHMSA was required to identify areas unusually sensitive to environmental damage in the event of a hazardous liquid pipeline accident. Through interactions with various regulatory and resources agencies, pipeline operators, private contractors, non-profit conservation organizations, academia, and the general public, a process was developed and adopted by PHMSA in 2000 to identify USAs for drinking water resources. Congress mandated in Section 6 of the Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011 that PHMSA maintain, biennially, maps of high consequence areas (HCA) in the National Pipeline Mapping System Repository (NPMS). In response to this objective, PHMSA has maintained and updated HCA data in the NPMS since 2000 except for the Drinking Water and Ecological USA data that were completed in 2002. In 2019, PHMSA updated the DW USA data sets for the United States including Washington, D.C. and Puerto Rico.

This document outlines and addresses:

- Pipeline Safety Laws 49 U.S.C. § 60109, 49 CFR Part 195.6 and definitions as applied to DW USAs;
- 49 CFR Part 195.6 Data Sources and Potential Data Gaps;
- Data Collection and Preprocessing;
- The Drinking Water USA Model; and
- DW USA Data Deliverable and Metadata.

2.0 PIPELINE SAFETY LAWS 49 U.S.C. § 60109, 49 CFR PART 195.6

The process for identifying DW USAs involves subjecting candidate drinking water resources to the appropriate filter criteria to identify those resources that are more susceptible to permanent or long-term environmental damage from a hazardous liquid pipeline incident.

2.1 Filter Criteria

The filter criteria definition per 49 CFR Part 195.6 used to determine which drinking water resources that should be considered as a DW USA are listed below:

1) The water intake for a Community Water System (CWS) or a Non-Transient Non-Community Water System (NTNCWS) that obtains its water supply primarily from a surface water source and does not have an Adequate Alternative Drinking Water Source (AADWS) shall be designated as a USA.
2) The Source Water Protection Area (SWPA) shall be designated as a USA for a CWS or a NTNCWS that obtains its water supply from a Class I or Class IIa aquifer and does not

have an AADWS. Where a state has not yet identified the SWPA, the Wellhead Protection Area (WHPA) will be designated as a USA until the state has identified the SWPA.

3) The sole source aquifer (SSA) recharge area, where the sole source aquifer is karst in nature, is designated as a USA.

2.2 Definitions

In order to more clearly understand the filter criteria and their utility in the identification of DW USAs, several terms and concepts require further definition. These definitions included in 49 CFR 195.6 are listed below.

Adequate Alternative Drinking Water Source (AADWS) – *a source of water that currently exists, can be used almost immediately with minimal effort and cost, involves no decline in water quality, and will meet the consumptive, hygiene, and firefighting requirements of the existing population of impacted customers for at least one month for a surface water source and at least six months for a groundwater source.*

Class I Aquifer – *an aquifer that is surficial or shallow, permeable, and is highly vulnerable to contamination (see the Aquifer Vulnerability Categories in Section 3.0).*

Class IIa Aquifer – *a Higher Yield Bedrock Aquifer that is consolidated and is moderately vulnerable to contamination (see the Aquifer Vulnerability Categories in Section 3.0).*

Community Water System (CWS) – *a public water system that serves at least 15 service connections used by year-round residents of the area or regularly serves at least 25 year-round residents.*

Karst aquifer – *an aquifer that is composed of limestone or dolomite where the porosity is derived from connected solution cavities. Karst aquifers are often cavernous with high rates of flow.*

Non-Transient Non-Community Water System (NTNCWS) – *a public water system that regularly serves at least 25 of the same persons over six months per year. Examples of these systems include schools, factories, and hospitals that have their own water supplies.*

Public Water System (PWS) – *a system that provides water to the public for human consumption through pipes or other constructed conveyances, if such a system has at least 15 service connections or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. These systems include the source of the water supplies – i.e., surface or ground. PWS can be community, non-transient non-community, or transient non-community systems.*

Sole Source Aquifer (SSA) – *an area designated by the U.S. Environmental Protection Agency (EPA) under the sole source aquifer program as the "sole or principal" source of drinking water for an area. Such designations are made if the aquifer's ground water supplies*

50% or more of the drinking water for an area, and if that aquifer were to become contaminated, it would pose a public health hazard. A sole source aquifer that is karst in nature is one composed of limestone where the porosity is derived from connected solution cavities. They are often cavernous, with high rates of flow.

Source Water Protection Area (SWPA) – *the area delineated by the state for a public water system supply or including numerous supplies, whether the source is ground water or surface water or both, as part of the state source water assessment program (SWAP) approved by EPA under section 1453 of the Safe Drinking Water Act.*

Transient Non-Community Water System (TNCWS) – *a public water system that does not regularly serve at least 25 of the same persons over six months per year. This type of water system serves a transient population found at rest stops, campgrounds, restaurants, and parks with their own source of water.*

Wellhead Protection Area (WHPA) – *the surface and subsurface area surrounding a well or well field that supplies a public water system through which contaminants are likely to pass and eventually reach the water well or well field.*

Additional definitions that are not included in 49 CFR 195.6 include:

Outcrop – *a portion of water-bearing rock unit exposed at the land surface.*

Subcrop – *a portion of water-bearing rock unit existing below other rock units.*

3.0 AQUIFER VULNERABILITY CATEGORIES

The process of identifying a DW USA utilizes a modified version of the Pettyjohn aquifer classification to aid in distinguishing among the differences in the characteristics of various hydrogeologic systems. The Pettyjohn aquifer classification scheme was created as part of a nationwide assessment of the potential contamination of groundwater by the subsurface emplacement of fluids through injection wells. Pettyjohn et al. (1991) developed the system for the U.S. Environmental Protection Agency (EPA) and published it in the report "Regional Assessment of Aquifer Vulnerability and Sensitivity in the Conterminous United States" (USEPA/600/2-91/043). The Pettyjohn classification scheme uses the geology of the aquifer(s) and well yields to determine the aquifer's vulnerability to contamination. The Pettyjohn classification scheme is listed below.

Class I Aquifers (Surficial or Shallow Permeable Units Highly Vulnerable to Contamination)

- **Ia** (Unconsolidated Aquifers): Consist of surficial, unconsolidated, and permeable alluvial, alluvial terrace, outwash, beach, dune, and similar deposits.
- **Ib** (Soluble and Fractured Bedrock Aquifers): Consist of potentially cavernous (karst) carbonate and evaporite lithologies such as limestone, dolomite, gypsum, and anhydrite, as well as fractured, jointed, or faulted metamorphic, igneous, and sedimentary units.

Ic (Semi-consolidated Aquifers): Consist of semi-consolidated systems that contain moderately to poorly indurated sand and gravel interbedded with clay and silt units.

Id (Covered Aquifers): Consist of any Class I aquifer that is overlain by less than 50 feet (ft) of low permeable, unconsolidated material, such as glacial till, lacustrine, and loess deposits.

Class II Aquifers (Consolidated Bedrock Aquifers, Moderately Vulnerable to Contamination)

IIa (Higher Yield Bedrock Aquifers): Consist of consolidated sedimentary or crystalline rocks. Fairly coarse sandstone or conglomerates that may contain lesser amounts of interbedded fine-grained clastics and occasional carbonate units are the most common aquifer types in this class. Well yields must generally exceed 50 gallons per minute (gpm) to be included in this class.

IIb (Lower Yield Bedrock Aquifers): Consist of the same lithologies as Class IIa but well yields are less than 50 gpm in general. Compared to Class IIa sedimentary-rock aquifers, sedimentary-rock aquifers in this class generally are finer grained and have a higher degree of cementation or induration. Most crystalline-rock aquifers are low-yield aquifers.

IIc (Covered Bedrock Aquifers): Consist of Class IIa or IIb aquifers that are covered by less than 50 ft of low permeability, unconsolidated material.

Class III Aquifers (Covered Consolidated or Unconsolidated Aquifers)

III: Consolidated or unconsolidated aquifers that are overlain by more than 50 ft of low permeability material. (Note: For the purpose of this project this definition has been broadened to include all confined aquifers).

Subclass u Aquifers (Undifferentiated Aquifers)

This classification is used where several lithologic and hydrologic conditions are present within a mappable area. Units are assigned to this class because of constrains of mapping scale, the presence of undelineated members within a formation or group, or the presence of nonuniformly occurring features, such as fracturing. This class is intended to convey a wider range of vulnerability than is usually contained within any other single class.

Subclass v Aquifers (Variably Covered Aquifers)

The modifier “v” is used to describe areas where an undetermined or highly variable thickness of low permeability sediments overlies the major water-bearing zone. In practice, this modifier was used sparsely. Usually it applies where the available geologic description indicates that a confining unit is above the zone of production, but little specific information about the thickness of confining layers is known.

Additional Aquifer Classifications

The following four aquifer classifications were added to expand the classification scheme to better handle situations where the source aquifer information is not known or is not available.

I (Surficial): Consist of CWS and NTNCWS groundwater wells 50 ft deep or shallower where the source aquifer information is unknown or cannot be validated. It is inferred that these wells derive water from a surficial or shallow, permeable aquifer.

VUN (Vulnerable): Consist of CWS and NTCWS groundwater wells deeper than 50 ft where the source aquifer information is unknown in which at least 90% of the surrounding wells (within a defined search radius and depth range) derive water from vulnerable aquifers (Class: I, Ia, Ib, Ic, Id, or IIa).

NVUN (Non-vulnerable): Consist of CWS and NTNCWS groundwater wells deeper than 50 ft where the source aquifer information is unknown in which at least 90% of the surrounding wells (within a defined search radius and depth range) derive water from non-vulnerable aquifers (Class: IIb, IIc, or III).

UNK (Unknown): Consist of CWS and NTNCWS groundwater wells where information necessary to classify the source aquifer is either inadequate or incorrect and precludes a Pettyjohn classification.

PHMSA applies the Pettyjohn classification scheme to the source aquifer information associated with each CWS or NTNWS groundwater well. This approach differs from classifying the aquifers alone and allows for a localized classification of the source aquifer at the specific location of each well by taking into account the presence or absence of any overlying confining geologic units. For example, two groundwater wells may derive water from the same consolidated, high-yield, bedrock aquifer, but receive different Pettyjohn classes. The well located in and deriving water from the outcrop of the aquifer is assigned Class IIa. However, the well located within the outcrop of a confining unit atop the source aquifer is a Class III, because the overlying confining units are relatively impermeable and impede the downward flow of fluids to the more sensitive bedrock aquifer below.

The determination of source aquifer information for the CWS and NTNCWS groundwater wells can be a complex problem, as no national database directly providing such information is available. Furthermore, for some CWS and NTNCWS, the source aquifer is not known. However, other information such as depth of well or vulnerability of nearby groundwater wells allows for a general aquifer classification with a high level of confidence. For example, a well that is 25 ft deep but the source aquifer information is unknown can be considered to source a vulnerable aquifer because of the shallow depth.

4.0 49 CFR PART 195.6 DATA SOURCE GUIDANCE

The definition in 49 CFR Part 195.6 provides guidance for determining DW USAs through an analysis of Public Water System intake data, Wellhead and Source Water Protection Areas, and Sole Source Aquifers. Additional information used in the analysis, not specifically identified in the definition, are geology, aquifer, and hydrography data. DW USAs are determined by subjecting these data to the appropriate filter criteria as outlined in the DW USA definition.

The definition mentions three specific data sets required to determine DW USAs: Community Water System or a Non-Transient Non-Community Water System, which are part of the Public Water System data; Source Water Protection Areas, which includes Wellhead Protection Areas; and Sole Source Aquifers. Potential data sources, known issues, and possible solutions to the issues for each data set are discussed in the following sections.

4.1 Public Water System (PWS) Data

Safe Drinking Water Information System (SDWIS)

The Safe Drinking Water Act requires states to report drinking water information periodically to EPA. This information is maintained in a federal database, the Safe Drinking Water Information System (SDWIS) Federal Data Warehouse that is managed by EPA.

When the DW USAs were completed in 2002, PWS data were obtained from each state where available, because there was no available national source for the required data. Due to the required reporting of the PWS data to SDWIS, the SDWIS data has become a reliable data source. The PWS data are the most critical base data set required to determine DW USAs and are also one of the base data layers that would have changed the most over time. Because these data are critical in the determination of each DW USA, it is important to understand potential changes and limitations to the SDWIS layer.

Potential changes in SDWIS over time:

- Significant changes in data collection technologies and accuracy;
- Changes in the status of a well or intake (i.e., becoming active or inactive); and
- Changes in community populations.

Potential limitations in SDWIS:

- PWS ID may not link to the state source water or wellhead protection areas;
- The data may not be as current as available state data due to reporting requirements; and
- The data do not contain groundwater source information (aquifer, depth, screening interval, etc.).

The source aquifer information associated with groundwater wells provides for a more accurate Pettyjohn classification. Because the SDWIS data lack this information, the preferred approach is to collect PWS data from each state along with supplemental tables and well logs that may contain the necessary source information. The SDWIS data set may be used when state data are not available due to state laws or regulations that restrict the distribution of sensitive PWS data.

USGS Groundwater Site Inventory (GWSI)

The U.S. Geological Survey (USGS) GWSI database is another possible national data set that could be leveraged for the determination of DW USA. These data contain source information that would be useful for improving the results of the DW USA model. Upon receipt and further evaluation of the data set, it was determined these data could not be used because there was no method to link the source aquifer information in the GWSI data to each well record in the SDWIS data.

4.2 Source Water Protection Area (SWPA) and Wellhead Protection Area (WHPA)

The Source Water Protection Areas and Wellhead Protection Areas data are essential to the determination of DW USA. For this report, these layers will be referred to as Source Water Protection Areas (SWPAs). The SWPA data are no longer managed by EPA, and the data for the SWPAs are now left up to each state for implementation and data management. Thus, there is not a national data structure or geospatial standard for the states to follow when developing SWPAs. The lack of any standard proved to be problematic when trying to use SWPAs to generate USAs.

Generally, available geospatial data for SWPAs consist of three different assessment areas or zones. These zones range in size from 100-ft buffers around a specific wellhead to entire watersheds. It was difficult to acquire information from the states on which SWPA zone was the appropriate zone to utilize for liquid pipeline releases. In such situations, the middle zone was used. There were numerous instances where spatial data were not available from the states; however, Source Water Protection Area or Wellhead Protection Area documents were available for each state. In these cases, distances specified within the documents were used during the determination of USAs for groundwater wells. Lastly, email communications from state agency staff specifying the appropriate protection distances or model default distances were used.

4.3 Sole Source Aquifer (SSA)

Most of the SSA data did not include details that indicated if the boundary for the SSA represented the recharge area of the aquifer. Only 5 of the 89 SSAs had a name attribute that did identify the recharge area for the SSA. These 5 SSAs are located in Florida, Oklahoma, and Texas. The lack of recharge information limits the identification of the recharge areas as specified in the DW USA filter criteria.

5.0 DATA COLLECTION AND PREPROCESSING

5.1 Data Sources and Collection

The basic process for determining DW USAs requires the following steps:

- Identifying active CWS and NTNCWS surface water intakes and groundwater wells;
- Classifying the source aquifers for the CWS and NTNCWS groundwater wells;
- Generating the DW USA boundaries using the SWPA or WHPA for the vulnerable CWS and NTNCWS groundwater wells and surface water intakes; and
- Identifying the recharge areas of SSAs that are karst in nature.

A significant guideline in the identification of DW USAs was that only publicly available reports, maps, and other data would be used for the identification of the DW USA. The ideal data sets to identify DW USAs would include a state-approved aquifer layer(s), a state geologic map (including bedrock units, Quaternary sediments, surficial deposits/sediments, and lithologic descriptions), SSA boundaries, well data (including accurate location, source aquifer information, pump rates, maximum and screened interval depths), surface water intake locations, approved SWPA or WHPA delineations, and accurate AADWS information. For the DW USA data created in 2018 – 2019, AADWS data were not acquired or collected due to the sensitivity of the AADWS data, which was not as sensitive in the 2000-2001 DW USA data creation. As discussed in Section 3.0, there are multiple sources for PWS data, including state PWS data. In reality, some of the available well data, from any of the sources, are incomplete (e.g., missing source aquifer and/or depth information for some wells, almost always missing screened interval depth). Additionally, the spatial quality of state geologic layer and state aquifer data are highly variable and sometimes incomplete. The SWPA or WHPA delineations may not be available or are incomplete. The approaches for determining SWPA or WHPA vary significantly from state to state. Because the amount of information available on a state-by-state basis differs, the model was developed to identify USA regardless of the variability of information in the input data set. All the source data are processed and formatted into a standard data format required by the DW USA model.

The model requires state PWS data in digital format. The PWS data should indicate the type of intake (i.e., surface water intake or groundwater well). Preferably, the data should also indicate the type of system (i.e., CWS, NTNCWS) and well depth information.

In addition to the PWS data, a statewide aquifer layer is required to run the model. If a statewide aquifer layer does not exist in digital format, aquifer outcrop and subcrop delineations may be converted into digital format from other "state-accepted" sources, such as bedrock and surface geology or groundwater basins. If state-approved aquifer subcrop delineations cannot be found or inferred from a source that is in a readily convertible format, the model requires a geologist to validate the source aquifer information for groundwater wells that could possibly be receiving water from the subcrop of an aquifer.

The ideal data sets to determine DW USAs include publicly available nationwide data sets for drinking water sources (PWS), aquifer boundaries, SWPAs/WHPAs, and SSAs. If these are not publicly available, the data will need to be collected from each state. The required data layers and the known optional data layers are:

- Required Data
  - Public Water System
  - Aquifer Boundaries
  - Hydrography

- Known Optional Data
  - Geology
    - Bedrock Geology (extent of surface contacts of geologic formations within a state)
    - Surficial Geology (extent and distribution of Quaternary deposits within a state)
    - Glacial Drift (extent and distribution of glacial deposits within a state)
    - Sediment Thickness
  - Sole Source Aquifer Boundaries
  - Source Water Protection Areas
  - Wellhead Protection Areas
  - Lookup tables or other related tables used to link the protection areas with the PWS data.

The data sets collected nationally or from each state are preprocessed to fit the requirements of the DW USA model. For consistency among states, data for the contiguous 48 states and Puerto Rico are projected to the North American Datum of 1983 Contiguous USA Albers Equal Area (Appendix A). Because Alaska and Hawaii are so far removed geographically from the contiguous 48 states and each other, a separate projection is used for each. Alaska data are projected to Alaska Albers Equal Area Conic, and Hawaii data are projected to Hawaii Albers

Equal Area Conic. Each data layer is formatted as described in the data dictionary (Appendix B). To ensure that all states are processed properly, detailed guidelines have been established and followed by the project team. Below is a brief discussion of the collection and processing guidelines.

Required and optional data collected from national or state sources were processed to meet the data requirements for use in the DW USA model. The data were then projected to the standard DW USA map projection

5.2 Required Data Layers

5.2.1 Public Water Supply System (PWS)

The data set including information on each source of water (e.g., groundwater well, surface water intake, or spring) for a PWS is referred to as the PWS data. Generally, each state maintains a PWS data set that includes information for CWS, NTNCWS, and TNCWS. The data may be maintained by the state as a geospatial layer or a non-spatial database. As the model works on a spatial premise, spreadsheets and databases are converted to geospatial layers. The statewide PWS data set required to run the DW USA model was collected in a variety of formats, including ESRI® File or Personal Geodatabases, Shapefiles, Export files, Microsoft® Access databases, Microsoft® Excel spreadsheets, Microsoft® SQL Server, or other databases. The data were converted to an ESRI® File Geodatabase using the appropriate method based on file type.

The PWS data are best represented as points since each PWS source can be stored as a single geographic location. Several attributes are added for each PWS source at the end of the attribute table provided with the source data (Appendix B). Table 1 lists the attribute(s) required to run the DW USA model for the PWS layer.

Table 1. Required attribute(s) for the PWS layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
PWS	PWS_ID (Text, 10 Character)	Public Water System Identifier	ST####### (e.g., ND1840049) or NULL Note: Could link to 1 or several SWPA. The field CANNOT be blank
	SWPABUFF (Numeric, type based on input data)	Source Water Protection Area or Wellhead Protection Area (WHPA) radius in meters	0-X (defaults to 609.6m or 2000ft) Note: The field CANNOT be NULL

Following is a brief description of how the required attributes were updated.

PWS_ID: In most cases, this item was already identified in the PWS data as PWS_ID or some close derivative.

SWPABUFF: This is only updated for groundwater wells. For those situations where the state uses a fixed-radius to determine the SWPA/WHPA boundary and there were no digital SWPA/WHPA boundary data available, this item would be updated to the radius, in meters, of the SWPA/WHPA as defined by the state. For those situations where the state has no fixed-radius method available to determine the SWPA/WHPA boundary and there were no digital SWPA/WHPA boundary data available, this item would be updated to the default radius of 609.6 m (or 2,000 ft).

Systems that were not classified as Public Water Systems by the definition above (e.g., irrigation, industrial, agricultural, etc.) and those systems located well outside the state were removed from the PWS layer.

5.2.2 Source Lookup Table (SOURCE_LUT)

One of the key data sets used for classifying groundwater wells is the source aquifer or source material description. The SOURCE_LUT is an optional table used in the DW USA model when source aquifer information or source material information is available in the PWS data. When source information is available, the model attempts to validate the listed source aquifer information for each well location. Because of the variability in the level of geologic detail used in describing the source aquifer or source material, as well as regional differences in the names of aquifers, the model makes use of a source aquifer lookup table. Table 2 is an example of the SOURCE_LUT for Ohio. The table allows for the standardizing of aquifer source descriptions or source material descriptions found in the PWS data to a standardized set of aquifer codes. For example, in the case of Texas, approximately 167 separate source descriptions were collapsed to approximately 36 aquifer codes. Sometimes a standardized aquifer code cannot be determined from the source information associated with each groundwater well due to lack of information in the SOURCE attribute. In this case, and when the groundwater wells do not have any geologic unit descriptions or source material information, they are assigned a standardized aquifer code of UNK representing unknown source aquifer. The source aquifer lookup table is generated for all PWS data in which some type of source aquifer, geologic unit descriptions, or source material information is available.

Table 2. Example of the source lookup table (SOURCE_LUT) for Ohio.

SOURCE	AQUIF_CODE
Unknown	UNK
Alluvial/River Valley	SURF
Beach Ridge	SURF
Buried Valley	SURF
Carbonate Bedrock	PZCA,NAPA
Fractured Bedrock	PZCA,PZSA,NAPA
Karst	PZCA,NAPA
Lacustrine	SURF
Multiple Settings	SURF,PZCA,PZSA,NAPA
Sand in Till/Moraine	SURF
Sandstone/Shale	PZSA,NAPA
Till/Moraine	SURF

5.2.3 Aquifer Boundaries

In addition to the PWS data, a statewide aquifer data set is required to run the model. This layer is either obtained from the state or created from other geologic data layers. The aquifer boundaries may depict only the surface contact boundaries of the aquifers, otherwise referred to as aquifer outcrops. In some states, the aquifer boundaries may contain the entire extent, surface and subsurface area, of the aquifer. If aquifer boundaries with state-wide coverage cannot be acquired from the state or do not exist, then a geologist is required to produce aquifer boundaries from other state-published data sets, such as surface or bedrock geology data. In most cases, when a geologist is responsible for creating the aquifer map for a given state, the aquifer delineations are limited to aquifer outcrops only.

In situations where the aquifer boundaries containing aquifer outcrop or outcrop and subcrop extents exist, a staff geologist is required to assess and control for data quality. The aquifer data received from the state are examined for consistency with other state-published geologic data sets, such as surface geology. The geologic units and their lithological descriptions from the state's geologic data sets are compared with the geologic formations that have been assigned to an aquifer. The aquifer data received from the state are also compared to similar maps from published literature as well as schematic geologic cross sections and cross sections produced from well data, where available. The locations and geometries of aquifer outcrops are compared with published maps for consistency. If the aquifer boundaries contain aquifer subcrop delineations, then subcrop extents are compared with known geologic basin boundaries. In situations where the aquifer extents are found by the geologist to be inconsistent with other state-published geologic data sets, or differ significantly from aquifer extents in published literature, a determination may be made to discard the aquifer extents received from the state and produce a new aquifer coverage from other state-derived geologic data sets.

In situations where the aquifer boundaries cannot be acquired or do not exist, then a geologist is required to produce the aquifer boundaries from state-published data sets, such as surface geology. In order to produce aquifer boundaries for a given state, the geologist will review the published literature and develop an understanding of the hydrogeologic framework for the state, including aquifer age, lithology, and extent. Then the geologist will group aquifer units based on location or physiographic designation and rock properties that affect how groundwater is stored in and flows through the aquifer matrix. These properties include the aquifer age and associated diagenetic history, rock chemistry (siliciclastic vs. carbonate), rock texture, rock permeability and extent of post-depositional alteration by secondary geologic/tectonic processes. After aquifer units have been grouped, the geologist will assign geologic units from the surface geology data layer to aquifers based on the age and lithologic descriptions of the geologic units. When multiple lithologic descriptions are assigned to a given geologic unit, the descriptions are checked against published lithologies based on geologic formation. If there are discrepancies between the lithologic descriptions contained in the geologic data sets and descriptions from published literature, preference is given to state-published data. When a geologic unit contains changes in lithology that could affect the vulnerability of the aquifer to contamination by infiltration, minor aquifer lithologies can play an important role in determining which aquifer a given geologic unit is assigned. This is particularly true when lithologic changes relate to the presence of carbonates in a geologic unit. Once all geologic units have been assigned to an aquifer, the resulting aquifer data layer is checked against published aquifer maps for the given state. Since preference is given to state-published geologic data sets, aquifer boundaries generated by the geologist are compared to published aquifer maps for general agreement only. Table 3 lists the attribute(s) required to run the DW USA model for the aquifer layer.

Table 3. Required attribute(s) for the aquifer layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
AQUIFER	AQUIF (Text, 10 Characters)	Four-letter aquifer abbreviation with suffixes _OUT or _SUB appended if subcrop info available	Free text (Aquifer Abbreviation) e.g., TRINITY AQUIFER subcrop avail = TRIN_OUT, TRIN_SUBNote: The field CANNOT be blank or NULL

5.2.4 Vulnerability Lookup Table (RULES_LUT)

The key to identifying vulnerable groundwater wells is distinguishing those systems that obtain their water from Pettyjohn Class I or Class IIa aquifers. Refer to Section 3.0 Aquifer Vulnerability Classification above for a detailed description of the Pettyjohn classification scheme. To aid in the process of classifying groundwater wells with a Pettyjohn class, rules for applying the Pettyjohn classification were developed for each state by a geologist (Appendix C). These guidelines take into account all available groundwater well data (e.g., location, depth, pump rate) and aquifer/geologic information. Once the guidelines are developed, a lookup table called RULES_LUT (Appendix D) is created for each state based on the information in the guidelines.

The attributes of the RULES lookup table will vary depending on what information is available in the state PWS data and aquifer/geology data. Table 4 lists the attribute(s) required to run the DW USA model for the RULES_LUT Lookup table.

Table 4. Required attribute(s) for the RULES_LUT Lookup table. See Appendix B for a complete list of possible attributes and attribute values for this table.

Lookup Table	Attribute Names	Description	Attribute Values
RULES_LUT	VAL_AQUIF (Text, 10 Characters)	Aquifer code of source aquifer identified in the guidelines	Free text (Aquifer Code) or NULL e.g., TRINITY AQUIFER = TRIN OR TRIN_OUT/TRIN_SUB Note: The field CANNOT be blank or NULL
	CLASS (Text, 10 Characters)	Pettyjohn class of the source aquifer identified by this set of criteria	Class Ia: Unconsolidated Aquifers Class Ib: Soluble and Fractured Bedrock Aquifers Class Ic: Semi-consolidated Aquifers Class Id: Covered Aquifers Class IIa: Higher Yield Bedrock Aquifers Class IIb: Lower Yield Bedrock Aquifers Class IIc: Covered Bedrock Aquifers Class III: Covered Consolidated or Unconsolidated Aquifers overlain by >50 ft low permeability material or NULL Note: The field CANNOT be blank or NULL
	MIN_DEPTH (Numeric, type based on input data)	Minimum well depth for the groundwater systems with this classification	0-X Note: The field CANNOT be NULL
	MAX_DEPTH (Numeric, type based on input data)	Maximum well depth for the groundwater systems with this classification	0-X Note: The field CANNOT be NULL
	RULE (Text, Characters)	Number of the guideline as described by the geologist in the Guidelines document	Free text e.g., 1a Note: The field CANNOT be blank or NULL

5.2.5 Hydrography

The USGS National Hydrography Dataset High Resolution FileGDB 10.1 Model Version 2.2.1 was used in the 2018-2019 DW USA update. These data were downloaded from the USGS by state. The model requires that the hydrology features extend 10 miles beyond the state border. Therefore, the hydrology features from the adjacent states were joined to the hydrology of the state being processed and then clipped with a buffer extending 10 miles past the state border. The state bordered used in the buffering process was provided by PHMSA. It was not necessary to edge-match the hydrology for the neighboring states due to the improved quality and structure of the National Hydrography Dataset (NHD). Table 5 lists the layers and attribute(s) required to run the DW USA model for the hydrography layer.

Table 5. Required layers and attribute(s) for the hydrography layers. See Appendix B for a complete list of possible attributes and attribute values for these layers.

Geographic Themes	Attribute Names	Description	Attribute Values
NHD_AREA)	FCode (Long Integer)	USGS Classification Code	Value or 0 Note: The field CANNOT be NULL
NHD_WATERBODY	FCode (Long Integer)	USGS Classification Code	Value or 0 Note: The field CANNOT be NULL
NHD_FLOWLINE	FCode (Long Integer)	USGS Classification Code	Value or 0 Note: The field CANNOT be NULL

5.2.6 LUT Open Water Lookup Table (OW_NHD_LUT)

The model needs to identify the potable open-water features in order to generate protection areas for surface water PWS sources. The Open Water Lookup Table (OW_NHD_LUT) is added to the geodatabase for each state when generating the state geodatabase as described in the Hydrography Section (Section 5.3). This table contains the descriptions and an open-water classification of all the water feature codes used in the NHD hydrography data (Appendix E).

The model only looks for values of OPEN WATER in the field CLASS. Values such as OTHER and blank values are ignored by the model. Table 6 lists the attribute(s) required to run the DW USA model for the Open Water Lookup table.

Table 6. Required attribute(s) for the Open Water Lookup table. See Appendix B for a complete list of possible attributes and attribute values for this table.

Lookup Table	Attribute Names	Description	Attribute Values
OW_NHD_LUT	CLASS (Text, Characters based on input data)	Used to determine if the feature is to be considered open water by the model	Free text or NULL Note: The field CANNOT be blank
	FCODE (Long Integer))	USGS Classification code	0-X Note: The field CANNOT be NULL
	DESCRIPTION (Text, Characters based on input data)	USGS description of the entity label	Free text or NULL Note: The field CANNOT be blank

5.3 Known Optional Data Layers

5.3.1 Geology

There are five possible geology data layers: Bedrock Geology (BGEO), Surficial Geology (SGEO), Glacial Drift (DRIFT), Sediment Thickness (SEDTHICK) and BASIN. The geologist determines the appropriate feature class for each layer. In general, a geology layer that has Alluvial, Holocene, and Pleistocene features are considered surficial geology (SGEO), and a layer composed of Cretaceous, Permian, Cambrian, etc. features are considered bedrock geology (BGEO).

The bedrock geology layer gives the spatial extent of the surface contacts of the geologic formations in the state. In some cases, such along the Gulf and southern Atlantic coasts, these formations may be unconsolidated or semi-consolidated sediments, and are not true rock formations. This is a polygon layer with no overlapping features. This information is obtained from the state preferably as a geospatial layer. Many states may refer to this layer as surficial geology. For the purpose of this project, this layer was always treated as bedrock geology. Table 7 lists the attribute(s) required to run the DW USA model for the BGEO layer.

Table 7. Required attribute(s) for the BGEO layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
BGEO	FM (Text, Characters based on input data)	Bedrock geology code	Free text or NULL Note: The field CANNOT be blank

The following is a brief description on how the required attributes were updated.

FM: This code is updated from the geologic code that is usually included in the geologic layer provided by the state.

The surficial geology (SGEO) layer gives the extent and distribution of the Quaternary deposits. The features that are included in this layer are unconsolidated sediments such as alluvium, loess, and till. In the states where these data are available, it is collected as a geospatial layer. This is a polygon layer with no overlapping features. When a surficial geology layer exists, it is assumed that the surficial geology features are present on top of the bedrock geology features. Table 8 lists the attribute(s) required to run the DW USA model for the SGEO layer.

Table 8. Required attribute(s) for the SGEO layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
SGEO	SGEO_DESC (Text, Characters based on input data)	Surficial geology description	Free text or NULL (e.g., Mississippi River Alluvium) Note: The field CANNOT be blank

The following is a brief description on how the required attributes were updated.

SGEO_DESC: This item is updated directly with the value for the description of the geologic feature that is included in the data file obtained from the state. It can be a code or full geologic description, such as Mississippi River alluvium.

The glacial drift (DRIFT) layer gives the extent and distribution of glacial deposits. The features that are included in this layer are usually glacial till, outwash, and alluvium. This layer provides information on the thickness of the glacial drift. In the states where these data are available, it is collected as a geospatial layer. This is a polygon layer with no overlapping features. When a glacial drift layer exists, it is assumed that the glacial drift features are present on top of the bedrock geology features. Table 9 lists the attribute(s) required to run the DW USA model for the DRIFT layer.

Table 9. Required attribute(s) for the DRIFT layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
DRIFT	THICK_GLAC (Text, 1 Character)	Code indicating thickness range of glacial drift	Free text or NULL (e.g., 1: <50 ft 2: >50 ft) Note: The field CANNOT be blank

The following is a brief description on how the required attributes were updated.

THICK_GLAC: This is updated to the thickness range of 1 when < 50 ft and 2 when > 50 ft based on the original data that are associated with the polygons in the layer.

The sediment thickness (SEDTHICK) layer gives the extent and distribution of surficial sediments. The features that are included in this layer are usually glacial till, outwash, and alluvium. In the states where these data are available, it is collected as a geospatial layer. This is a polygon layer with no overlapping features. Table 10 lists the attribute(s) required to run the DW USA model for the SEDTHICK layer.

Table 10. Required attribute(s) for the SEDTHICK layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
SEDTHICK (Surficial geology thickness)	THICK_SGEO (Text, 1 Character based on input data)	Code indicating the thickness of the overlying sediment or the depth to the bedrock	Free text or NULL (e.g., 1: <50 ft 2: >50 ft) Note: The field CANNOT be blank

The following is a brief description on how the required attributes were updated.

THICK_SGEO: This is updated to the thickness range based on the original data that are associated with the polygons in the layer.

The basins (BASINS) layer shows the boundaries of the defined aquifer basins within the state. In the states where these data are available, it is collected as a geospatial layer. This is a polygon layer with no overlapping features. Table 11 lists the attribute(s) required to run the DW USA model for the BASINS layer. Table 11 lists the attribute(s) required to run the DW USA model for the BASINS layer.

Table 11. Required attribute(s) for the BASINS layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
BASINS	BASIN (Text, Characters based on input data)	Name or code of aquifer basin	Free text or NULL (e.g., SALINAS VALLEY) Note: The field CANNOT be blank

The following is a brief description on how the required attributes were updated.

BASIN: This is updated to the name or code for the basin based on the original data that are associated with the polygons in the layer.

5.3.2 Sole Source Aquifers (SSA)

The sole source aquifer layer was available as a nationwide data set from EPA. All SSAs in EPA Regions 1 – 6 and 8 – 10 were available in geospatial format except for the St. Joseph SSA in Indiana which is EPA Region 5. The St. Joseph SSA was extracted from the Aquifer Systems Unconsolidated geospatial layer provided by the Indiana Department of Natural Resources. There were no SSAs in EPA Region 7. The nationwide SSA layer was clipped by the state boundary provided by PHMSA and is a polygon layer with no overlapping features. Table 12 lists the attribute(s) required to run the DW USA model for the SSA layer.

Table 12. Required attribute(s) for the SSA layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
SSA *(Bolded attributes required)*	KARST (Text, 1 Character)	Indicates if the SSA is Karst	Y or NULL Note: The field CANNOT be blank
	RECHARGE (Text, 1 Character)	Indicates if the feature is a recharge area	Y or NULL Note: The field CANNOT be blank
	NAME (Text, Characters based on input data)	The official (EPA) name of the SSA	Free text or NULL (e.g., EDWARDS II) Note: The field CANNOT be blank
	AQUIF (Text, Characters based on input data)	4-10 Letter code for the SSA	Free text or NULL Note: If in AQUIFER FC, = AQUIF, else _SSA suffix denoting SSA FC only Note: The field CANNOT be blank

The following is a brief description on how the required attributes were updated:

KARST: If the sole source aquifer is a karst aquifer, based on information provided by the geologist, this field is updated with a 'Y', otherwise it is NULL.

RECHARGE: If the boundaries for the sole source aquifer represents the recharge area, this field is updated with a 'Y', otherwise it is NULL.

NAME: This field is the official name of the sole source aquifer as provided by EPA.

AQUIF: Is updated with the 4 to 10 letter code that the model uses for identifying aquifers. If the SSA is already included in the AQUIFER layer, this item gets updated to the same value as AQUIF in the AQUIFER layer. Otherwise it is given a new 4-letter code, and _SSA is appended to it to indicate that it is from the SSA layer.

5.3.3 Source Water Protection Areas (SWPA)

The Source Water Protection Area and Wellhead Protection Area data, further referred to as SWPA in this section, are delineated protected areas around public water systems (groundwater wells, surface water intakes, and springs). The SWPA data are typically delineated and managed through the state Source Water Protection or Wellhead Protection programs and, in some cases, both programs. When both SWPA and WHPA exist for a single state, they are merged into the SWPA layer for use in the DW USA Model.

The SWPA layer is used to identify the protected areas associated with each well or intake. If the well is classified as vulnerable, then the SWPA becomes the USA or preliminary USA. SWPA polygons from various wells or intakes may overlap so the resulting USAs will have overlapping polygon topology.

The primary requirement for being able to use the SWPA data provided by the state is some method to link the SWPA polygon with the appropriate well, surface water intake, or spring. The link is either on PWS_ID or a unique well or intake identifier. Because PWS_ID is a system identifier, it is possible for multiple wells and multiple SWPA polygons to have the same PWS_ID. In this case, a unique identifier is assigned to each SWPA, and that identifier is also assigned to the appropriate wells. Because it is possible for DW USAs to overlap, when there are overlapping SWPA polygons, the original data must accurately represent the overlap, showing all unique SWPA polygons in the overlapped area. Table 13 lists the attribute(s) required to run the DW USA model for the SWPA layer.

Table 13. Required attribute(s) for the SWPA layer. See Appendix B for a complete list of possible attributes and attribute values for this layer.

Geographic Themes	Attribute Names	Description	Attribute Values
SWPA	PWS_ID (Text, 10 Character)	Public Water System Identifier	ST####### (e.g., ND1840049) or NULL Note: Could link to 1 or several SWPA. The field CANNOT be blank

The following is a brief description on how the required attributes were updated.

PWS_ID: In most cases, this item was already identified in the SWPA data as PWS_ID or some close derivative.

5.4 QA/QC Procedures

Once the required data layers and available optional layers are collected and preprocessed, the data undergo a thorough Quality Assurance and Quality Control (QA/QC) process prior to executing the DW USA model. Throughout data collection and preprocessing, a series of documents were maintained to keep track of the collection and preprocessing steps for each layer. These documents were frequently referenced during the QA/QC process to ensure the final data conform to the DW USA data schema. A detailed data processing QA/QC checklist (Appendix F) was created to facilitate the data review. After the data are reviewed and updated as needed, the final preprocessed data are organized in a standardized file geodatabase (Figure 1) and submitted to the DW USA GIS Model.

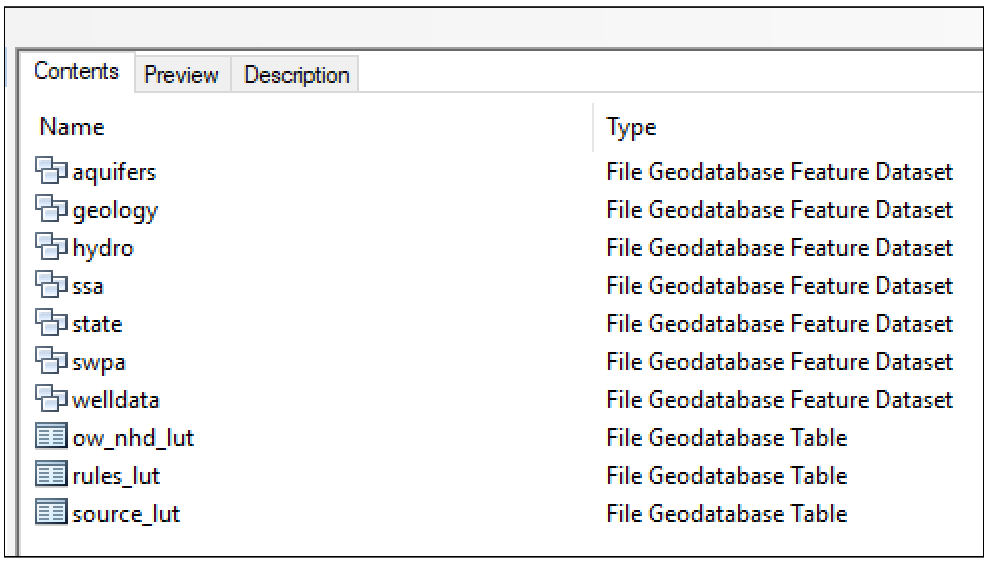


Figure 1. Standardized file geodatabase format required by the DW USA GIS Model.

6.0 DRINKING WATER USA GIS MODEL

6.1 DW USA Model Conversion

The utilization of a model to determine the DW USAs ensured that the filter criteria and USA designation process are applied consistently for all the states. It also ensured that all the ground water wells are classified with an appropriate aquifer vulnerability when edits or updates are necessary regarding the aquifer vulnerability classification.

The original DW USA model algorithms were developed using ESRI Arc Macro Language (AML) for ArcInfo version 8 Geographic Information System (GIS) software. ArcInfo, now known as ArcInfo Workstation, was last released July 2010, and the product was officially retired on 1 January 2016. The model was re-written to work with the later version of ESRI

ArcGIS for Desktop software using the Python programming language in order to keep up with GIS software updates. The new model code was developed using Python version 2.7.10 to work with ArcGIS 10.4 Desktop Advanced.

6.2 Converted Model Testing

Once the code was translated, the model was tested using data from the 2001 DW USAs to ensure that the AML-to-Python conversion worked properly. The testing included comparing the resulting number of preliminary DW USAs and total area determined by the Python version of the model to the number of preliminary DW USAs and total area determined by the AML version of the model in 2001. Four states (Texas, North Dakota, Alabama, and Maryland) were used in the testing and were chosen in order to test the wide variability in input data sets used by the models. The number of preliminary DW USA s were the same for both versions of the model as shown in Table 14. However, the total area of the preliminary DW USAs increased with the Python version of the model as shown in Table 15.

Table 14. Number of preliminary USAs.

Number of Preliminary Drinking Water USAs		
Prior 2001 State Data	2001 ArcInfo Coverage (AML)	2019 ArcGIS Geodatabase (Python)
Texas	7106	7106
North Dakota	706	706
Alabama	520	520
Maryland	729	729

Table 15. Total area of preliminary USAs.

Total Area of Preliminary Drinking Water USAs (square miles)				
Prior 2001 State Data	2001 ArcInfo Coverage (AML)	2019 ArcGIS Geodatabase (Python)	Area Difference	Percent Difference
Texas	24,926.3	25,220.7	294.4	1.2%
North Dakota	1,509.4	1,519.0	9.6	0.6%
Alabama	4,424.5	4,454.7	30.1	0.7%
Maryland	2,677.1	2,693.7	16.5	0.6%

The increase in total area of the preliminary DW USAs was due to algorithm differences in the software tool used for buffering spatial features within the ESRI GIS software and not due to the translation of the model. The buffer tool in ArcGIS produced more accurate results than the buffer tool in ArcInfo. This was most notable with the buffers of open-water features used for surface water intakes, as shown in Figure 2.

In addition, the improvements to the buffer tool extended to the buffers of point features such as ground water wells. In ArcInfo, circles and other curves were approximated using small straight segments between two vertices. However, ArcGIS utilizes parametric curves when generating buffers when utilizing a geodatabase storage format. These parametric curves also increased the total area of the preliminary DW USAs by a small amount by representing the area of the buffer more accurately (Figure 3).

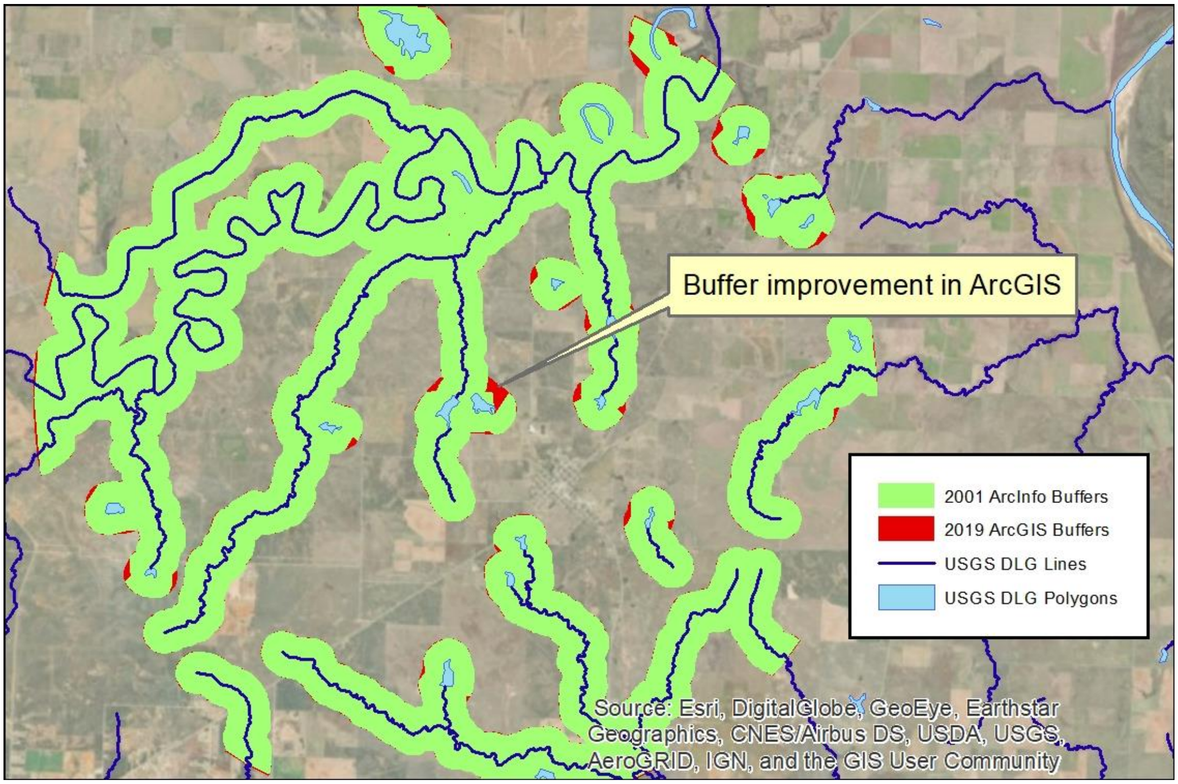


Figure 2. ArcInfo vs. ArcGIS buffer tool polygon buffer improvement.

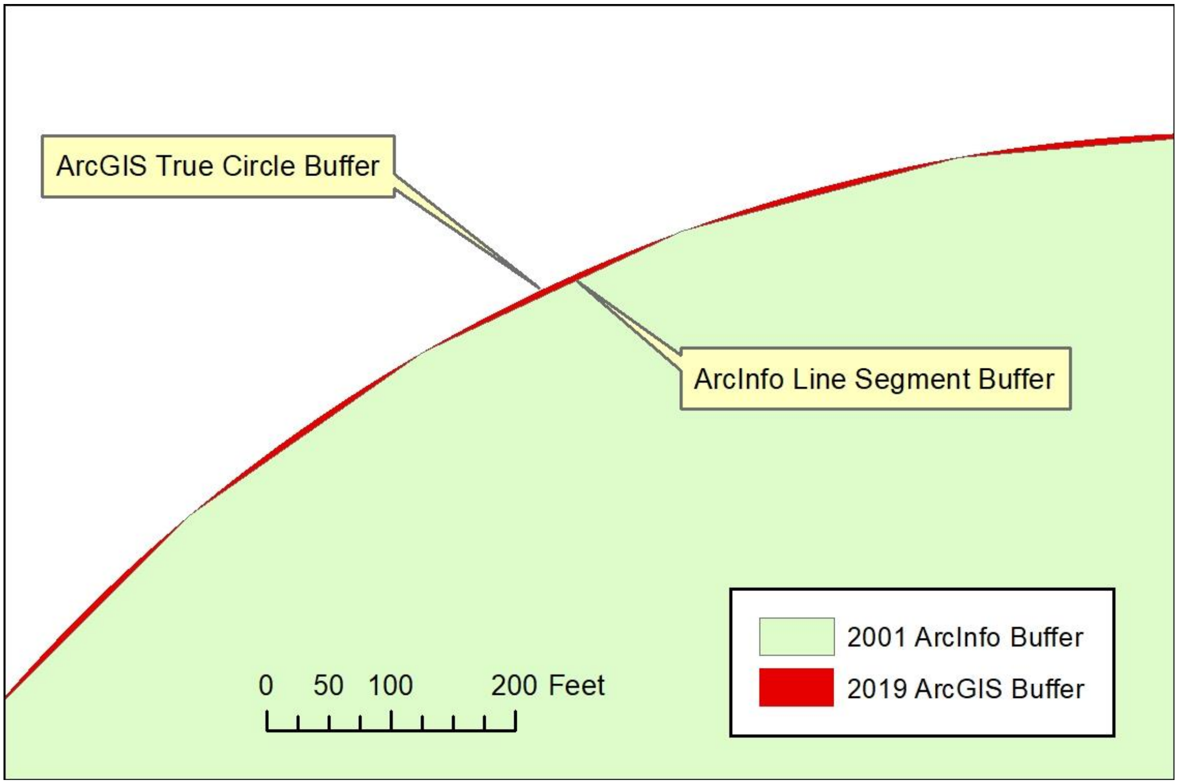


Figure 3. ArcInfo line segment versus ArcGIS true curves.

The parametric curves generated by the improved buffer tool can potentially cause issues when projecting the data to another projection. There are several different methods for addressing this issue. One option is to export the data into the ESRI shapefile format, which does not support parametric curves. This causes the export tool to automatically densify any parametric curves in the data. The densify process adds vertices along a line or polygon and replaces the parametric generated curves with line segments. Table 16 is a comparison of the total area of preliminary DW USAs in the geodatabase format that incorporates the parametric curves to the total area of the same preliminary DW USAs data exported to the ESRI shapefile format. As expected, the densify process slightly reduced the total area of the preliminary DW USAs.

Table 16. Area difference with densify handled by exporting shapefile.

Total Area of Preliminary Drinking Water USAs (square miles)				
Prior Data	ArcGIS Geodatabase	ArcGIS Shapefile Densify	Area Difference	Percent Difference
Texas	25,220.7	25,220.0	(0.76)	-0.003%
North Dakota	1,519.0	1,518.9	(0.06)	-0.004%
Alabama	4,454.7	4,454.6	(0.08)	-0.002%
Maryland	2,693.7	2,693.6	(0.08)	-0.003%

Another option was to incorporate the densify process in the model which allowed for more control of the densify process before the data is exported to the ESRI shapefile format. This option yielded preliminary DW USAs with a finer density of line segments and more closely matched the total area of preliminary DW USAs represented with parametric curves (Table 17). This option was used by the model for updating the DW USAs.

Table 17. Area difference with densify handled by model.

Total Area of Preliminary Drinking Water USAs (square miles)				
Prior Data	ArcGIS Geodatabase	ArcGIS Shapefile Model Densify	Area Difference	Percent Difference
Texas	25,220.7	25,220.3	(0.45)	-0.002%
North Dakota	1,519.0	1,519.0	(0.03)	-0.002%
Alabama	4,454.7	4,454.6	(0.05)	-0.001%
Maryland	2,693.7	2,693.6	(0.04)	-0.002%

6.3 Model Flow

The greatest challenge of the DW USA process is determining the aquifer vulnerability of each groundwater well. The model was designed to ensure the integrity of the aquifer vulnerability classification. A flowchart indicating the process utilized by the model can be found in Appendix G. The process used by the model can be divided into the following categories:

- Setup and Initial Filter Criteria
- Source Aquifer Validation
- Aquifer Vulnerability Classification
- Source Aquifer Assignment
- Assignment of Quality Codes
- Delineate Preliminary DW USAs
- Upstream/Downstream Buffer Process
- Determine Final DW USAs

6.4 Setup and Initial Filter Criteria

The model first creates a unique identifier for each source feature within the PWS data layer. This identifier allowed one to track the process of each PWS source throughout all the processing steps of the model. Following the creation of the unique identifier, the model performs some of the preliminary filter criteria for determining DW USAs by the following steps:

- Select only active PWS sources from the PWS data layer for further processing (ACTIVITY_CODE = ‘A’);
- Select only CWS and NTNCWS from the PWS data layer for further processing (SYSTEM_TYPE in (‘C’,’P’));

- Separate the different types of PWS sources (i.e., groundwater wells, surface water intakes, and springs) into separate data layers in order to process and delineate any potential DW USAs for each source appropriately; and
- Add fields necessary to properly identify groundwater sources as DW USAs are added to the groundwater well data layer.

These fields and their corresponding descriptions are listed in Table 18. It is important to note the following assumptions made by the model during the initial filter process.

- If the item ACTIVITY_CODE does not exist on the PWS data layer, the model assumes that all PWS source are active.
- If the item SYSTEM_TYPE does not exist on the PWS data layer, the model assumes that all PWS sources are CWS.

Table 18. Fields necessary to properly identify USAs for groundwater wells.

Necessary Fields for Identifying USAs for Groundwater Wells	
Field	**Description**
VAL_AQUIF	Validated or assigned source aquifer of the groundwater well
CLASS	Aquifer vulnerability classification of the groundwater well
QUALITY	Identifier of the process used to classify a groundwater well
RULE_ID	Identifier of the rule used to classify a groundwater well

6.5 Source Aquifer Validation

The source aquifer information is a key part in the aquifer vulnerability classification. When source aquifer information is available for each groundwater well, the model tries to ensure the integrity of this information by validating the source aquifer for each well. If source aquifer information is not available for a particular groundwater well, the model proceeds to assign a source aquifer to the groundwater well so an aquifer vulnerability classification can be determined. Note that any field attributes regarding the source aquifer information in the PWS data take precedence over any deductions or assignments the model tries to infer during processing.

If the field SOURCE exists on the groundwater data layer, the model attempts to validate the source aquifer information for each groundwater well by joining the AQUIF_CODE attribute from the source lookup table, SOURCE_LUT, onto the groundwater well data layer using the SOURCE field on the both the lookup table and the groundwater well data layer as the relatable field. This provides each groundwater well a standardized 4-letter source aquifer code or list of aquifer codes that the model can use to validate the source aquifer information. The model then creates a unique list of 4-letter aquifer codes from the AQUIFER data layer and steps through each value in the list selecting the groundwater wells with the 4-letter source aquifer code, AQUIF_CODE, and overlays the subset of wells onto the AQUIFER data later to verify that the wells lie within their specified source aquifer, with the following outcomes:

- If the groundwater well lies within its specified source aquifer, the model updates the item VAL_AQUIF with the validated AQUIF_CODE.
- If the groundwater well lies outside of its specified source aquifer, the model updates the item VAL_AQUIF as "CANNOT_DETERMINE."

There are two exceptions to the above process:

1. If no alluvial aquifer boundary exists in the aquifer data layer (AQUIF= 'ALLU'), it is assumed that any groundwater well with an alluvial source aquifer is sourcing the alluvial aquifer regardless of location because alluvial aquifers occur almost everywhere. In this situation the model updates the VAL_AQUIF as "ALLU."
2. If no glacial aquifer boundary exists in the aquifer data layer (AQUIF='GLAC'), it is assumed that any groundwater well with glacial source aquifer is sourcing the glacial aquifer regardless of location because glacial aquifers occur almost anywhere. In this situation the model updates the VAL_AQUIF as "GLAC."

During the source aquifer validation, the model will append either "_OUT" or "_SUB" to the 4-letter aquifer code in the VAL_AQUIF field. The "_OUT" indicates the groundwater well lies within the outcrop of the validated aquifer while the "_SUB" indicates the groundwater well lies within the subcrop of the validated aquifer. It is important to note that the groundwater wells are validated against the outcrop boundary first.
After the source aquifer validation, the model checks to see if an interactive aquifer validation is necessary. The interactive validation step is required if the SOURCE item exists for the groundwater wells and the AQUIFER data layer contains no aquifer subcrop delineations. In this situation, there is not enough digital information available for the model to validate whether the groundwater well could be sourcing the aquifer subcrop. The model stops and notifies the user that a geologist needs to validate the source aquifer information for the subset of wells where the source aquifer could not be validated by the model.

The geologist utilizes the geologic maps, cross sections, well data (location and depth), and other references to assist in validating the source aquifer subcrop for the wells in question. If the source aquifer information of the well is consistent with the available geologic data, then the well is given a validated source aquifer subcrop value. If the source aquifer information of the well is inconsistent with the available geologic data, then the source aquifer of the well remains as "CANNOT DETERMINE."

6.6 Determining Source Aquifer Vulnerability

The aquifer vulnerability of a well differs from determining the Pettyjohn classification of the aquifer alone, in that the aquifer vulnerability of a well may change based on the location of the well, depth of the well, well yield, and other variables. For example, two wells may derive water from the same consolidated, high-yield, bedrock aquifer, but may receive two different aquifer vulnerability classifications. The well located in and deriving water from the outcrop of the aquifer may get a vulnerability classification of IIa. However, the well located within the outcrops of confining units atop the aquifer may get a classification of III, because the overlying confining units are relatively impermeable and impede the downward flow of fluids to the more vulnerable bedrock aquifer below.

Once the source aquifer information has been validated or assigned, the model overlays the groundwater well data layer with any existing geology data layers (i.e., bedrock geology, surficial geology, glacial drift information) using an identity operation. This identity combines the attributes of the various geology layers onto the groundwater wells based on the location of each well. The model then steps through each record in the Rules Lookup Table, selecting the wells that meet the criteria for that record and that do not already have an aquifer vulnerability classification. After selecting the wells that meet the criteria for that particular rule, the model assigns the groundwater well the source aquifer vulnerability classification associated with the specific rule. As an example, the following simple rules are followed for determining the aquifer vulnerability.

1. Wells deriving water from the Alluvial aquifer (ALLU) that are covered in loess and derive water from depths <200 ft are Class Id.
2. Wells located within the Alluvial aquifer (ALLU) that derive water from depths <200 ft are Class Ia.
3. Wells deriving water from depths greater than 200 ft are classified as unknown.

The corresponding rules are developed and added to the Rules Lookup Table (see Table 19).

Table 19. Rules Lookup Table.

Row	VAL_AQUIF	CLASS	BGEO_DESC	MIN_DEPTH	MAX_DEPTH	MIN_SCREEN	MAX_SCREEN	RULE
1	ALLU_OUT	Id	Loess	0	0	0	200	1
2	ALLU_OUT	Id	Loess	0	200	0	0	1
3	ALLU_OUT	Ia		0	0	0	200	2
4	ALLU_OUT	UNK		0	0	200	0	3
5	ALLU_OUT	Ia		0	200	0	0	2
6	ALLU_OUT	UNK		200	0	0	0	3
7	ALLU_OUT	Ia		0	0	0	0	2

The model starts with the first row of the table and selects all the groundwater wells that have a validated aquifer value of ALLU_OUT, located within a loess bedrock geologic formation, have a depth of screen less than or equal to 200 ft, and have not been assigned a source aquifer vulnerability classification. The model then assigns the selected set of groundwater wells the aquifer vulnerability classification of Id. The model then moves to the next row in the table and selects all the groundwater wells that meet the criteria assigns the selected set of wells the associated source aquifer vulnerability classification. There are three standard processes associated with the Rules Lookup Table:

1. Selection statements are always performed with an AND operator between the field values (i.e., VAL_AQUIF = 'ALLU_OUT' and BGEO_DESC = 'Loess').
2. For MIN and MAX fields the selection is always: MIN < $n \leq$ MAX.
3. For MIN and MAX fields a value of 0 means no data, therefore field not included in selection statement.

6.7 Processing Groundwater Wells with No Source Aquifer Information

At this point, the model has validated and classified wells that had source aquifer information. For the wells where the source information is either ambiguous or unknown, the model attempts to assign a source aquifer so that an aquifer vulnerability classification can be determined for the well. If the groundwater wells within the PWS data layer do not have source aquifer information, the well is inferred to draw water from the single shallowest aquifer the well overlies. In most cases, the well will overlie only one aquifer and the model updates the VAL_AQUIF field with the aquifer code of the overlain aquifer. If the groundwater wells within the PWS data layer have source aquifer information, the model tries to assign a source aquifer based on the following process:

1. If the groundwater well overlays no aquifers, a source aquifer cannot be determined or assigned and the VAL_AQUIF value remains CANNOT_DETERMINE.
2. If the groundwater well overlays only one aquifer and the AQUIFER data layer contains both outcrop and subcrop delineations, the well is inferred to draw water from the single aquifer it overlies. The model updates the VAL_AQUIF field with the aquifer code of the overlain aquifer.
3. If the groundwater well overlays only one aquifer and the AQUIFER data layer contains only outcrop delineations, then the model looks at the validated source aquifer of nearby wells to see if a source aquifer assignment can be made. The model calculates a search radius distance which is equal to 1/10th the diagonal geographic extent of the aquifer boundary. The model selects groundwater wells within the search radius that have validated source aquifer information.
    a. If the well in question has a well depth greater than zero, then the selected set of wells with validated source aquifer information is limited to only wells that have depths within a 10 percent range of the depth of the well in question. If 90 percent of the selected wells with a validated source aquifer specify the same source aquifer, the groundwater well is inferred to draw water from this aquifer and the model updates the VAL_AQUIF field with the aquifer code of this aquifer. If no consensus exist for the source aquifer, but at least 90 percent of the wells draw water from a vulnerable aquifer (Class I or IIa) or non-vulnerable aquifer (Class IIb, IIc, or Class III), the groundwater well in question is inferred to draw water from the same aquifer type and the model updates the CLASS field with either VUN or NVUN respectively. If no consensus can be established, the VAL_AQUIF value remains CANNOT_DETERMINE.

   b. If the well in question has no well depth information or well depth is zero, then no refinement is made to the selected set of wells with validated source aquifer and the same conditional tests are applied as above but the consensus must be 100 percent.
4. If the groundwater well overlays more than one aquifer, the model determines the area common to all aquifers that the well overlays. The model then calculates a search radius equal to $1/10^{th}$ the diagonal of the geographic extent of the common area. The model selects groundwater wells within the search radius that have validated source aquifer information. The conditional tests of depth and aquifer vulnerability are applied in the same manner as described above when only one aquifer is intersected.

For the groundwater wells that still have no source aquifer or aquifer vulnerability validated or assigned, the model analyzed these wells further to see if they are likely drawing water from shallow/surficial aquifer or a SSA, as follows:

- If the groundwater well in question has a well depth greater than zero and less than or equal to 50 ft, then the well is inferred to draw water from a surficial or shallow, permeable aquifer. The model updates the VAL_AQUIF field with SURFICIAL and the CLASS field with I.
- If the groundwater well in question has no well depth information, the well depth is equal to zero, or the well depth is greater than 50 ft, then the model checks to see if the well overlies a SSA. If the well lies within a SSA boundary, then the well is inferred to draw water from the SSA, and the model updates the VAL_AQUIF field with the aquifer code of the SSA.

Once all the groundwater wells have stepped through the source aquifer assignments, the model attempts to determine the source aquifer vulnerability for these wells using the same methods described earlier in this document.

6.8 Assignment of Quality Codes

In order to provide documentation of how the aquifer vulnerability classifications were determined, each groundwater well is assigned a quality code. The quality-coding scheme is listed below:

Quality Code = 1
Source aquifer information for the well is available, and the well is located within the boundary of the well's stated source aquifer.

Quality Code = 2
Source aquifer information for the well is available, the well is located outside the boundary of the well's stated source aquifer, and the source was interactively validated or negated based on other geologic data.

Quality Code = 3
Source aquifer information for the well is not available or is unknown, but the geographic position and source aquifer information of surrounding wells within a defined search radius were used to classify the well.

Quality Code = 4
Source aquifer information was not included in the PWS data set and the wells were assigned a source aquifer based on the location of each well.
-or-
Source aquifer information was included in the PWS data set but the source aquifer information for this well is unknown or is ambiguous, and the source aquifer could not be validated or assigned, and the source aquifer vulnerability classification is not possible.

Quality code = 5
Source aquifer information for the well is not available or is unknown, and could not be determined from other geological information, but the location of the well is within a SSA and the source aquifer vulnerability is classified as though the well draws water from the SSA.

6.9 Delineate Preliminary DW USAs

A preliminary DW USA is a PWS source for a CWS or a NTNCWS that draws water from a vulnerable aquifer or from a surface water source in which the AADWS information is unknown or is unavailable. For the purpose of the model, all surface water intakes, springs, and vulnerable groundwater wells are to be considered preliminary DW USAs until the AADWS information can be applied.

For groundwater wells, the model selects all the vulnerable groundwater wells (i.e., wells with a source aquifer vulnerability of Class I, Class IIa, or Class VUN) and delineates the preliminary DW USA as follows:

- If the value in the SWPAUNIQUE field is not null for a well, the model uses this value to determine the appropriate SWPA boundary as provided by the state to use to delineate the preliminary DW USA for the well.
- If the value in the SWPAUNIQUE field is null for a well, the model uses the value in the SWPABUFF field to generate a fixed-radius buffer around the well. The value in the SWPABUFF field represents a buffer radius in meters to be used to define the preliminary DW USA of the well using the fixed-radius buffer method.

For surface water intakes, the model delineates the preliminary DW USAs as follows:

- If the value in the SWPAUNIQUE field is not null for an intake, the model uses this value to determine the appropriate SWPA boundary as provided by the state to use to delineate the preliminary DW USA for the intake.
- If the value in the SWPAUNIQUE field is null for an intake, the model uses an Upstream/Downstream Buffer process to delineate the preliminary DW USA for the intake.

For springs, the model delineates the preliminary DW USAs as follows:

- If the value in the SWPAUNIQUE field is not null for an intake, the model uses this value to determine the appropriate SWPA boundary as provided by the state to use to delineate the preliminary DW USA for the spring.
- If the value in the SWPAUNIQUE field is null for an intake, the model uses the value in the SWPABUFF field to generate a fixed-radius buffer around the spring. The value in the SWPABUFF field represents a fixed radius in meters to be used to define the preliminary DW USA of the spring using the fixed radius buffer method.
- If both the SWPAUNIQUE and SWPABUFF fields are null for a spring, the model uses an Upstream/Downstream Buffer process to delineate the preliminary DW USA for the spring.

The model also checks to see if there are any SSAs that are composed of karst. If the KARST field on the SSA data layer has a value of "Y", it indicates the SSA is composed mostly of karst. The model selects the boundary of the SSA to be included in the preliminary DW USA data layer. Note that most SSA boundaries do not distinguish the recharge area of the aquifer versus the aquifer boundary itself. Due to this situation, if a SSA boundary does not delineate the recharge area, the entire boundary of the SSA is used to define the DW USA boundary.

6.10 Upstream/Downstream Buffer Process

The model was coded to generate buffers based on flow direction attributes that exist in the USGS NHD to implement flow direction into the DW USA update. The 5-mile upstream and 0.25-mile downstream hydrography buffers are applied when there are no other protection areas or SWPAs identified for a specific spring or surface water intake. The process utilizes the flow direction information supplied in the NHD to achieve this. One of the key issues with this process is determining the starting location for measuring the up- and downstream distances for each spring or surface water intake. This section explains the process the model utilizes to determine the start location for each intake, the decision-making process for where there is no flow direction, and the process used for when the starting location could not be determined.

The model makes use of three NHD data layers: 1) flowline features; 2) waterbody features; and 3) area features (Figure 4). The flowline features are the fundamental flow network consisting predominantly of stream/rivers and artificial path vector features. The model utilizes the flowlines to determine the upstream/downstream flow direction and measurement up/down stream. The waterbody features represent waterbodies such as lakes, ponds, reservoirs, and swamp/marshes. The area features represent additional hydrology polygons such as streams and rivers. Both the waterbody and area polygons may contain associated flowlines known as artificial paths that are used to represent water flow within the hydrology polygons.

NHD does include features that are not potable water sources (e.g., aquaculture reservoirs, decorative pools, etc.). Because these features are included in the NHD, the model makes use of a lookup table, referred to as the Open Water Lookup Table, to identify potable water sources that should be considered sensitive drinking water resources when processing the hydrology data for up/down stream buffers. The table consists for two columns: FCode and CLASS. The FCode item is a field from the NHD data that identifies the type of hydrology feature along with any combinations of characteristics associated with the hydrology feature. The CLASS field is used by the model to determine which hydrology features are considered open-water features. See Appendix E for a copy of the open-water lookup table for DW USAs with descriptions of the hydrological feature types within the NHD data.

Unfortunately, the intakes associated with the PWS data processed by the model are not directly associated with a particular hydrology feature in the NHD data. Therefore, it is necessary to determine the starting location of the intake or spring before any up/down stream measurements

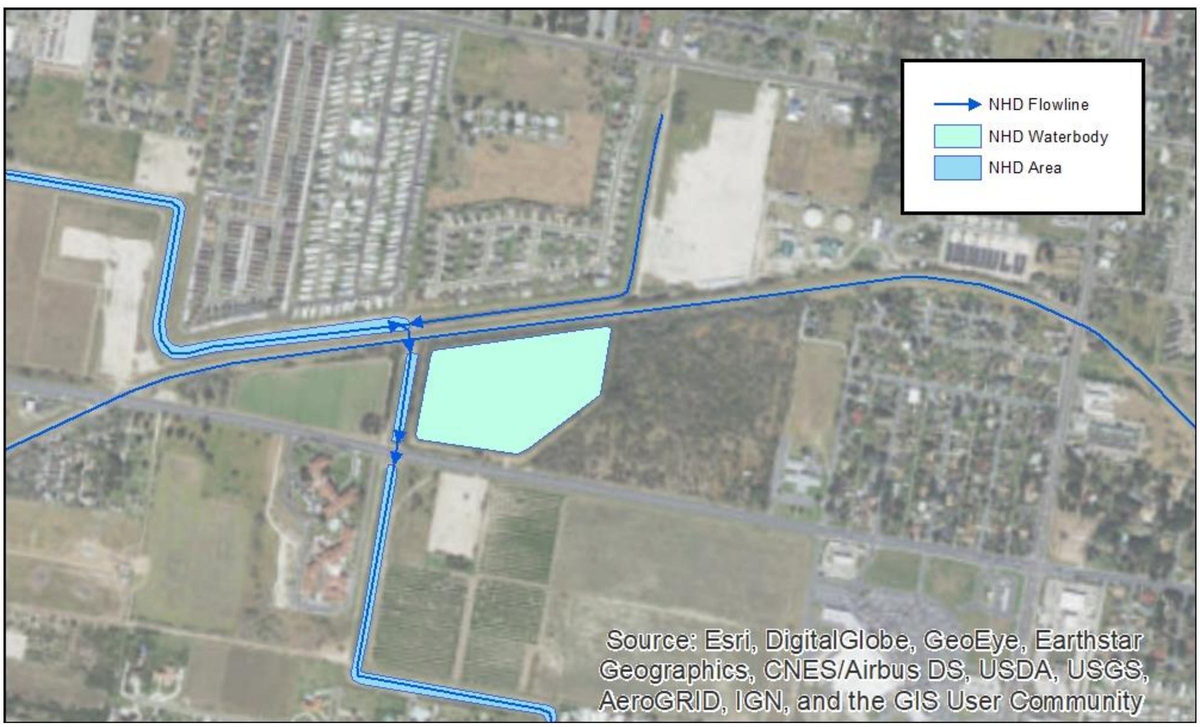


Figure 4. NHD features used by the DW USA model.

can take place. The model achieves this by using the following basic logic:

- For intakes that lie within an open-water, NHD area, or NHD waterbody polygon:

- If the polygon has no associated flowline, then buffer the hydrology polygon 0.25-mile landward (Figure 5).
- If the polygon has an associated flowline(s), then determine the closest point along the flowline from the intake or spring and use that point as the starting location for upstream and downstream measurements (Figure 6).

- For intakes that lie outside of any open-water, NHD area, or NHD waterbody polygon:
  - If the closest feature within 100 meters is an NHD area or NHD waterbody, check for associated flowline:
    - If the polygon has no associated flowline, buffer the hydrology polygon 0.25-mile landward (Figure 7).
    - If the polygon has an associated flowline, determine the closest point along the flowline from the intake or spring and use that point as the starting location for upstream and downstream measurements (Figure 8).
  - If the closest feature within 100 meters is an NHD flowline, use the closest point along the flowline from the intake or spring and use that point as the starting location for upstream and downstream measurements (Figure 9).
  - If there is not an open-water, NHD area, NHD waterbody, or NHD flowline feature within 100 meters of the intake or spring, then a starting point for the upstream and downstream measurements cannot be determined with any confidence. In such cases, all open-water features within a 5-mile radius for the intake or spring are selected and buffered 0.25-mile inland to represent the area of the preliminary DW USA.

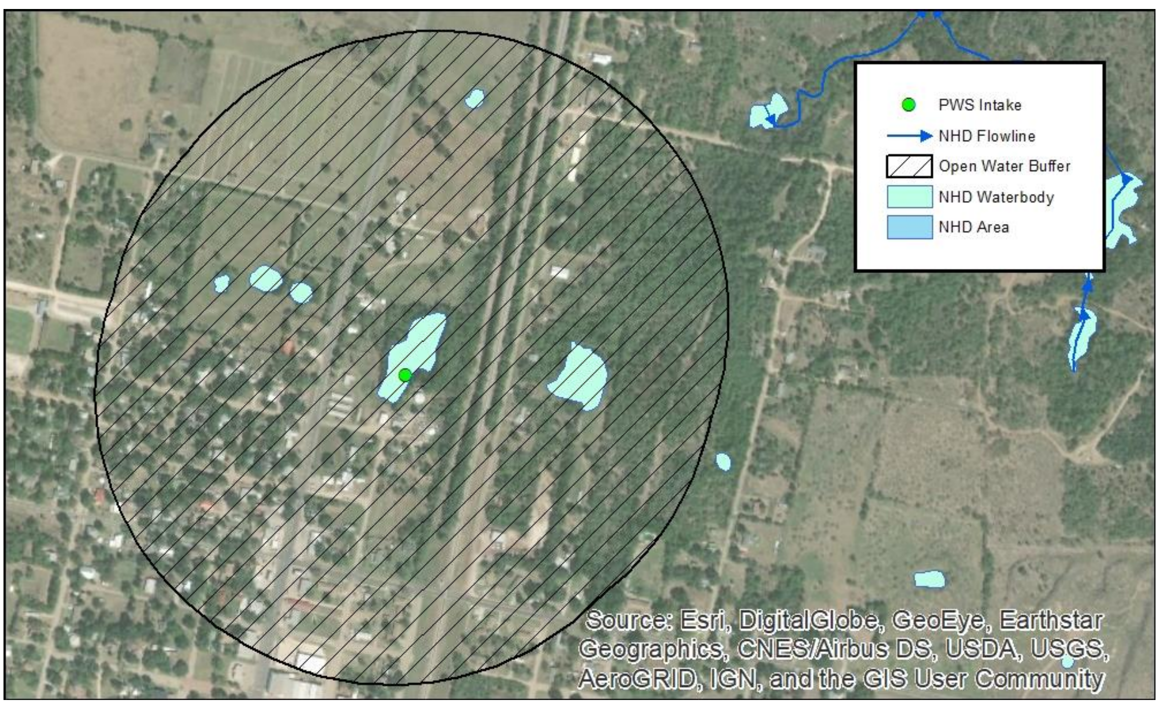


Figure 5. Buffer for intake within an open-water area or waterbody with no associated flowline.

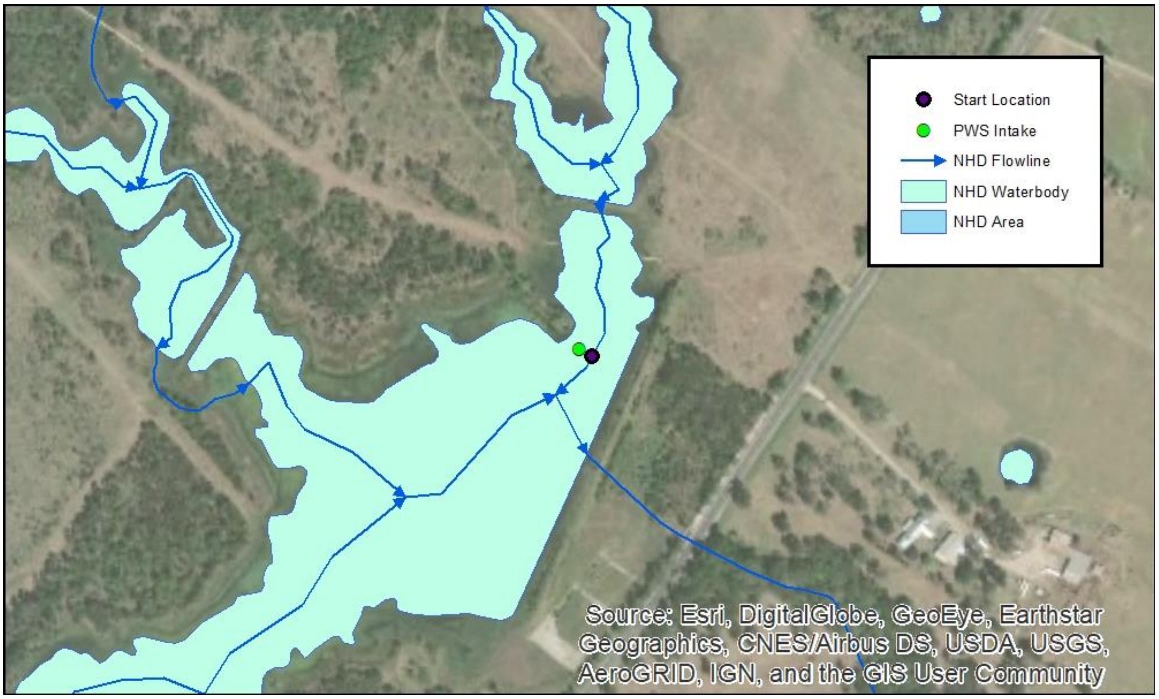


Figure 6. Starting location for intake within an open-water area or waterbody with an associated flowline.

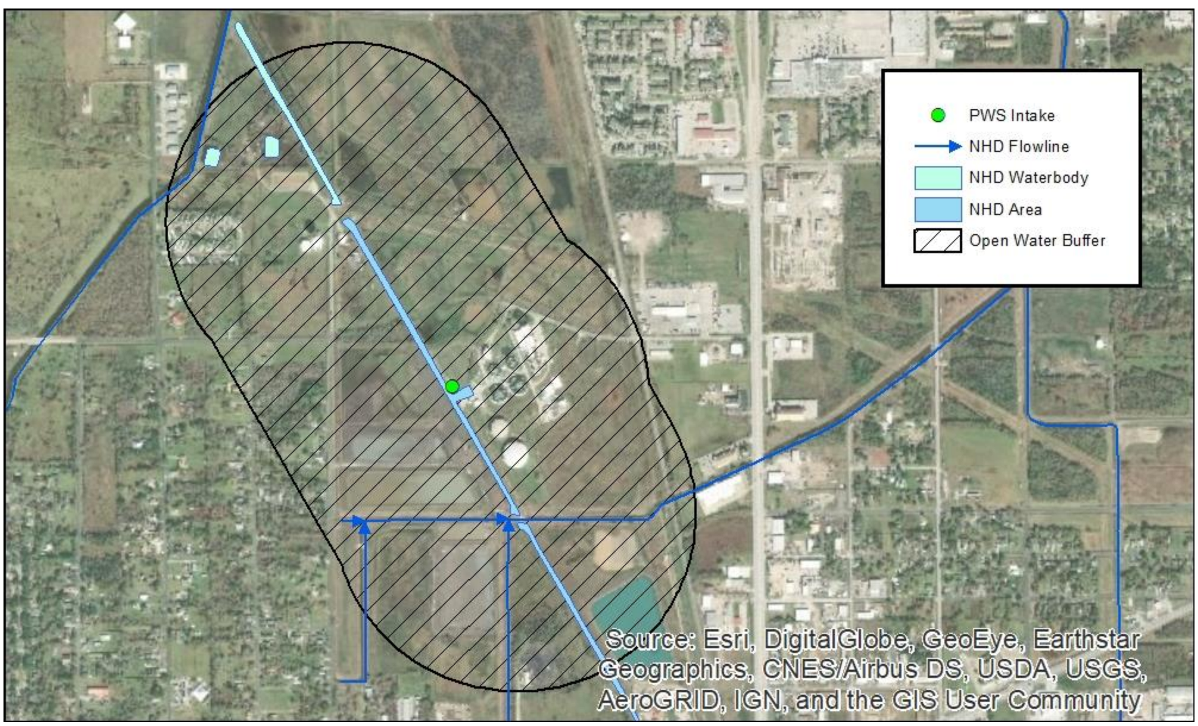


Figure 7. Buffer for intake closest to an open-water area or waterbody with no associated flowline.

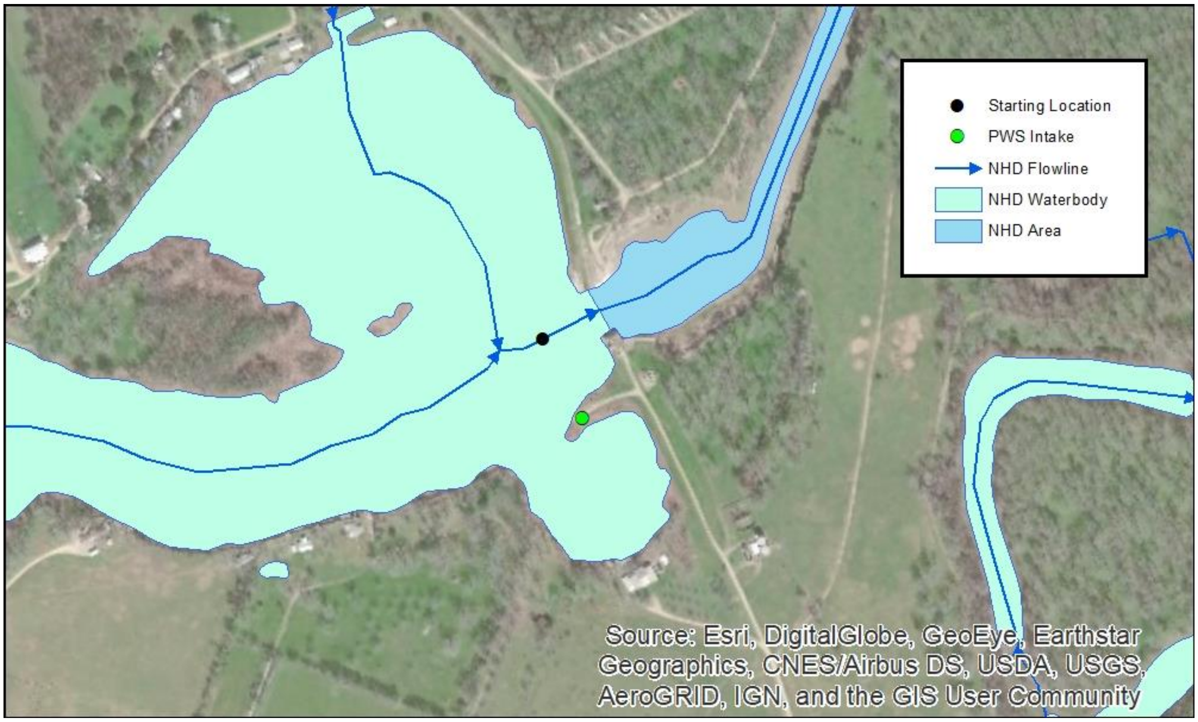


Figure 8. Starting location for intake closest to an open-water area or waterbody with an associated flowline.

Figure 9. Starting location for intake closest to an open-water flowline.

Starting locations are determined for intakes or springs within or closest to features with flowlines as described above. Before the process of measuring the upstream and downstream paths can begin, there are two issues that need to be considered: 1) not all flowlines within the NHD data set have a flow direction; and 2) there might be non-open-water features connecting the open-water features along the 5-mile path.

Flow direction in the NHD data set is stored on each flowline in two ways: 1) the digitized direction of the line; and 2) the field FlowDir. The FlowDir field indicates whether the flowline has a determinant flow direction relative to the digitized direction of the flowline. The field is a binary field with a value of 0 indicating that flow could not be determined for the line and a value of 1 indicating that the flow direction is based on the digitized direction of the line.

In cases where the flowline has a flow direction indicated, the process of determining the path upstream and downstream is fairly simple. The 5-mile path upstream and 0.25-mile path downstream are determined by following all the connected flowlines that are digitized in the same direction as the flowline associated with the starting point (Figure 10).

In cases where the flowline does not have a determinant flow direction, where FlowDir = 0, indicating an uninitialized flow, the actual flow direction cannot be assumed to be the digitized direction of the flowline at the starting location (Figure 11). In these cases, the model utilizes the digitized direction of the flowline associated with the starting point to determine path lengths.

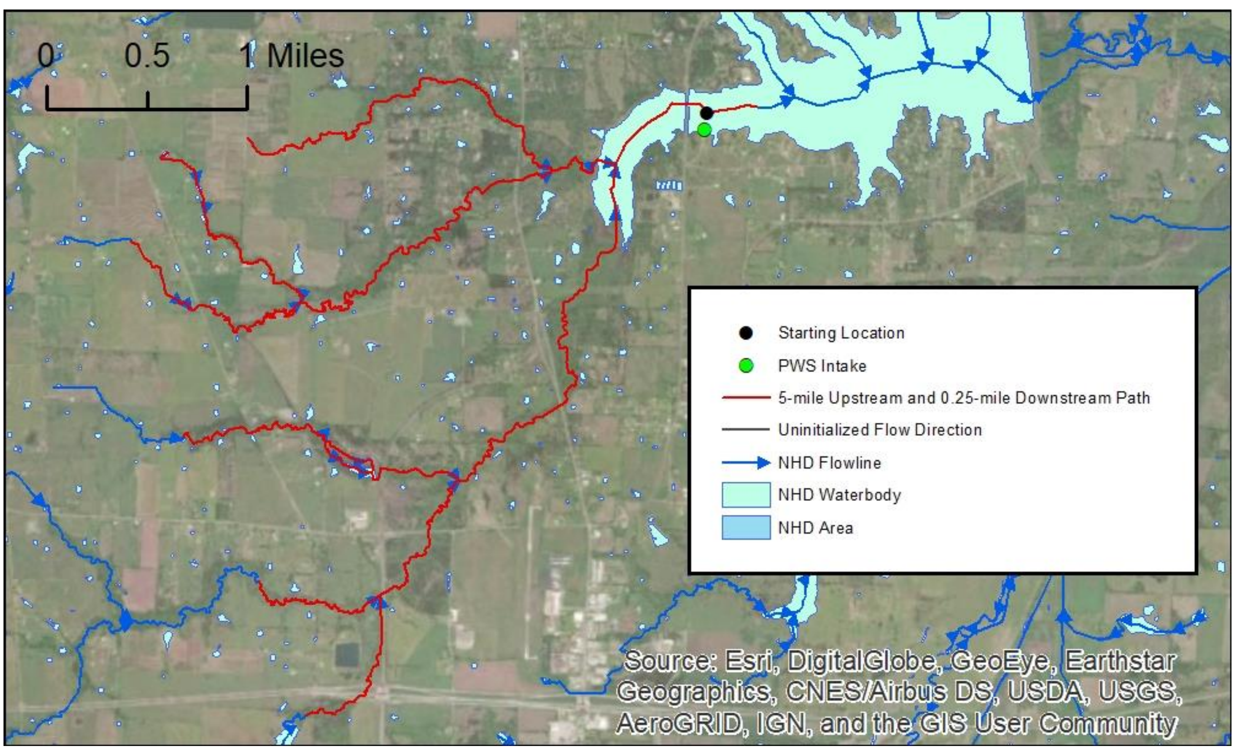


Figure 10. 5-mile path upstream and 0.25-mile path downstream for flowline with flow direction.

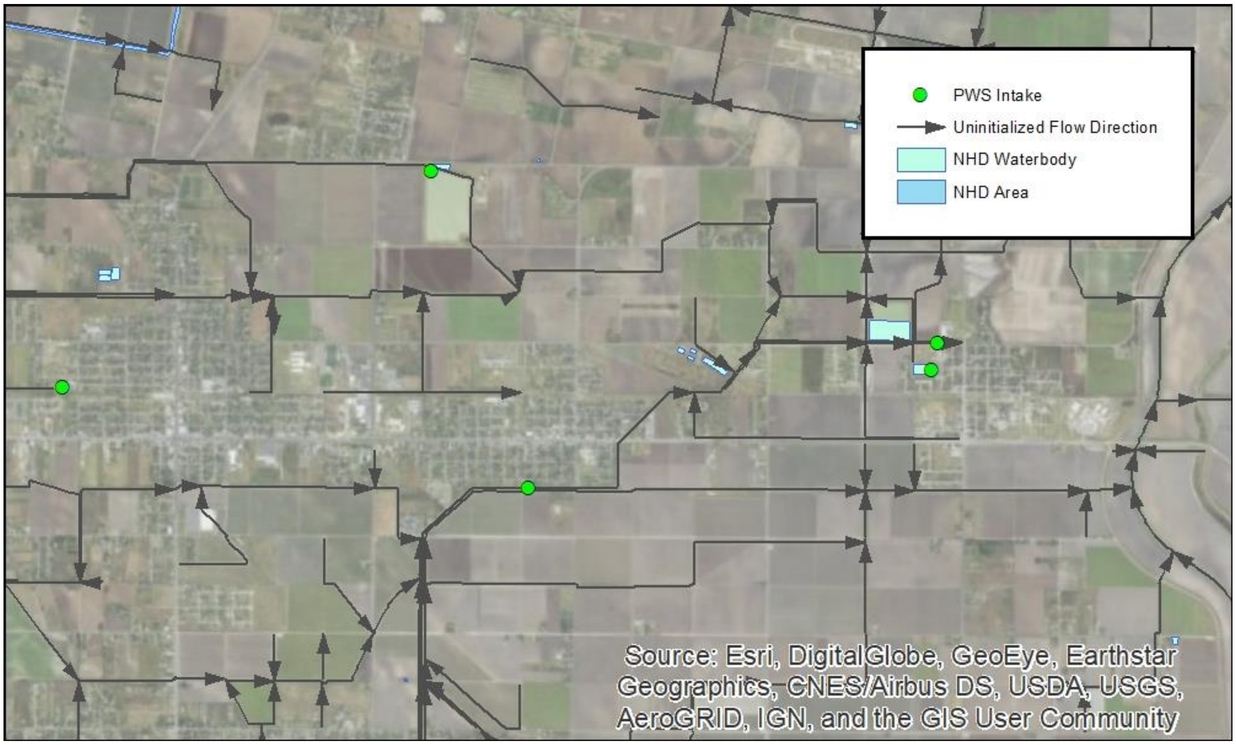


Figure 11. NHD flowlines with uninitialized flow direction.

The processing is the same as when flow direction is indicated, except flow direction cannot be assumed and the model determines 5-mile paths in length in both directions from the starting point using the digitized directions of all the connected flowlines (Figure 12).

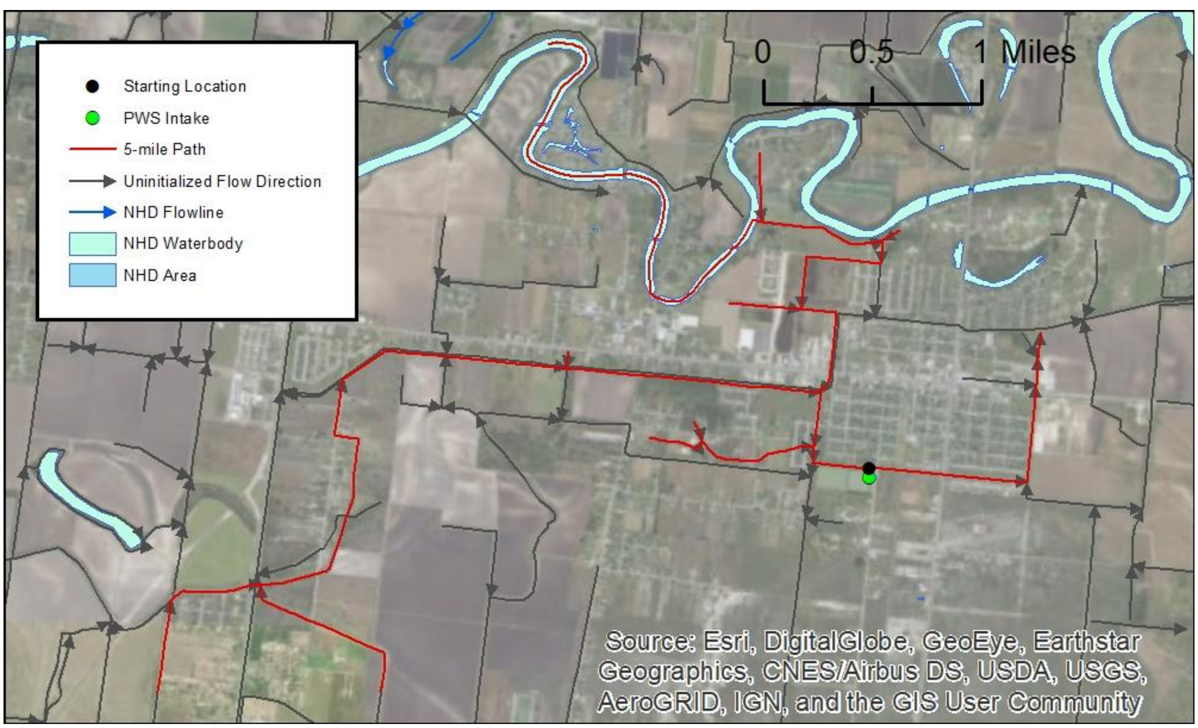


Figure 12. 5-mile path in both directions along flowlines without flow direction indicated.

It is important to note that, regardless of the value in the FlowDir field, the measurement paths are determined by traversing the flowlines that are digitized in the same direction with regards to each other. In other words, downstream paths follow the digitized direction of the flowlines, while upstream paths go opposite of the digitized direction of the flowlines.

When determining the upstream and downstream paths from a starting location, there might be non-open-water features connecting other open-water features; for example, a stream that has a pipeline, or culvert, where the stream goes under a road. All flowlines, regardless of whether they are considered open-water features or not, are considered when determining the upstream and downstream paths and total distance along the path (Figures 13 and 14).

Once the upstream and downstream paths have been determined, the model needs to select and/or cut all the open-water flowlines, areas, and waterbodies that lie within the upstream and downstream path. This task is straightforward for the flowlines, but other issues arise when it comes to handling the polygonal waterbody and area features.

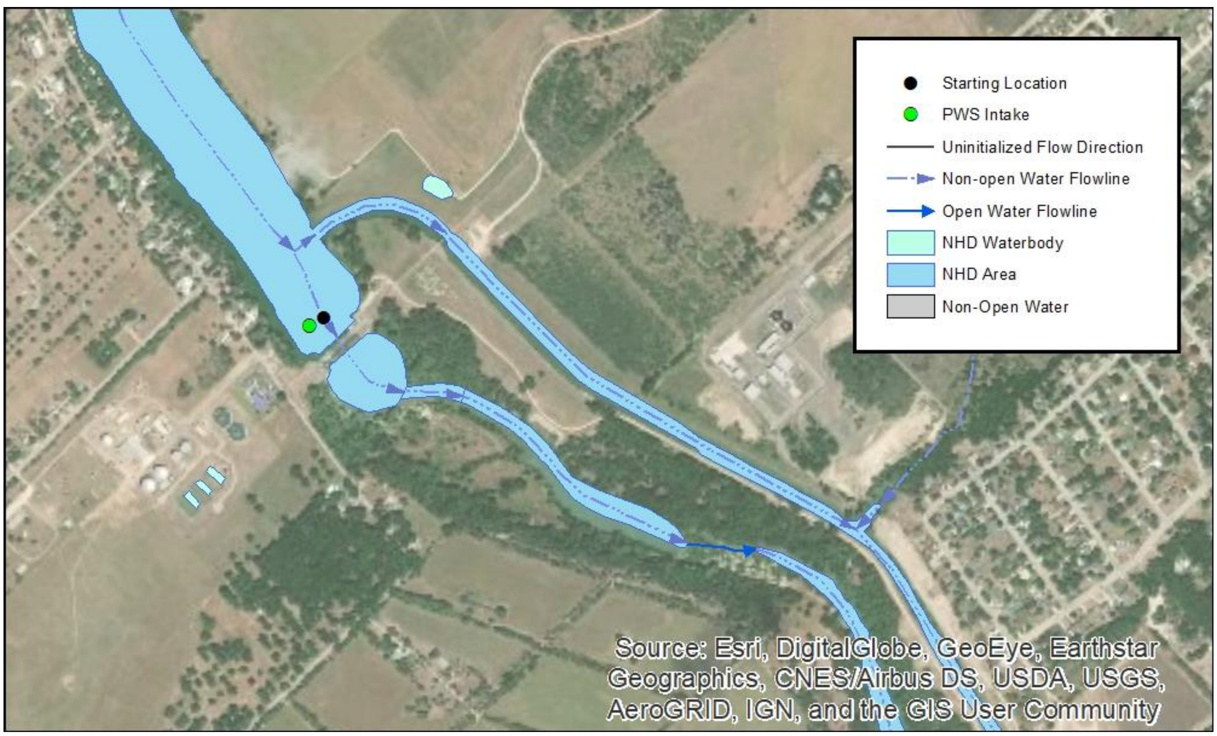


Figure 13. Open-water and non-open-water flowlines.

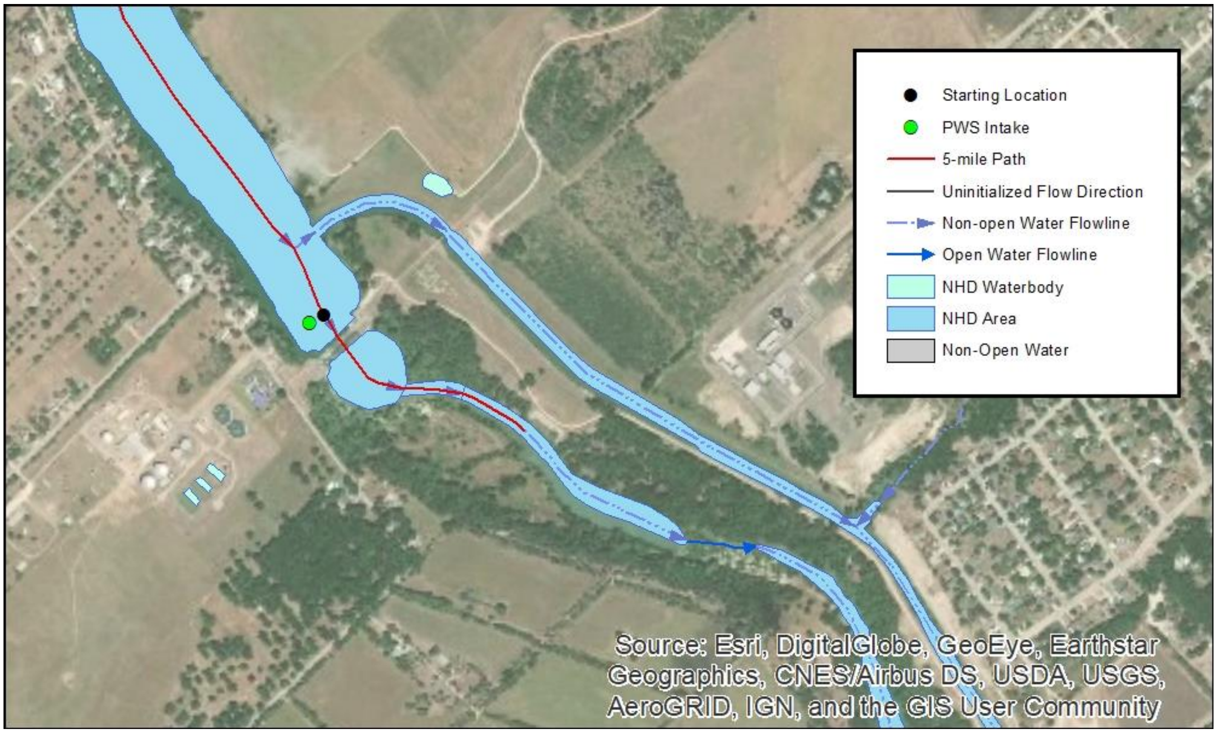


Figure 14. Path using both open-water and non-open-water flowlines.

Upon reaching the 5-mile or 0.25-mile mark along a path, the flowline is split at that location. If the flowline is considered an open-water feature, then the model selects the correct portion of the open-water flowline along with all the other open-water flowlines along the upstream and downstream paths and stores these features for a 0.25-mile landward buffer. If the flowline is not considered an open-water feature, the model selects all the open-water flowlines along the upstream and downstream paths and stores these features for a 0.25-mile landward buffer.

Figure 15 is an example of an intake located near one of the source tributaries of a lake and resulting upstream and downstream paths determined from the starting location. Due to the difficulties involved with the flow direction within a lake, pond, or reservoir, or any other NHD waterbody feature, the entire waterbody feature along the upstream and downstream path is selected and buffered 0.25-mile inland. The resulting buffer is clipped to a 5-mile radius buffer generated from the original intake or spring location (see Figure 16).

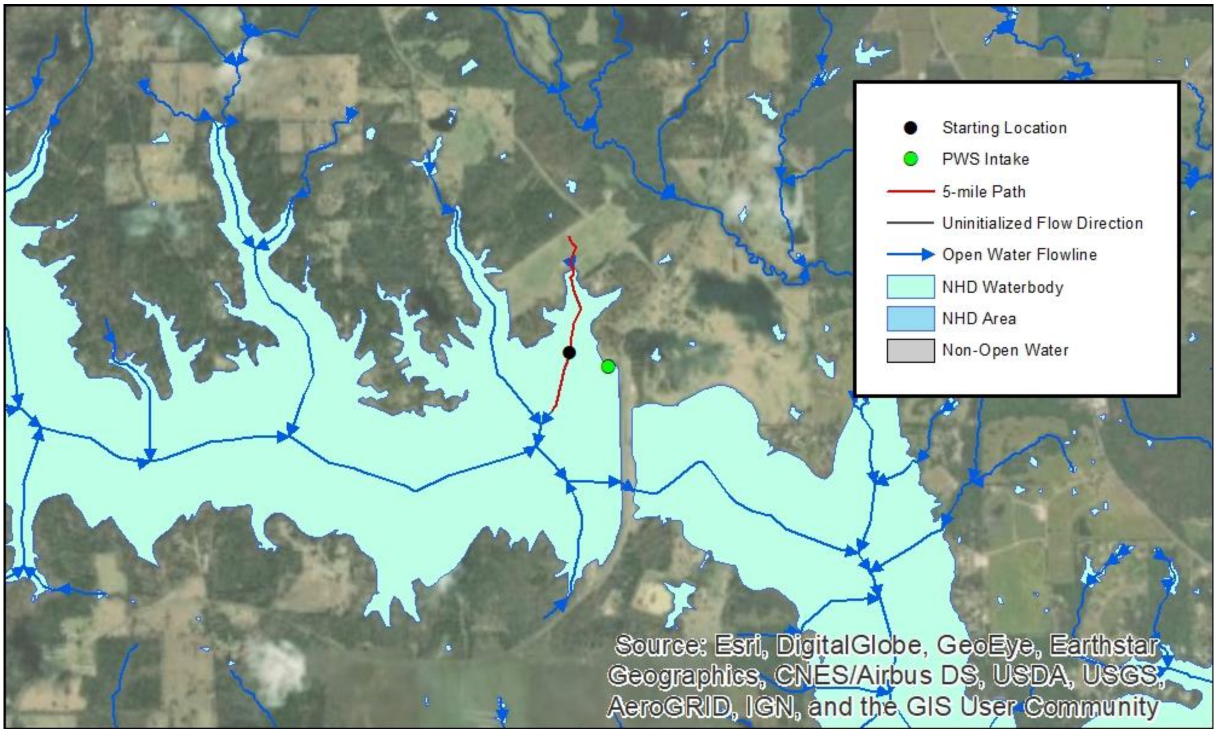


Figure 15. Upstream/downstream path for intake located near tributary of lake.

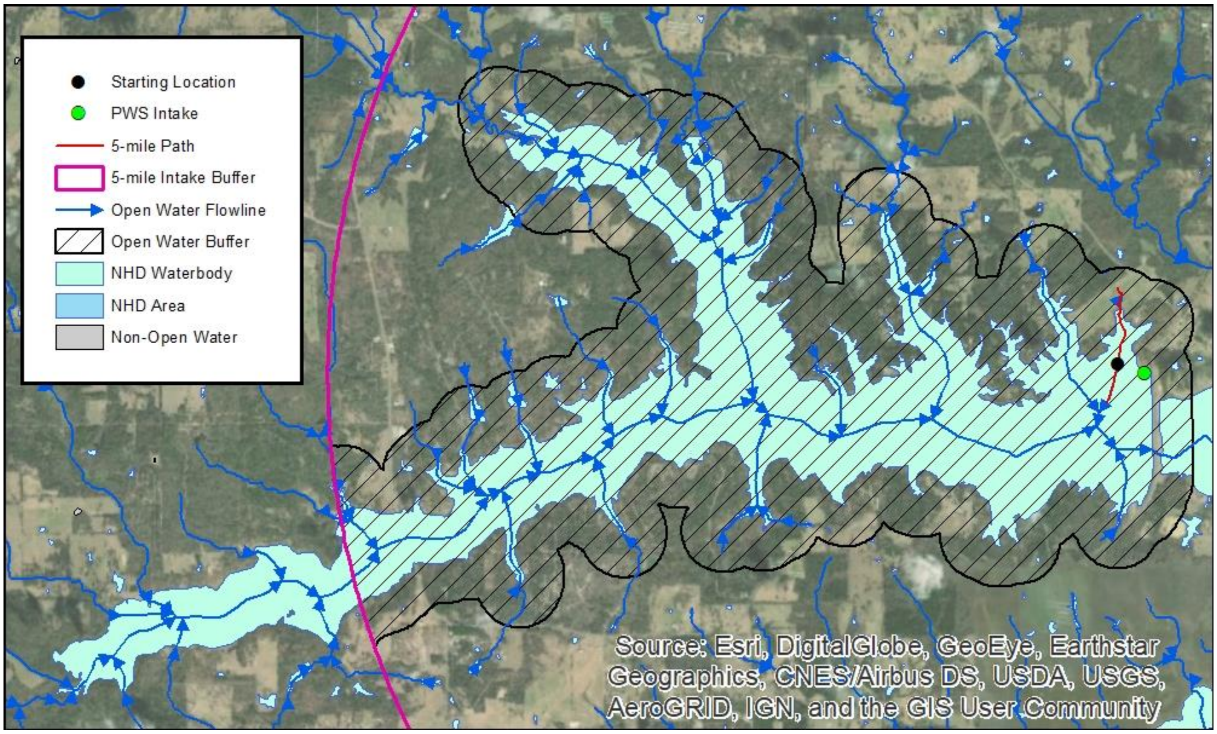


Figure 16. 0.25-mile buffer of open-water waterbody feature clipped to the 5-mile fixed radius buffer of intake location.

Selecting out the open-water rivers/streams from the NHD areas for the 0.25-mile inland buffer also presents some issues. A process involving perpendicular cut lines and Thiessen polygons was developed to cut the river/stream polygons. This process generated points at 10-meter intervals along the upstream and downstream path along with all incoming and outgoing tributaries within the boundary of the river or stream, built Thiessen polygons based on these points, and generated perpendicular lines at the ends of the upstream and downstream flowline path (Figure 17).

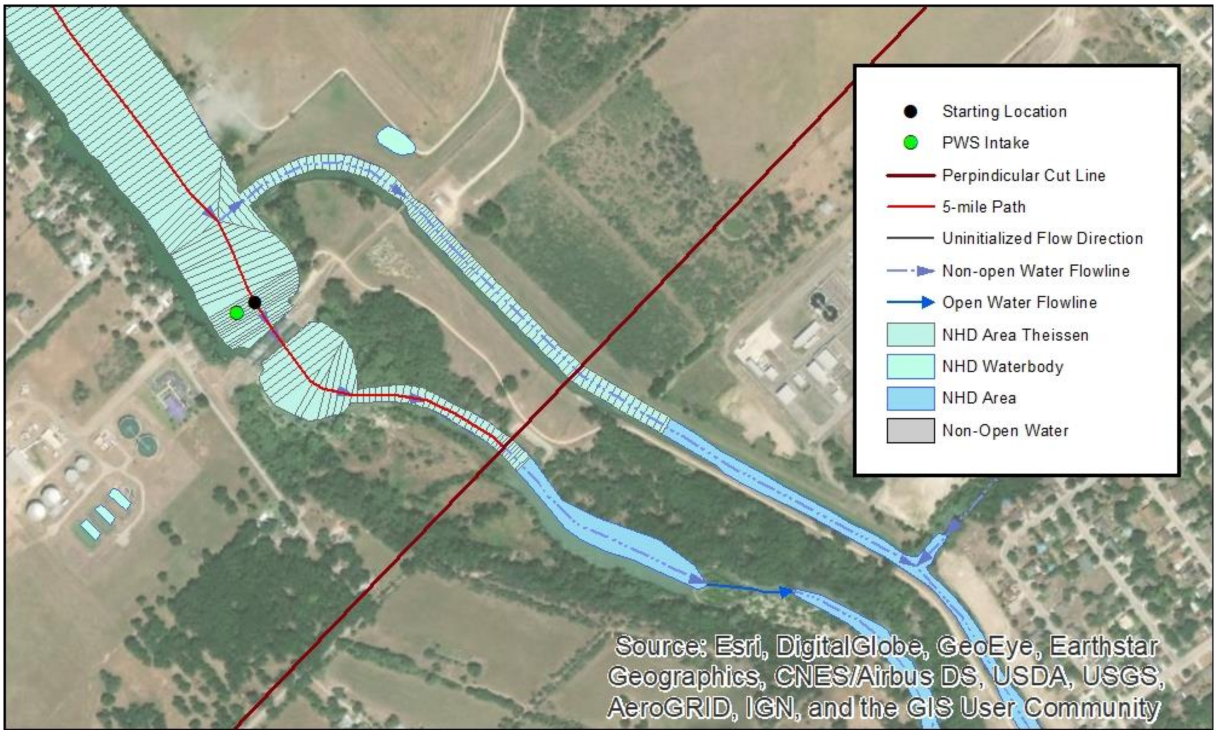


Figure 17. Example of Thiessen polygons and perpendicular cut lines at end of flowline path.

The perpendicular lines at the ends of the upstream and downstream path are then clipped by the river or stream polygons, and the Thiessen polygons associated with the river or stream polygon and the upstream and downstream path are dissolved into a single polygon feature (Figure 18). The resulting polygon feature represents the appropriate upstream and downstream portion of the river or stream for the 0.25-mile inland buffer (Figure 19).

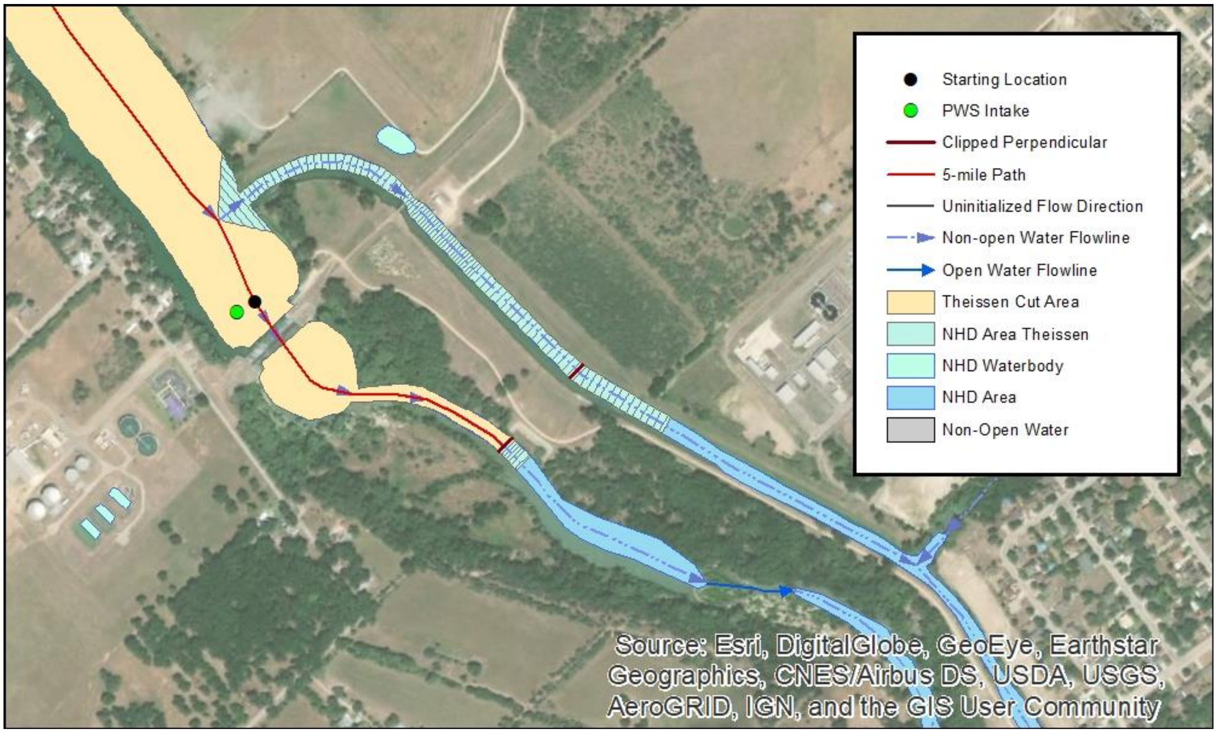


Figure 18. Example of clipped perpendicular line and dissolved Thiessen polygons.

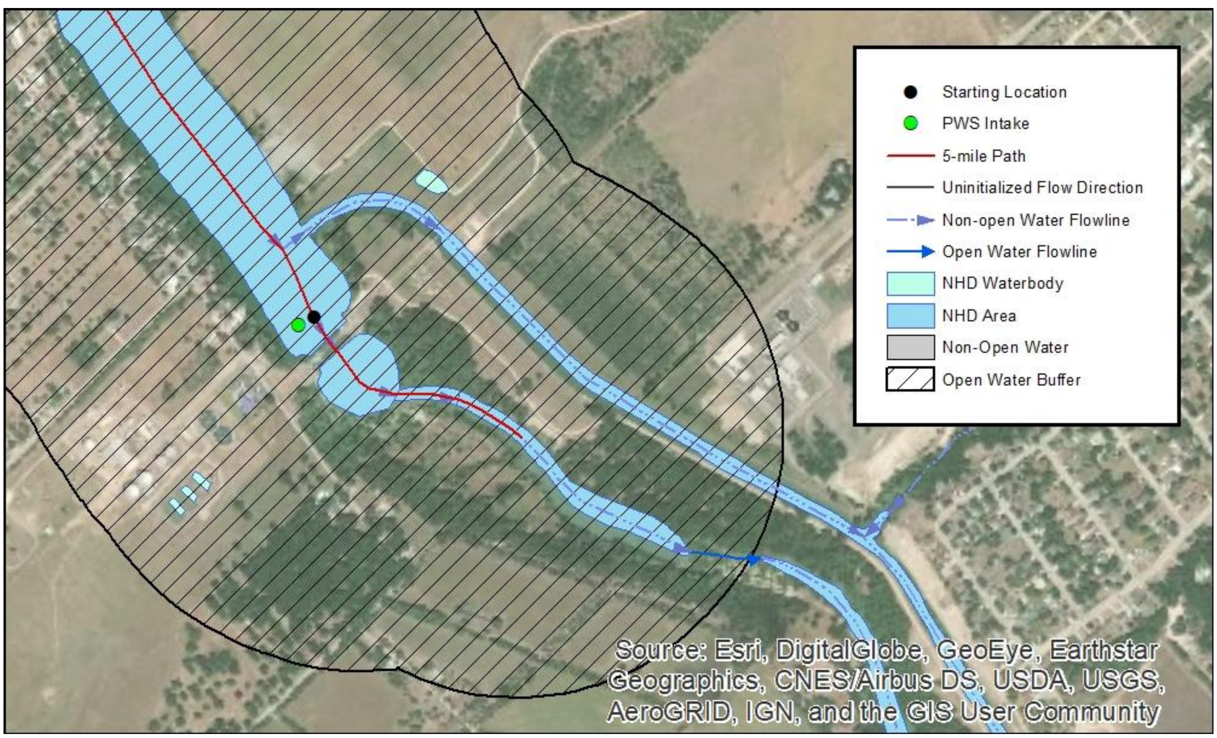


Figure 19. Example of 0.25-mile buffer for the open-water river/stream polygon.

6.11 Determine Final DW USAs

In accordance with the filter criteria, the determination of the final DW USAs depends on whether there is an adequate alternative drinking water source. The AADWS information is applied to the preliminary DW USAs with the following outcomes:

- If there is no AADWS, the preliminary USA becomes a final DW USA;
- If it could not be determined if there was an AADWS, the preliminary DW USA becomes an interim DW USA; and
- If there is an AADWS, the preliminary USA does not become a final or preliminary DU USA.

Because the AADWS data are highly sensitive and unlikely to be provided by most municipalities, AADWS determination was not part of this update. Therefore, all the preliminary DW USAs based on the vulnerable groundwater wells or surface water intakes are considered interim DW USAs. The DW USAs based upon karst SSAs do not have an AADWS component and are considered final DW USAs.

7.0 DESCRIPTION OF DW USA DIGITAL DATA AND METADATA

The final digital product is an ESRI shapefile spatial data layer for each state with polygons for the final and interim DW USAs as delineated by the model and a lookup table that relates each DW USA in the shapefile to the PWS or SSA feature. The lookup table could potentially provide a method for users to track changes in future DW USA data sets.

The shapefile is named using the following naming convention dwusa_<2-letter state code>. The fields associated with the state shapefiles are defined in Table 20. Each DW USA in the shapefile is an individual feature, even when there are overlapping DW USAs. An FGDC-compliant metadata document is associated with each shapefile that provides more information regarding the process description, fields, and data sources for each data set used to delineate the DW USAs.

Table 20. Fields associated with the DW USA shapefile.

Field	Description
DWUNIQUE	Unique identifier for each DW USA
STATE	2-letter state code
QUALITY	Identifier of the process used to classify a groundwater well
NAME	Name of Sole-Source Aquifer SSA
TYPE	Indicates type of DW USA. Either DW for a final DW USA or INTERIM for an interim DW USA

The lookup table provides a potential method of tracking new DW USAs in future updates. The table is named dwusalut_<2-letter state code> and is delivered as a Microsoft Excel spreadsheet.

The columns of the spreadsheet are fields that relate to each DW USA and to each PWS or SSA associated with the USA. The fields associated with the lookup table are defined in Table 21.

Table 21. Fields associated with the DW USA lookup table.

Field	Description
DWUNIQUE	Unique identifier for each DW USA
STATE	2-letter state code
NAME	Name of Sole-Source Aquifer SSA
LAST_YEAR	Indicates the last year the specific PWS or SSA led to a DW USA designation
<PWS Identifier(s)>	Unique identifier(s) that relate the DW USA back to a specific PWS well or intake in the PWS data layer. These fields have the same naming convention of the unique identifier fields associated with the original PWS data layer as received from each State or SDWIS.

The last set of fields associated with the lookup table (<PWS Identifier(s)>) come directly from the original PWS data as received from either the State PWS data or the SDWIS data layer. These fields maintain the same field name to make it easier in the future to potentially relate updated PWS data to the current DW USAs.

The purpose of the DW USA lookup table is to provide some basic change detection in the DW USAs during future updates. The idea is to utilize this table before DW USAs are processed during the next update by relating the DWUNIQUE field to the updated PWS data based on the unique PWS identifiers provided in this table and generating a new DWUNIQUE identifier only when one does not exist already for the PWS or SSA feature that leads to a DW USA. For example, if a groundwater well with the following unique identifiers (PWSID = XX0001 and WELL_ID = 03) from the State PWS data exists in a future update, the following steps could be taken to determine if an update is needed:

- If the groundwater well, PWSID=XX0001 and WELL_ID=3, exists in the DW USA lookup table, then assign it the associated DWUNIQUE value.
  - If this well leads to a DW USA in a future update, change the LAST_YEAR value to the year of the update.
  - If this well does not lead to a DW USA in a future update, leave row in the lookup table as is.
- If the groundwater well, PWSID=XX001 and WELL_ID=3, does not exists in the DW USA lookup table
  - If the well leads to a DW USA in a future update, assign it the next available DWUNIQUE number and add it the DW USA lookup table.
  - If the well does not lead to a DW USA, no additional steps are required

8.0 SUMMARY

Final and preliminary Drinking Water Unusually Sensitive Areas were created for all 50 states, Washington, D.C., and Puerto Rico for U.S. Department of Transportation, Pipeline and

Hazardous Materials Safety Administration, Office of Pipeline Safety. The DW USA project was conducted from September 2016 to May 2019.

The DW USAs were generated by running the preprocessed source data for each state through the filter criteria in the DW USA GIS Model. The resulting DW USAs generated by the model were affected in many ways by issues with the source data including:

- Availability of the state-provided PWS data;
- Missing source aquifer, well depth, activity code, system type, etc. information in the PWS data;
- Lack of source aquifer and well depth information in the SDWIS data;
- Availability and usability of the state SWPA and/or WHPA boundaries;
- Inability to identify the recharge areas for the SSAs; and
- The exclusion of the AADWS information.

The geospatial extent for the preliminary and final DW USAs were determined in part by the baseline or input data for each state. These data varied significantly state by state; therefore, it was important to develop a precedence for processing the baseline date used to generate the DW USAs. The order for processing the baseline data yielded different geospatial results for the DW USAs as you move across (left to right) the Baseline Data Precedence (Figure 20).

Baseline Data Precedence

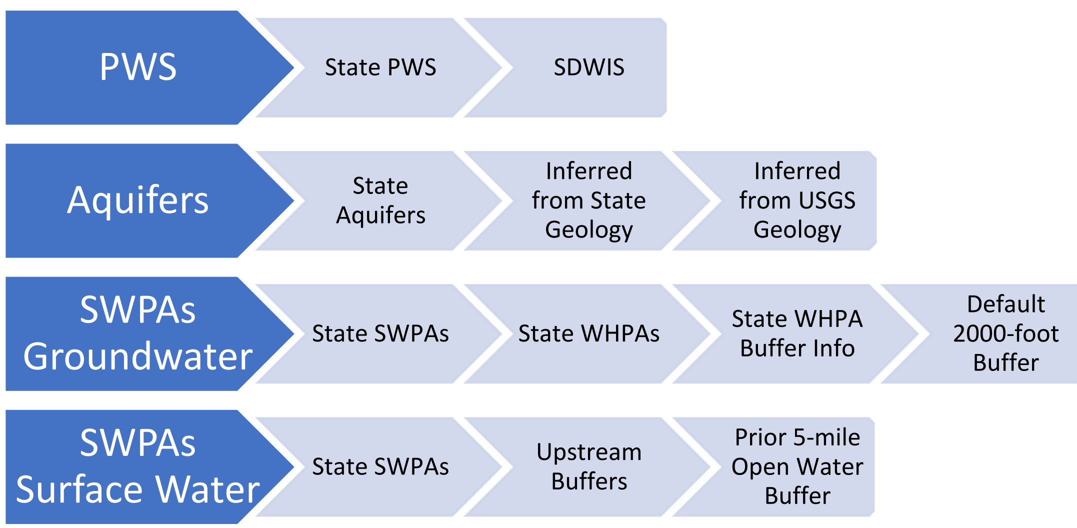


Figure 20. Order for processing baseline data to generate DW USAs.

Examples of differences seen in the final spatial extent for the DW USAs based on the input data are (see Appendix H):

1. Use of state-provided SWPAs versus the prior WHPA buffers for USAs based on vulnerable groundwater wells;

2. Use of the state-provided SWPAs versus the open-water buffer process to identify USAs for surface water intakes;
3. Utilization of the upstream/downstream buffer process versus the 5-mile open-water buffer when a SWPA was not available for a surface water intake; and,
4. Sole Source Aquifers which may include the SSA recharge area.

The PWS data acquired from each state were vastly different from each other, and some were lacking in source and/or well depth information, which are essential inputs for the model. Eighteen states required some sort of confidentiality, data sharing, or non-disclosure agreement or Freedom of Information Act request to gain access to the PWS data and any corresponding source information. Formatting and thoroughly reviewing the preprocessed PWS data were important steps in preparing the data for use in the model. When PWS data were not available from the state, the EPA SDWIS data were the source data for the PWS input layer. SDWIS data are a nationally standardized data set and could provide some consistency among the states in the resulting DW USAs; however, the SDWIS data lack source aquifer and well depth information. It is important to note that PWS data for tribal lands across the U.S. were extracted from the SDWIS data. In some cases, state PWS data and SDWIS data were used for the same state. Table 22 shows the PWS data source (State or SDWIS) for each state and the total number of groundwater wells and surface water intakes for each source. For this update, PHMSA collected PWS data from 39 of the 50 states. SDWIS data were used for Washington, D.C. and PWS data were collected from Puerto Rico.

Table 22. PWS source (State or SDWIS) and number for each source type.

State	State Public Water Supply			EPA SDWIS Public Water Supply		
	Groundwater	Surface Water	Total	Groundwater	Surface Water	Total
Alabama (AL)				1059	90	1149
Alaska (AK)	1422	185	1607			
Arizona (AZ)	4877	108	4985	333	6	339
Arkansas (AR)	1756	147	1903			
California (CA)	13049	803	13852	161	9	170
Colorado (CO)	3376	478	3854		1	1
Connecticut (CT)				3323	213	3536
Delaware (DE)	1052	7	1059			
District of Columbia (DC)					2	2
Florida (FL)	9810	30	9840	10		10
Georgia (GA)	4139	156	4295			
Hawaii (HI)				454	14	468
Idaho (ID)	3569	116	3685	26		26
Illinois (IL)	8275	208	8483			
Indiana (IN)				5029	44	5073
Iowa (IA)	3010	39	3049	10		10
Kansas (KS)	3320	122	3442			
Kentucky (KY)	253	185	438			
Louisiana (LA)	3173	49	3222			
Maine (ME)	2038	70	2108			
Maryland (MD)				4542	52	4594
Massachusetts (MA)	3609	263	3872	4		4
Michigan (MI)	15486	77	15563	44	2	46
Minnesota (MN)	13190	86	13276	70	2	72
Mississippi (MS)	4024		4024		7	7
Missouri (MO)	5681	172	5853			
Montana (MN)	2326	102	2428	104	4	108
Nebraska (NE)	3071	6	3077	10		10
Nevada (NV)				868	16	884
New Hampshire (NH)	5602	90	5692			
New Jersey (NJ)	5915	63	5978			
New Mexico (NM)	3137	113	3250	216	5	221
New York (NY)	13399	397	13796			
North Carolina (NC)	8125	200	8325	21	3	24
North Dakota (ND)				731	31	762
Ohio (OH)	6448	242	6690			
Oklahoma (OK)				2555	233	2788

State	State Public Water Supply			EPA SDWIS Public Water Supply		
	Groundwater	Surface Water	Total	Groundwater	Surface Water	Total
Oregon (OR)	3381	239	3620	12	3	15
Pennsylvania (PA)	11733	471	12204			
Puerto Rico (PR)	1243	184	1427			
Rhode Island (RI)				593	25	618
South Carolina (SC)	1664	67	1731			
South Dakota (SD)	1095	60	1155	41	3	44
Tennessee (TN)	1332	210	1542			
Texas (TX)	17681	549	18230			
Utah (UT)	2991	108	3099	22	4	26
Vermont (VT)	1624	59	1683			
Virginia (VA)	3791	180	3971			
Washington (WA)	10490	363	10853	95	2	97
West Virginia (WV)				847	155	1002
Wisconsin (WI)	11237	34	11271	69		69
Wyoming (WY)				1092	66	1158

Source aquifer and/or well depth information was available for 20 of the 50 states, as listed below.

- Alaska
- Arkansas
- California
- Colorado
- Delaware
- Florida
- Illinois
- Iowa
- Kansas
- Kentucky
- Louisiana
- Minnesota
- Mississippi
- Missouri
- Montana
- New Hampshire
- New Jersey
- Ohio
- South Dakota
- Texas

Having this information increases the level of confidence in the Pettyjohn classification for the DW USAs. There other factors that provide additional assurances in the classification, such as PWS_ID, system type (CWS, NTNCWS, TNCWS), activity code, pump rates, yield, etc.

The SWPA/WHPAs identified in previous updates as a nationally standardized layer are no longer available or managed by the EPA. These programs are now left up to each individual state to manage, resulting in significantly different types of data provided by each state, if these data are available at all. There are three main concerns with these types of Protection Area data:

- Some of the Protection Areas apply to the entire public water system, rather than each individual well/intake within the public water system. This can lead to USAs that are larger than they need to be;

- There is often no direct link between the Protection Areas and the individual wells/intakes in the PWS data; and
- Without a national Protection Area (SWPA/WHPA) data set, the data structure of the SWPAs will differ from state to state.

For this update, SWPA and WHPA were merged into a single layer (SWPA) when a state provided both data sets.

The SSA data layer is a nationally standardized data set that is available from the EPA. However, most SSAs in this data set do not have the recharge area identified which makes it impossible to determine the recharge areas for all the SSAs composed of karst as specified in the DW USA filter criteria. One SSA, St. Joseph SSA, was not included in the national data set and was extracted from data provided by the state of Indiana. In the majority of situations, where there is a SSA composed of karst, the model utilized the entire boundary of the SSA as the DW USA.

Determining Adequate Alternative Drinking Water Sources (AADWS) for each public water supply was not required for this update.

The DW USA data were delivered to PHMSA for use by pipeline operators in their pipeline integrity management plans. Table 23 shows the total number of DW USAs and area (square miles) for each state. The DW USA data are stored by PHMSA and made available to vetted and approved operators through the National Pipeline Mapping System (NPMS).

Table 23. Total number and area (sq. mi.) for the DW USAs delivered to PHMSA.

	Drinking Water USAs (Number)				Drinking Water USAs (Area Sq. Mi)			
State	Ground water	Surface Water	Sole Source Aquifer	Total	Ground water	Surface Water	Sole Source Aquifer	Total
Alabama (AL)	992	90		1082	112.4	1373.2		1485.6
Alaska (AK)	323	140		463	1435.8	8873.2		10308.9
Arizona (AZ)	2365	68		2433	1856.0	414.4		2270.4
Arkansas (AR)	756	91		847	931.6	6331.7		7263.3
California (CA)	9595	646		10241	4349.6	7887.3		12236.9
Colorado (CO)	823	367		1190	4743.4	18122.0		22865.4
Connecticut (CT)	689	213		902	297.5	746.0		1043.5
Delaware (DE)	613	7		620	276.3	65.5		341.8
District of Columbia (DC)		2		2		10.4		10.4
Florida (FL)	2128	30	3	2161	243.8	3305.4	12894.4	16443.6
Georgia (GA)	3516	156		3672	297.1	7043.6		7340.7
Hawaii (HI)	451	14		465	203.3	108.9		312.1
Idaho (ID)	2090	85		2175	12108.0	4315.9		16423.9
Illinois (IL)	1443	147		1590	416.8	4395.9		4812.6
Indiana (IN)	1929	44		1973	3073.4	366.3		3439.6

	Drinking Water USAs (Number)				Drinking Water USAs (Area Sq. Mi)			
State	Ground water	Surface Water	Sole Source Aquifer	Total	Ground water	Surface Water	Sole Source Aquifer	Total
Iowa (IA)	1808	39		1847	1344.2	2986.8		4331.0
Kansas (KS)	1561	79		1640	1422.7	13696.1		15118.8
Kentucky (KY)	187	183		370	118.8	8254.5		8373.3
Louisiana (LA)	1714	49		1763	4587.7	2858.3		7446.0
Maine (ME)	690	53	1	744	120.3	6.0	12.1	138.4
Maryland (MD)	1448	50		1498	58.7	427.1		485.8
Massachusetts (MA)	1837	260		2097	938.8	1092.0		2030.8
Michigan (MI)	3871	79		3950	6208.5	290.9		6499.4
Minnesota (MN)	1591	31		1622	7072.7	15652.3		22725.1
Mississippi (MS)	753	7		760	412.9	175.8		588.8
Missouri (MO)	1503	105		1608	1180.5	534.7		1715.2
Montana (MN)	445	81		526	3161.0	1054.1		4215.2
Nebraska (NE)	1332	6		1338	12797.3	39.5		12836.7
Nevada (NV)	651	16		667	660.2	395.4		1055.6
New Hampshire (NH)	437	49		486	669.0	9.6		678.5
New Jersey (NJ)	1937	52	1	1990	688.5	276.8	1644.1	2609.4
New Mexico (NM)	1027	71		1098	3226.3	559.8		3786.0
New York (NY)	4393	318	1	4712	660.0	2976.4	67.0	3703.4
North Carolina (NC)	1938	200		2138	891.8	10818.6		11710.4
North Dakota (ND)	618	31		649	950.1	559.0		1509.0
Ohio (OH)	2591	237	2	2830	3785.2	2759.4	307.8	6852.4
Oklahoma (OK)	2171	226	2	2399	22.0	3575.2	356.4	3953.6
Oregon (OR)	1695	214		1909	760.7	19061.3		19822.0
Pennsylvania (PA)	3323	461	1	3785	2609.7	3151.2	80.5	5841.3
Puerto Rico (PR)	813	122		935	206.1	901.6		1107.7
Rhode Island (RI)	142	24		166	64.0	142.5		206.5
South Carolina (SC)	372	67		439	110.1	2836.2		2946.2
South Dakota (SD)	472	60		532	16098.3	3996.4		20094.8
Tennessee (TN)	662	117		839	1713.1	9764.3		11477.4
Texas (TX)	5552	453	13	6018	2260.6	19303.3	2331.0	23894.9
Utah (UT)	1491	81	1	1573	3554.2	2893.6	39.8	6487.6
Vermont (VT)	646	50		696	76.8	167.7		244.5
Virginia (VA)	1763	180	1	1944	202.6	3134.4	7.6	3344.6
Washington (WA)	4600	126		4726	1493.8	1151.5		2645.2

	Drinking Water USAs (Number)				Drinking Water USAs (Area Sq. Mi)			
State	Ground water	Surface Water	Sole Source Aquifer	Total	Ground water	Surface Water	Sole Source Aquifer	Total
West Virginia (WV)	373	150		523	845.9	2859.2		3705.1
Wisconsin (WI)	1997	31		2028	502.0	1520.5		2022.6
Wyoming (WY)	433	56		489	999.5	697.0		1696.5

PHMSA would like to thank the numerous state and federal agencies that provided data and supported this very important project. These agencies are identified in the lineage section of each metadata document. Protecting our drinking water resources from hazardous liquid pipeline spills is of the upmost importance.

Appendix A

Drinking Water USAs Project Projections
48 Contiguous States, Alaska, and Hawaii

Standard Map Projection for the 48 Contiguous States

Projection:	Albers	
Datum:	NAD83	
Units:	Meters	
Spheroid:	GRS 1980	
Parameters:		
	1st standard parallel:	29 30 0.000
	2nd standard parallel:	45 30 0.000
	Central meridian:	-96 00 0.000
	Latitude of origin:	23 00 0.000
	False easting:	0
	False northing:	0

Standard Map Projection for Alaska

Projection:	Albers	
Datum:	NAD83	
Units:	Meters	
Spheroid:	GRS 1980	
Parameters:		
	1st standard parallel:	55 00 0.000
	2nd standard parallel:	65 00 0.000
	Central meridian:	-154 00 0.000
	Latitude of origin:	50 00 0.00
	False easting:	0
	False northing:	0

Standard Map Projection for Hawaii

Projection:	Albers	
Datum:	NAD83	
Units:	Meters	
Spheroid:	GRS 1980	
Parameters:		
	1st standard parallel:	8 00 0.000
	2nd standard parallel:	18 00 0.000
	Central meridian:	-157 00 0.000
	Latitude of origin:	13 00 0.00
	False easting:	0
	False northing:	0

Appendix B

Drinking Water USAs Data Schema and Definitions

PWS Layer

Geographic Themes	Attribute Names	Description	Attribute Values
PWS ***(Bolded attributes required)***	**PWS_ID** **(Text, 10 Character)**	**Public Water System Identifier**	**ST####### (e.g. ND1840049)** **or NULL** **Note: Could link to 1 or several SWPA. The field CANNOT be blank**
	ACTIVITY_CODE (Text, 1 Character)	Indicates whether the PWS intake is active or inactive	A = Active I = Inactive or NULL Note: The field CANNOT be blank
	SYSTEM_TYPE (Text, 1 Character)	Identifies the type of PWS	C = Community Water System (default) P = Non-transient Non-community N = Transient Non-community or NULL Note: The field CANNOT be blank
	SOURCE_TYPE (Text, 2 Characters)	Identifies the type of PWS intake	GW = Groundwater Well (default) SW = Surface Water Intake SP = Spring or NULL Note: The field CANNOT be blank
	DEPTH_WELL (Numeric, type based on input data)	Depth of well in feet	0-X Note: The field CANNOT be NULL
	DEPTH_SCREEN (Numeric, type based on input data)	Depth to the top of the first screened interval in feet	0-X Note: The field CANNOT be NULL
	DEPTH_CASE (Numeric, type based on input data)	Depth of well casing in feet	0-X Note: The field CANNOT be NULL
	PUMP_RATE (Numeric, type based on input data)	Pump rate, in gallons per minute (gpm)	0-X Note: The field CANNOT be NULL
	SOURCE (Text, Characters based on input data)	Description of water source (e.g. aquifer, description of source materials)	Free text or NULL Note: The field CANNOT be blank
	THICK_CONF (Numeric, type based on input data)	Thickness of the confining unit in feet. Usually the surface confining layer of loess, till, etc.	0-X Notes: If multi. thicknesses, this is the sum of confining unit thickness above the topmost source aquifer.
	LITHOLOGY (Text, Characters based on input data)	Description of the sediment/rock type in the strata from which the well is sourcing water	Free text or NULL (e.g. sandstone, carbonate, etc) Note: The field CANNOT be blank
	SWPABUFF **(Numeric, type based on input data)**	**Source Water Protection Area or Wellhead Protection Area (WHPA) radius in meters**	**0-X (defaults to 609.6m or 2000ft)** **Note: The field CANNOT be NULL**
	SWPAUNIQUE (Text, 20 Characters)	Unique link to a SWPA or WHPA boundary.	ST-PWSID-###### (example: AL-1111111-000001) or NULL Note: The field CANNOT be blank
	SDWIS (Text, 1 Characters)	Identifies if the facility information came from SDWIS	Y = SDWIS data N = State data or NULL Note: The field CANNOT be blank

Brief description of how the attributes for the PWS layer are updated:

PWS_ID: In most cases, this item was already identified in the PWS data as PWS_ID or some close derivative.

ACTIVITY_CODE: In some cases, the PWS data had an item indicating whether PWS intake was active or not. Some databases contained a status code identifying a PWS intake as permanent, seasonal, or emergency status. Permanent status was treated as an active intake while seasonal and emergency status were treated as inactive. In the rare case where this information was not available in the PWS data, all intakes were considered to be active.

SYSTEM_TYPE: In most cases, the type of PWS was identified in the PWS data. In the rare case where this information was not available in the PWS data, all wells/intakes were considered Community Water Systems.

SOURCE_TYPE: In most cases, the type of PWS intake was identified in the PWS data. If not, all intakes were treated as groundwater wells.

DEPTH_WELL: In some cases, well depth information was provided in the PWS data. All well depth information not already reported in feet was converted to feet.

DEPTH_SCREEN: In some cases, the depth to the top of the screened intervals was provided in the PWS data. If this was available, this field was updated with the depth value for the top up of the first screened interval. The units were converted to feet, if not already in feet. When available, this value was used in preference to DEPTH_WELL and DEPTH_CASE, when determining the source depth for the well.

DEPTH_CASE: In some cases, the depth of the well casing was provided. All casing depth information not already reported in feet was converted to feet. DEPTH_CASE was used in conjunction with DEPTH_WELL in determining the depth of the source aquifer.

PUMP_RATE: In some cases, pump rate information, usually in gallons per minute, was provided in the PWS data. All pump rate information was converted to gallons per minute.

SOURCE: In some cases, information regarding the source of water (e.g., source aquifer, or description of source materials) was available in the PWS data.

THICK_CONF: In some cases, information on the thickness of the confining unit was available. All thickness information not already in feet was converted to feet. This usually only included the surficial confining units such as till and loess. On rare occasions, it may have included subsurface confining layers. If more than one confining unit thickness was reported, the value of the sum of the thickness of each confining unit above the topmost source aquifer was included in this field.

LITHOLOGY: A description of the type of rock or sediment of the source strata was sometimes included. Usually this field had values such as sandstone, carbonate, crystalline, metamorphic, unconsolidated sand and gravel. This information is used to help determine the permeability and thus Pettyjohn classification of the source aquifer. The values were usually kept exactly as reported in the original database, and the rules were adjusted to recognize these values.

SWPABUFF: For those situations where the state uses a fixed-radius to determine the SWPA/WHPA boundary and there were no digital SWPA/WHPA boundary data available, this item would be updated to the radius, in meters, of the SWPA/WHPA as defined by the state. For those situations where the state has no fixed-radius method available to determine the SWPA/WHPA boundary and there were no digital SWPA/WHPA boundary data available, this item would be updated to the default radius of 609.6 m (or 2,000 ft).

SWPAUNIQUE#: It is populated with a value to uniquely link a well to a delineated SWPA. It is necessary in cases where the PWS_ID may link to 2 or more delineated SWPAs, or there is no link possible on PWS_ID. The value is determined by overlaying the well point with the SWPA coverage and assigning the well the SWPAUNIQUE# from the SWPA that the well falls within and has the same PWS_ID or some other linkable field.

SWPA Layer

Geographic Themes	Attribute Names	Description	Attribute Values
SWPA ***(Bolded attributes required)***	**PWS_ID** **(Text, 10 Character)**	**Public Water System Identifier**	**ST####### (e.g. ND1840049)** **or NULL** **Note: Could link to 1 or several SWPA. The field CANNOT be blank**
	SWPAUNIQUE (Text, 20 Characters)	Unique link to a SWPA or WHPA boundary, if PWS_ID cannot provide the necessary link	ST-PWSID-###### (example: AL-1111111-000001) or NULL Note: The field CANNOT be blank

Brief description of how the attributes for the SWPA and WHPA layers are updated:

PWS_ID: In most cases, this item was already identified in the SWPA data as PWS_ID or some close derivative.

SWPAUNIQUE#: It is populated with a value to uniquely link a delineated SWPA to a well. It is necessary in those cases where the PWS_ID may link to 2 or more delineated SWPAs, or where there is no link possible on PWS_ID. This a unique identifier created from the record number.

NOTE: If SWPA and WHPA data are available for the same state, the WHPA data are merged with the SWPA data.

AQUIFER Layer

Geographic Themes	Attribute Names	Description	Attribute Values
AQUIFER	**AQUIF** **(Text, 10 Characters)**	**Four-letter aquifer abbreviation with suffixes _OUT or _SUB appended if subcrop info available**	**Free text (Aquifer Abbreviation)** **e.g. TRINITY AQUIFER subcrop avail = TRIN_OUT, TRIN_SUB** **Note: The field CANNOT be blank or NULL**

Brief description of how the attribute for the Aquifer layer is updated:

AQUIF: Is updated with the 4 to 10 letter code that the model uses for identifying aquifers.

SSA Layer

Geographic Themes	Attribute Names	Description	Attribute Values
SSA *(Bolded attributes required)*	**KARST (Text, 1 Character)**	**Indicates if the SSA is Karst**	**Y or NULL Note: The field CANNOT be blank**
	RECHARGE (Text, 1 Character)	**Indicates if the feature is a recharge area**	**Y or NULL Note: The field CANNOT be blank**
	NAME (Text, Characters based on input data)	**The official (EPA) name of the SSA**	**Free text or NULL (e.g. EDWARDS II) Note: The field CANNOT be blank**
	AQUIF (Text, Characters based on input data)	**4-10 Letter code for the SSA**	**Free text or NULL Note: If in AQUIFER FC, = AQUIF, else _SSA suffix denoting SSA FC only Note: The field CANNOT be blank**

Brief description of how the attributes for the SSA layer are updated:

KARST: If the sole source aquifer is a karst aquifer, based on information provided by the geologist, this field is updated with a 'Y', otherwise it is NULL.

RECHARGE: If the boundaries for the sole source aquifer represents the recharge area, this field is updated with a 'Y', otherwise it is NULL.

NAME: This field is the official name of the sole source aquifer as provided by EPA.

AQUIF: Is updated with the 4 to 10 letter code that the model uses for identifying aquifers. If the SSA is already included in the AQUIFER layer, this item gets updated to the same value as AQUIF in the AQUIFER layer. Otherwise it is given a new 4-letter code and _SSA is appended to it to indicate that it is from the SSA layer

GEOLOGY Layers

Geographic Themes	Attribute Names	Description	Attribute Values
BGEO *(Bolded attributes required)*	**FM (Text, Characters based on input data)**	**Bedrock geology code**	**Free text or NULL Note: The field CANNOT be blank**
	BGEO_DESC (Text, Characters based on input data)	Bedrock geology description that groundwater wells have to overlie	Free text or NULL Note: The field CANNOT be blank

Geographic Themes	Attribute Names	Description	Attribute Values
SGEO *(Bolded attributes required)*	**SGEO_DESC (Text, Characters based on input data)**	**Surficial geology description**	**Free text or NULL (e.g. Mississippi River Alluvium) Note: The field CANNOT be blank**

Geographic Themes	Attribute Names	Description	Attribute Values
DRIFT *(Bolded attributes required)*	**THICK_GLAC (Text, 1 Character)**	**Code indicating thickness range of glacial drift**	**Free text or NULL (e.g. 1: <50 feet 2: >50 feet) Note: The field CANNOT be blank**

Geographic Themes	Attribute Names	Description	Attribute Values
SEDTHICK (Surficial geology thickness) ***(Bolded attributes required)***	**THICK_SGEO (Text, Character based on input data)**	**Code indicating the thickness of the overlying sediment or the depth to the bedrock**	**Free text or NULL (e.g. 1: <50 feet 2: 50-100 feet) Note: The field CANNOT be blank**

Geographic Themes	Attribute Names	Description	Attribute Values
BASINS (Hydrological Features) ***(Bolded attributes required)***	**BASIN (Text, Characters based on input data)**	**Name or code of aquifer basin**	**Free text or NULL (e.g. SALINAS VALLEY) Note: The field CANNOT be blank**

Brief description of how the attributes for the Geology layers are updated:

FM: This code is updated from the geologic code that is usually included in the geologic coverage provided by the state.

BGEO_DESC: This item is usually updated directly with the values for the description of the bedrock geologic code used in FM.

SGEO_DESC: This item is updated directly with the value for the description of the surficial geologic feature that is included in the data file obtained from the state. It can be a code or full geologic description such as Mississippi River alluvium.

THICK_GLAC: This is updated to the thickness range of < 50 and > 50 feet based on the original data that are associated with the polygons in the layer.

THICK_SGEO: This is updated to the thickness range based on the original data that are associated with the polygons in the layer.

BASIN: This is updated to the name or code for the basin based on the original data that are associated with the polygons in the layer.

HYDRO Layers

Geographic Themes	Attribute Names	Description	Attribute Values
NHD_AREA ***(Bolded attributes required)***	**FCode (Long Integer)**	**USGS Classification Code**	**Value or 0** **Note: The field CANNOT be NULL**

Geographic Themes	Attribute Names	Description	Attribute Values
NHD_WATERBODY ***(Bolded attributes required)***	**FCode (Long Integer)**	**USGS Classification Code**	**Value or 0** **Note: The field CANNOT be NULL**

Geographic Themes	Attribute Names	Description	Attribute Values
NHD_FLOWLINE ***(Bolded attributes required)***	**FCode (Long Integer)**	**USGS Classification Code**	**Value or 0** **Note: The field CANNOT be NULL**

TABLES

Lookup Table	Attribute Names	Description	Attribute Values
RULES_LUT ***(Bolded attributes required)***	**VAL_AQUIF** **(Text, 10 Characters)**	**Aquifer code of source aquifer identified in the guidelines**	**Free text (Aquifer Code) or NULL** **e.g. TRINITY AQUIFER = TRIN OR TRIN_OUT/TRIN_SUB** **Note: The field CANNOT be blank or NULL**
	CLASS **(Text, 10 Characters)**	**Pettyjohn class of the source aquifer identified by this set of criteria**	**Class Ia: Unconsolidated Aquifers** **Class Ib: Soluble and Fractured Bedrock Aquifers** **Class Ic: Semi-consolidated Aquifers** **Class Id: Covered Aquifers** **Class IIa: Higher Yield Bedrock Aquifers** **Class IIb: Lower Yield Bedrock Aquifers** **Class IIc: Covered Bedrock Aquifers** **Class III: Covered Consolidated or Unconsolidated Aquifers overlain by >50 ft low permeability material** **or NULL** **Note: The field CANNOT be blank or NULL**
	FM (Text, Characters based on input data)	Bedrock geology formation code that groundwater wells have to overlie	Free text or NULL e.g. Note: The field CANNOT be blank
	BGEO_DESC (Text, Characters based on input data)	Bedrock geology description that groundwater wells have to overlie	Free text or NULL e.g. Note: The field CANNOT be blank
	SGEO_DESC (Text, Characters based on input data)	Surface geology description that groundwater wells have to overlie	Free text or NULL (e.g. Mississippi River Alluvium) Note: The field CANNOT be blank
	THICK_SGEO (Text, Characters based on input data)	Surface geology thickness code that groundwater wells have to overlie.	Free text or NULL (e.g. 1: <50 feet 2: >50 feet) Note: The field CANNOT be blank
	THICK_GLAC (Text, 1 Character)	Code indicating thickness range of glacial drift	Free text or NULL (e.g. 1: <50 feet 2: >50 feet) Note: The field CANNOT be blank
	AQUIF (Text, 10 Characters)	Aquifer code of aquifer that groundwater wells have to overlie	Free text or NULL e.g. TRINITY AQUIFER = TRIN OR TRIN_OUT/TRIN_SUB Note: The field CANNOT be blank
	SOURCE (Text, Characters based on input data)	Descriptive source aquifer or source material information associated with the groundwater well	Free text or NULL Note: The field CANNOT be blank
	LITHOLOGY (Text, Characters based on input data)	Descriptive lithologic information associated with the groundwater well	Free text or NULL (e.g. sandstone, carbonate, etc) Note: The field CANNOT be blank
	MIN_DEPTH **(Numeric, type based on input data)**	**Minimum well depth for the groundwater systems with this classification**	**0-X** **Note: The field CANNOT be NULL**
	MAX_DEPTH **(Numeric, type based on input data)**	**Maximum well depth for the groundwater systems with this classification**	**0-X** **Note: The field CANNOT be NULL**
	MIN_CONF (Numeric, type based on input data)	Minimum confining unit thickness associated with the groundwater well	0-X Note: The field CANNOT be NULL
	MAX_CONF (Numeric, type based on input data)	Maximum confining unit thickness associated with the groundwater well	0-X Note: The field CANNOT be NULL
	MIN_YIELD (Numeric, type based on input data)	Minimum pump rate associated with a groundwater well	0-X Note: The field CANNOT be NULL
	MAX_YIELD (Numeric, type based on input data)	Maximum pump rate associated with a groundwater well	0-X Note: The field CANNOT be NULL

Lookup Table	Attribute Names	Description	Attribute Values
	MIN_CASE (Numeric, type based on input data)	Minimum casing depth associated with the groundwater well	0-X Note: The field CANNOT be NULL
	MAX_CASE (Numeric, type based on input data)	Maximum casing depth associated with the groundwater well	0-X Note: The field CANNOT be NULL
	MIN_SCREEN (Numeric, type based on input data)	Minimum screen depth associated with the groundwater well	0-X Note: The field CANNOT be NULL
	MAX_SCREEN (Numeric, type based on input data)	Maximum screen depth associated with the groundwater well	0-X Note: The field CANNOT be NULL
	RULE (Text, 3 Characters)	**Number of the guideline as described by the geologist in the Guidelines document**	**Free text e.g. 1a Note: The field CANNOT be blank or NULL**

Lookup Table	Attribute Names	Description	Attribute Values
OW_NHD_LUT ***(Bolded attributes required)***	**CLASS (Text, Characters based on input data)**	**Used to determine if the feature is to be considered open water by the model**	**Free text or NULL Note: The field CANNOT be blank**
	FCODE (Long Integer))	**USGS Classification code**	**0-X Note: The field CANNOT be NULL**
	DESCRIPTION (Text, Characters based on input data)	**USGS description of the entity label**	**Free text or NULL Note: The field CANNOT be blank**

Lookup Table	Attribute Names	Description	Attribute Values
SOURCE_LUT (*Bolded attributes required*)	**SOURCE (Text, Characters based on input data)**	**Source aquifer or source material description**	**Free text or NULL Note: The field CANNOT be blank**
	AQUIF_CODE (Text, Characters based on input data)	**Standardized aquifer code**	**Free text or UNK Note: The field CANNOT be blank or NULL**

Lookup Table	Attribute Names	Description	Attribute Values
DW_DAT (*Bolded attributes required*)	**DWUNIQUE (Text 20 Characters)**	**Unique well identifier generated by the model**	**Value STDW-PWS-###### (e.g. WYDW-PWS-000001)**
	STATE (Text, 2 Characters)	**Standardized state code**	**Free text Note: The field CANNOT be blank or NULL**
	NAME (Text, Characters based on input data),	**Name of the Sole Source Aquifer.**	**Free text or NULL Note: The field CANNOT be blank**
	State PWS identifier (Name same as used in state PWS rawdata table) (Text, Characters based on input data),	**The state field that contains the PWS identifier. Preferable the EPA PWS_ID. But if not available the State PWS_ID.**	**Free text or NULL Note: The field CANNOT be blank**
	State Facility Identifier (Name same as used in state PWS rawdata table) (Text, Characters based on input data),	**The state field that contains the unique facility (well/intake) identifier**	**Free text or NULL Note: The field CANNOT be blank**

FINAL DELIVERABLE (DW USAs)

Geographic Themes	Attribute Names	Description	Attribute Values
USA	DWUNIQUE (Text 20 Characters)	Unique well identifier generated by the model	Value: <ST>DW-<PWS|SSA>-00000# e.g. TXDW-SSA-000008
	STATE (Text, 2 Characters)	Standardized state code 2 letter state abbreviation	Free text e.g. SC = South Carolina Note: The field CANNOT be blank or NULL
	QUALITY (Short Integer)	Identifier for the process used to classify a groundwater well	1: Source aquifer info avail & well in data layer boundary 2: Source aquifer info avail & well outside spatial tolerance of data layer 3: Source aquifer info not avail & geog position, dist to aquifer, and surrounding well source info used to classify well aquifer 4: Source aquifer info not avail & well assigned aquifer based on location OR source aquifer info avail but indiv well data not avail. Classification based on location or well depth. 5: Source aquifer info not avail, classification impossible. Well assigned aquifer based on location within a SSA
	NAME (Text, Characters based on input data),	Name of the Sole Source Aquifer.	Free text or NULL Note: The field CANNOT be blank
	TYPE (Text, 7 Characters)	Describes status of USA	DW: Final USA INTERIM: Interim USA

Appendix C

Rules for Applying the Pettyjohn Classification Scheme
Final Rules – States listed in Alphabetical Order Including Puerto Rico

Rules for Applying the Pettyjohn Classification Scheme in Alabama

12 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-G (also called Ground Water Atlas of the United States, Segment 6; Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Well location
2. Bedrock geology
3. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology and the Segment 6 Atlas (Olcott, 1995) as a guide.

Due to the lack of source or depth data, classification of all wells is based solely on the location of the well within the aquifer coverage.

There are twelve aquifers in the state of Alabama:

1. Surficial
2. Coastal Lowlands
3. Floridan
4. Pearl River
5. Chattahoochee River
6. Black Warrior River
7. Piedmont
8. Valley and Ridge Carbonate
9. Valley and Ridge Siliciclastic
10. Appalachian Plateaus
11. Interior Low Plateaus
12. Not a principal aquifer

The aquifer features were constructed from the bedrock geology features (BGEO).

Rule 1. Surficial Aquifer (SURF)

The unconsolidated sediments of the Surficial aquifer are present within the major river valleys of Alabama such as the Tombigbee, Mobile, Black Warrior, Coosa and Alabama rivers as well as on the flanks of these river valleys in the form of high terrace deposits. The aquifer predominantly consists of sand and gravel from modern fluvial deposition as well as sand, silt and clay from Pleistocene fluvial deposition. The aquifer is unconfined throughout the entire state of Alabama.

1a. Wells located within the Surficial aquifer outcrop (SURF) are <u>Class Ia</u> because these unconsolidated sand and gravel deposits are predominantly under unconfined conditions.

Rule 2. Coastal Lowlands aquifer (COAS)

The unconsolidated to semi-consolidated sediments of the Coastal Lowlands aquifer outcrop across most of southwest Alabama with the exception of the major river valleys in the area. The aquifer predominantly consists of sand and gravel with interbedded silt and clay deposited from the Miocene to the early Pleistocene in deltaic environments. In most locations, the aquifer contains two permeable zones, the upper "surficial zone" and the lower "main producing zone" separated by a less permeable sand and clay unit. In south Mobile, southern Baldwin and southwestern Escambia counties Alabama, the upper surficial zone is mostly used for water supply because the lower zone is predominantly clay in this area. In Washington, northern Mobile, northern Baldwin and eastern Escambia counties Alabama, the lower main producing zone is the predominant water source. The aquifer is known as the Sand and Gravel aquifer in Florida.

2a. Wells located within the Coastal Lowlands aquifer outcrop (COAS) are conservatively Class Ia because without depth data, determining if a given well is sourcing the unconfined surficial zone or the semi-confined main producing zone is not possible.

Rule 3. Floridan aquifer (FLOR)

The consolidated carbonate rocks of the Floridan Aquifer outcrop in the extreme south-central and southeastern portions of the Alabama. In Alabama, the Floridan aquifer consists of surficial residuum underlain by more consolidated limestone of Eocene age.

3a. Wells located within the Floridan aquifer outcrop (FLOR) are Class Ib because the aquifer predominantly consists of karstic limestone containing possible solution cavities.

Rule 4. Pearl River aquifer (PEAR)

The predominantly unconsolidated sediments of the Pearl River aquifer outcrop in a band across southern Alabama. The Pearl River aquifer consists of thick sequences of sand with minor sandstone, gravel and limestone beds of Pliocene to Eocene age. The aquifer grades laterally and is hydrologically connected to the Floridan aquifer. The Chattahoochee River aquifer underlies the Pearl River aquifer and in western Alabama the confining unit separating the two aquifers is extremely thin to non-existent.

4a. Wells located within the Pearl River aquifer outcrop (PEAR) are Class Ia because the sediments are unconsolidated and the water is under unconfined or water table conditions.

Rule 5. Chattahoochee River aquifer (CHAT)

The unconsolidated to semi-consolidated sediments of the Chattahoochee River aquifer outcrop in a band across southern Alabama. The Chattahoochee River aquifer consists of sand beds with thin clay lenses and locally glauconitic sand and limestone deposited in marine environments of Cretaceous to Paleocene age. The aquifer is overlain by the Chattahoochee River confining unit and underlain by the Black Warrior River confining unit.

5a. Wells located within the Chattahoochee River aquifer outcrop (CHAT) are conservatively Class Ia because these sediments are predominantly unconsolidated sands under unconfined conditions.

Rule 6. Black Warrior River aquifer (BLAC)

The unconsolidated to semi-consolidated sediments of the Black Warrior River aquifer outcrop in a in a band from northwest to east central Alabama. The Black Warrior River aquifer consists of sand and clay deposited in fluvial deltaic and marine environments during the Cretaceous period. The aquifer is overlain by the Black Warrior confining unit and is underlain by crystalline basement rock.

6a. Wells located within the Black Warrior River aquifer outcrop (BLAC) are conservatively Class Ia because these sediments are predominantly unconsolidated and under unconfined conditions.

Rule 7. Piedmont aquifer (PIED)

The consolidated igneous and metamorphic rocks of the Piedmont aquifer outcrop in east central Alabama. The Piedmont aquifer consists of low to medium grade metamorphic rocks such as schist and gneiss and intrusive igneous rocks such as granite. These rocks are of Precambrian to Devonian age. Water is most commonly obtained from highly fractured contact zones between crystalline rock types.

7a. Wells located within the Piedmont aquifer outcrop (PIED) are Class IIa because the aquifer is consolidated and generally unconfined.

Rule 8. Valley and Ridge Carbonate aquifer (VALC)

The consolidated carbonate rocks of the Valley and Ridge Carbonate aquifer outcrop in bands trending in a northeast direction from central Alabama to the northern Georgia border as well as in valleys along the Tennessee border. The Valley and Ridge Carbonate aquifer consists of limestones, dolomites and chert of Cambrian to Mississippian age. These carbonate rocks are most productive where solution cavities have developed along valley floors which are favorable areas for recharge.

8a. Wells located within the Valley and Ridge Carbonate aquifer outcrop (VALC) are Class Ib because the aquifer consists of karstic limestone containing solution cavities.

Rule 9. Valley and Ridge Siliciclastic aquifer (VALS)

The consolidated siliciclastic rocks of the Valley and Ridge Siliciclastic aquifer outcrop in bands trending in a northeast direction from central Alabama to the northern Georgia border. The Valley and Ridge Siliciclastic aquifer consists of primarily sandstones, mudstones and shales of Cambrian to Pennsylvanian age. Much of the water in the Valley and Ridge Siliciclastic aquifer is obtained from fractures in the Red Mountain Formation and the Rome Formation.

9a. Wells located within the Valley and Ridge Siliciclastic aquifer outcrop (VALS) are Class IIa because the aquifer is consolidated and generally unconfined.

Rule 10. Appalachian Plateaus aquifer (PLAT)

The consolidated siliciclastic rocks of the Appalachian Plateaus aquifer outcrop in the high plateau region of north central and northeast Alabama. The Appalachian Plateaus Aquifer consists of sandstones and shales of Mississippian to Permian age. Water is obtained from fractures in the sandstone beds especially in the Pottsville and Parkwood Formations.

10a. Wells located within the Appalachian Plateaus aquifer outcrop (PLAT) are Class IIa because the aquifer is consolidated and generally unconfined.

Rule 11. Interior Low Plateaus aquifer (INTE)

The consolidated carbonate rocks of the Interior Low Plateaus aquifer outcrop in northern Alabama in the topographic low areas where the sandstone plateaus have eroded away, exposing the underlying carbonate rock. The Interior Plateaus aquifer consists of limestones, dolomites and chert of Mississippian age. The aquifer is most productive where solution cavities have created extremely permeable zones in the limestone such as in the Bangor Limestone where flows have been reported exceeding 4,000 gallons per minute.

11a. Wells located within the Interior Low Plateaus aquifer outcrop (INTE) are Class Ib because the aquifer consists of karstic limestone containing solution cavities.

Rule 12. Not a principal aquifer (NAPA)

The semi-consolidated low permeability sediments of the Not a Principal aquifer predominantly outcrop in east-west oriented bands across southern Alabama. The Not a Principal aquifer consists of clay, silt, and chalk of Cretaceous to Paleocene age. These sediments make up the confining units between the Pearl River, Chattahoochee and Black Warrior River aquifers.

12a. Wells located within the Not a Principal aquifer outcrop (NAPA) excluding those located in a predominantly chalk or limestone lithologies are conservatively Class Id because they are overlain by a low permeability clay, silt or chalk.

12b. Wells located within the Not a Principal aquifer outcrop (NAPA) located in a predominantly chalk or limestone lithologies, formation codes of Kd, Km, Kpb, To, and Tsm, are Class Ib because chalk has dissolution potential.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Alaska

22 March 2018

Introduction

The following rules were devised primarily on the basis of information provided in the USGS Hydrologic Investigations Atlas 730-N (Miller et al., 1999) and the previously published DW USA reports (RSPA, 2002). The dataset available at the time these rules were written consisted of:

1. Well location, source, confinement status, depth, screen depth
2. Bedrock geology

Spatial extent of aquifers is generally derived from detailed bedrock geology data (Wilson et al., 2015), using Miller et al., (1999) as a guide. Wells are classified primarily on basis of their described source, confinement status, depth, and the lithology of the bedrock or sedimentology of the unconsolidated material in the area. Well source data required preprocessing to enable Pettyjohn rule assignment. This preprocessing process is described below.

The following aquifers of Alaska were distinguished for this work:

1. Surficial Unconsolidated
2. Buried Unconsolidated
3. Soluble and Fractured Bedrock
4. Lower-Yield Bedrock

Well Source Preprocessing

PWS data possessed two attributes that were used to generate the final source aquifer information for each well. These were AQUIFER_TYPE and FORMATION. AQUIFER_TYPE contained free text descriptions of confinement status (e.g., “unconfined”, “partially confined”, etc.). FORMATION contained free text descriptions of material the well is sourcing (e.g., “sand and gravel”, “rock”, etc.). The fields were concatenated and all resulting unique values were assigned to one of the aquifers below.

All wells with formation descriptions that included terms such as “sand”, “gravel”, “unconsolidated”, or similar, were considered to source either surficial or buried unconsolidated aquifers. All wells with formation descriptions that included terms such as “volcanic”, “basalt”, “lava”, or similar, were considered to source soluble or fractured bedrock aquifers as described below. All wells with formation descriptions that included terms such as “schist”, “slate”, “sandstone”, “granite” or other specific lithology that is not part of the soluble or fractured bedrock aquifers above, were considered to source low-yield bedrock aquifers. All wells with formation descriptions that included terms such as “rock”, or other non-specific bedrock aquifers were assumed to source *either* soluble or fractured bedrock aquifers or low-yield bedrock aquifers, depending upon their location and other characteristics. Note that the term “fractured” was considered to indicate only characteristics of rock as extracted from the well log, and not a description of bedrock aquifer type. All unconfined or semi-confined wells were considered as unconfined in the rules below. All wells where the confinement status was unclear were considered as unconfined. A full list (source reassignment lookup table) of all unique well attribute values and the assigned source values should accompany this document.

Rule 1. Surficial unconsolidated aquifers (SURF)

Unconsolidated deposits of sand and gravel that were deposited as alluvium or glacial outwash or both form the most productive aquifers in Alaska. These aquifers are found in the lowland areas, primarily in the flood plains of major rivers. In addition, unconsolidated-deposit aquifers may underlie low, rolling hills developed on alluvial-fan deposits that separate flood plains from adjacent mountains. Principal surficial unconsolidated aquifers in the state include:

- Cook Inlet aquifer system
- River-valley alluvial aquifers
- Tanana Basin aquifer
- Coastal valley aquifers

1a. Unconfined wells that derive water from surficial Quaternary unconsolidated-deposit aquifers are Class Ia, because these aquifers can have high hydraulic conductivity and contain water primarily under unconfined or water-table conditions.

Rule 2. Buried unconsolidated aquifers (BUDA)

Unconsolidated sand and gravel aquifers may also underlie, and be partially confined by, low-permeability surficial deposits such as glacial till (predominantly moraine deposits), loess, and other fine-grained material.

2a. Confined sourcing Quaternary unconsolidated-deposit aquifers that are shallower than 50 ft, with screened intervals shallower than 50 ft, or with unknown depth and screened interval, are Class Id.

2b. Confined wells sourcing Quaternary unconsolidated-deposit aquifers with screened intervals deeper than 50 ft, are Class III.

Rule 3. Soluble and fractured bedrock aquifers (SFBA)

Consolidated rocks are exposed across the majority of the surface area of the state, but are used as a source of water in Alaska only where unconsolidated-deposit aquifers are absent, thin, or poorly permeable (Miller et al., 1999). Information about the water-yielding characteristics of these rock is generally scarce. A subset of bedrock aquifers in Alaska are thought to have increased permeability. Carbonate units, found in the eastern part of the Brooks Range and on Admiralty Island in the southeast part of the state, though not extensively utilized as groundwater sources, may contain solution cavities and other karst features. These bedrock units may locally yield large quantities of groundwater. Similarly, basalt flow units and other volcanic rocks, widespread throughout the state, can be highly permeable as they contain open spaces associated with fractures and joints, rubble zones and vesicular basalt at the top and bottom of flows, and unconsolidated-deposit interbeds.

3a. Because of this potential for enhanced permeability, unconfined or partially-confined wells located within the boundaries of, and sourcing these aquifers are Class Ib.
3b. Confined wells sourcing these aquifers that are shallower than 50 ft, with screened intervals shallower than 50 ft, or with unknown depth and screened interval, are Class IIc.
3c. Confined wells sourcing these aquifers with screened intervals deeper than 50 ft are Class III.

Rule 4. Lower-yield bedrock aquifers (LYBA)

Other consolidated bedrock aquifers found across Alaska are composed primarily of sedimentary (typically sandstone,) and metamorphic rocks (typically fractured slate, schist, and metagraywacke). These aquifers generally yield less than 50 gpm and are considered lower-yield bedrock aquifers.

4a Because of the generally low permeability and yield of these aquifers, unconfined or partially-confined wells located within the boundaries of, and sourcing these aquifers are Class IIb.

4b. Confined wells sourcing these aquifers that are shallower than 50 ft, with screened intervals shallower than 50 ft, or with unknown depth and screened interval, are Class IIc.

4c. Confined wells sourcing these aquifers with screened intervals deeper than 50 ft are Class III.

Metadata Sources References

Miller, J.A., R.L. Whitehead, D.S. Oki, S.B. Gingerich, and P.G. Olcott. 1997. Ground Water Atlas of the United States: Segment 13, Alaska, Hawaii, Puerto Rico, and the US Virgin Islands (No. 730-N, pp. N1-N36). Geological Survey, Reston, VA, 33 pp.

Wilson, F.H., C.P. Hults, C.G. Mull, and S.M. Karl. 2015. Geologic map of Alaska: U.S. Geological Survey Scientific Investigations Map 3340, pamphlet 196 p., 2 sheets, scale 1:1,584,000, http://dx.doi.org/10.3133/sim3340.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Arizona

28 February 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-C (referred to as Segment 2 atlas below; Robson and Banta, 1995) and the previously published DW USA reports (RSPA, 2002). The available data set included:

1. Well location
2. Bedrock geology

All aquifer coverages were interpreted from the bedrock geology coverage provided in the Digital Geologic Map of Arizona (Hirschberg and Pitts, 2000). It should be noted that the well database included no source aquifer information, thus wells are classified based on location and depth alone.

The following aquifers of Arizona were distinguished for this work:

1. Alluvial
2. Basin and Range
3. Colorado Plateau: Mesaverde
4. Colorado Plateau: Dakota-Glen Canyon
5. Colorado Plateau: Coconino-De Chelly
6. Not a Principle Aquifer: Volcanic
7. Not a Principle Aquifer: Igneous and Metamorphic Intrusives
8. Not a Principle Aquifer: Carboniferous
9. Not a Principle Aquifer
10. Sole Source Aquifers

Rule 1. Alluvial aquifers (ALLU)

Unconsolidated Tertiary and Quaternary deposits of sand and gravel constitute two principal aquifers in Arizona, the Alluvial aquifers and the Basin and Range aquifers. Unconsolidated Quaternary deposits of alluvial gravel, sand, silt, and clay or Quaternary deposits of eolian sand and silt are largely confined to stream valleys and generally form the shallowest ground water aquifers in the state. Where these deposits are of appreciable thickness and extent, they may form locally important aquifers, such as along the Little Colorado River in Navajo and Apache Counties. Collectively, these deposits are referred to as the Alluvial aquifers. In much of the mountainous parts of Arizona, alluvial deposits are too thin, narrow, and discontinuous to be considered major aquifers. Along the Gila, Salt, and Santa Cruz Rivers, these deposits are ~100 ft thick and 1 to 2 miles wide. Along the lower Colorado River, stream alluvium may be more than 700 ft thick. All Alluvial aquifers contain water primarily under unconfined or water-table conditions. The hydraulic conductivity of these aquifers is variable, depending on the sorting of the materials and the amount of silt and clay present, but generally it is high. Accordingly, Alluvial aquifers are considered to be susceptible to contamination. Alluvial deposits also form aquifers in the Basin and Range Physiographic Province. However, these shallow aquifers are part of deeper and more extensive basin-fill aquifers that are discussed below.

1a. Wells throughout the state, located within the Alluvial aquifer, that derive water from the surficial (Holocene) sediments (primarily alluvial valley and floodplain deposits, small regions of eolian sands, landslide deposits, alluvial fans etc.) are Class Ia, because these Holocene sands and gravels are unconsolidated deposits that connect directly with the surficial water table. The small and often discontinuous alluvial valleys of Arizona contain extremely thin saturated zones. Wells deriving water from these units should be no deeper than 100 ft. In the upstream areas, aquifer thickness probably drops to as little as 20 ft, but there is no way to delineate these areas with the data available.

1b. Wells deriving water from depths greater than 100 ft should be categorized on the basis of the subcrop type they derive water from. However, there is no spatial information on subcrop boundaries and no source information in the wells. For this reason, wells within the Alluvial aquifer, deeper than 100 ft, will be classified as Unknown.

Rule 2. Basin and Range aquifers (BNRG, BASI)

The Basin and Range Physiographic Province is a vast arid region in the western US that extends from northern Mexico to southern Idaho and Oregon, encompassing much of southern and western Arizona. It consists of broad alluvial basins in downfaulted blocks of the Earth's crust bordered by mountain ranges formed by uplifted blocks. Aquifers present in the down-faulted, alluvium-filled basins constitute the Basin and Range aquifers *(BNRG)*, the principal sources of ground water in southern Arizona.

Basin fill material consists primarily of Quaternary and Tertiary unconsolidated to moderately consolidated, poorly to well-sorted beds of gravel, sand, silt, and clay that were deposited on alluvial fans, pediments, floodplains, and playas. Stream alluvium is also present within most of the larger stream valleys. More cemented or compact sediments in the older basin fill and finer-grained sediments near the center of basins are less permeable than coarser-grained sediments near the margins of basins. Evaporites are present in the deeper fine-grained sediments in the centers of some basins. Extrusive volcanic rocks are interspersed with basin fill in some basins and overlie basin fill in a few areas. The thickness of basin fill typically ranges from 1000 to 5000 ft and may exceed 10,000 ft in a few deep basins in south-central Arizona. The Basin and Range aquifers contain water primarily under unconfined or water-table conditions. Fine-grained deposits of silt and clay may form local confining units.

In the Basin and Range, basin fill generally contains fine-grained playa deposits near the center of basins *(BASI)* and coarse-grained alluvial fan deposits near the basin margins *(BRNG)*. However, in the digital geologic map of Arizona (Hirschberg and Pitts, 2000), these different sediment types of the basin fill are not differentiated from each other. Because these deposits have very different hydraulic characteristics, a spatial buffering scheme was devised to differentiate them and to aid in well classification. Sediments within 10 km of the margin of the Quaternary basin fill are presumed to be coarse-grained alluvial fan deposits (basin-margin deposits). Sediments further than 10 km inward from the basin margin are presumed to be fine-grained playa deposits (central-basin deposits).

2a. Wells within 10 km of the edge of the Quaternary basin fill most likely derive water for the coarser portions of the basin-fill alluvium and are hence Class Ia.

2b. Wells further than 10 km inward from the edge of the basin fill region *(BASI)* are classified as Unknown. It is likely that these wells derive water from confined aquifers but the potential exists for shallow, unconfined aquifers.

2c. Wells may be as deep as 5000 ft and conceivably derive water from basin fill sediments. Wells deeper than this derive water from an unknown underlying aquifer and are classified as Unknown.

Colorado Plateau aquifers (MESA, DAKO, COCO)

In the Colorado Plateaus region of northeastern Arizona, a thick Permian to Cretaceous sequence of poorly to well-consolidated conglomerate, sandstone, and shale form the Colorado Plateaus aquifers. Volcanic rocks, carbonate rocks, and evaporite deposits also form locally productive aquifers.

The Colorado Plateaus aquifers underlie an area of ~110,000 square miles in western Colorado, northwestern New Mexico, northeastern Arizona, and eastern Utah. This area is roughly coincident with the Colorado Plateaus Physiographic Province. Structural deformation and faulting, associated with uplift of the Rocky Mountains, and lateral changes in the lithology of the rocks have produced a complex sequence of water-yielding layers. Uplift of the Colorado Plateaus steepened stream gradients accelerated the downcutting of the Colorado River. Broad structural basins were developed between some of the uplifted areas. The thickness and hydraulic characteristics of the geologic units that compose the aquifers vary greatly. Thickness of aquifers generally increases toward the central parts of basins. The principal aquifers of the Colorado Plateaus aquifers that are found in Arizona are the Mesaverde aquifer *(MESA)*, Dakota-Glen Canyon aquifer system *(DAKO)*, and Coconino-De Chelly aquifer *(COCO)*. Relatively impermeable confining units separate these aquifers. The two thickest of these confining units are the Mancos Shale, which underlies the Mesaverde aquifer, and the Chinle-Moenkopi confining unit, which underlies the Dakota-Glen Canyon aquifer system.

Rule 3. Mesaverde aquifer (MESA)

The Mesaverde aquifer is found in the Black Mesa Basin of northeastern Arizona and comprises water-yielding units in the Upper Cretaceous Mesaverde Group, which, in the Black Mesa area, includes the Yale Point Sandstone, Wepo Formation, and Toreva Formation. In the Black Mesa Basin, the upper part of the Mesaverde group consists of sandstone. The lower part consists of sandstone or silty sandstone interbedded with siltstone and coal. In most of the Black Mesa area, the upper part of the Mesaverde Group has been removed by erosion. Thus, the interbedded sequence of the lower part of the Mesaverde Group forms the Mesaverde aquifer.

3a. Wells located within the aquifer derive water from the lower, siltier portions of the Mesa Verde Group because most of the upper units have been removed through erosion (USGS Segment 2 Atlas, p. C28). Wells within the Mesa Verde aquifer are therefore most likely low yield (< 50 gpm) and hence are Class IIb.

3b. In general, wells within the Mesa Verde aquifer should not exceed 2000 ft depths. Wells with depths greater than 2000 ft derive water from the subcrop of the Dakota sandstone and are Class III, due to overlying confining units.

Rule 4. Dakota-Glen Canyon aquifer system (DAKO)

The Dakota-Glen Canyon aquifer system consists of water-yielding Upper Triassic to Cretaceous rocks, which underlie most of the Colorado Plateaus area including the Black Mesa Basin in northeastern Arizona. The geologic units that form the bulk of these aquifers are the Dakota Sandstone, the lower part of the Morrison Formation, the San Rafael Group, and the Glen Canyon Group. Sandstone, conglomerate, and conglomeratic sandstone are the principal water-yielding rocks. Low-permeability layers of mudstone, claystone, siltstone, shale, and limestone form confining units that separate individual aquifers in the Dakota-Glen Canyon aquifer system. Lithology of the Upper Cretaceous Dakota Sandstone varies widely and includes conglomerate, sandstone, siltstone, mudstone, carbonaceous shale, and coal. The Upper Jurassic Morrison Formation consists of interbedded fine to medium sandstone, siltstone, and mudstone. Water-yielding units in the Jurassic San Rafael Group include the Cow Springs and Entrada Sandstones. The Entrada Sandstone is generally a very fine- to fine-grained sandstone commonly of eolian origin.

4a. The Dakota-Glen Canyon aquifer system is found in the northeastern portion of the state. Wells within the outcrop of and deriving water from the Dakota sandstone, Morrison Formation, Cow Springs and Entrada Sandstones of the San Rafael group, and/or the Glen Canyon Group (Kd, Jm, Jsr, and JTRgc respectively) are conservatively categorized as Class IIa, because the aquifers have the potential for high yields, though this cannot be confirmed by the USGS Segment 2 Atlas or with the digital data available. It should be noted that laterally equivalent units in northwest New Mexico have high rates of production.

4b. Wells within the outcrop of the Dakota Sandstone (Kd), which in Arizona is in direct contact with the underlying Morrison, Cow Springs and Entrada Sandstones, and deriving water from that unit should be no deeper than 1000 ft (Table 1, USGS Segment 2 Atlas p. C29). Wells deeper than this derive water from the underlying and confined Glen Canyon aquifer subcrop and are therefore Class III.

4c. Wells in the outcrop belt of the Morrison Formation (Jm) and deriving water from that unit should be no deeper than 900 ft (Table 1, USGS Segment 2 Atlas p. C29). Wells with depths > 900 ft are Class III because they derive water from the underlying Glen Canyon aquifer or deeper Coconino-DeChelly aquifer.

4d. Wells in the outcrop belt of the San Rafael Group (Jsr) and deriving water from that unit should be no deeper than 400 ft (Based on a maximum Entrada Sandstone thickness of 350 ft plus a 50 ft buffer to account for possible Cow Spring Sandstone, see Fig 121 and Table 1, USGS Segment 2 Atlas p. C29). Wells >400 ft deep are Class III because they derive water from the underlying Glen Canyon or deeper Coconino-DeChelly aquifer.

4e. Wells within the outcrop belt of the Glen Canyon aquifer (JTRgc) and deriving water from that unit should be no deeper than 2300 ft (Table 1, USGS Segment 2 Atlas p. C29). Wells deeper than this are deriving water from deeply underlying subcrops of the Coconino and De Chelly Sandstones and are Class III.

Rule 5. Coconino-De Chelly aquifer (COCO)

The Coconino-De Chelly aquifer consists of water-yielding Permian rocks that underlie the southern part of the Colorado Plateaus including the Black Mesa Basin and Defiance Uplift in northeastern Arizona. The formations that compose the Coconino-De Chelly aquifer in this region are the Coconino and its lateral equivalents, the De Chelly Sandstones and the Cutler Formation. The Coconino and De Chelly Sandstones generally consist of well-sorted quartz sandstone with thin interbeds of siltstone, mudstone, and carbonates. The Cutler Formation consists of shale, siltstone, sandstone, arkose, and arkosic conglomerate. The maximum thickness of the Coconino Sandstone is about 900 ft near the Wupatki National Monument (Irwin et al., 1971).

5a. Despite the aquifer's widespread nature, it has only limited outcrops in the central and northeastern portions of the state. In the Grand Canyon area, the Coconino crops out but is of little use as a water resource due to drainage directly into the Colorado River via internal fracturing. Wells located in the primary outcrops of the Coconino and DeChelly sandstones and deriving water from those units at depths less than or equal to 900 ft are Class IIa.

5b. The Coconino Sandstone overlies the Supai Formation which is a low-yield bedrock aquifer (see rule 9a) with a thickness of 1600-1700 ft in the Black Mesa Basin. Wells located in the primary outcrops of the Coconino and DeChelly sandstones with depths greater than 900 ft are likely deriving water from the Supai Formation, which has a maximum thickness of 1700 ft (Irwin et al., 1971) and are Class IIb.

Not a Principle Aquifer (VOLC, IGNE, CARB, NAPA)

The outcrop belts of some rock units of Arizona are designated as 'not a principal aquifer' (Figure 1; modified from Fig. 11, Robson and Banta, 1995). This designation covers areas where aquifers either do not exist, yield too little water to be significant, or yield sufficient water to supply only local requirements, but are not extensive enough to be considered major aquifers. These outcrop belts consist of Precambrian to Quaternary igneous, metamorphic, and sedimentary rocks and have been split up into four categories on the basis of the rock type in the area they are located: volcanic *(VOLC)*; instrusive igneous and metamorphic *(IGNE)*; carbonate *(CARB)*; and all other including clastic bedrock units *(NAPA)*. Wells located atop sparse limestone outcrops are of particular importance.

Rule 6. Volcanic aquifers (VOLC)

6. Wells in volcanic regions possibly tap into highly fractured igneous units and are therefore conservatively labeled Class Ib.

Rule 7. Igneous and metamorphic intrusives aquifers (IGNE)

7. Wells located in intrusive igneous and metamorphic units are most likely deriving water from low yield aquifers and are therefore Class IIb.

Rule 8. Carboniferous aquifers (CARB)

8. Wells deriving water from carbonates of any age are Class Ib, due to the probability of solution cavities within the limestone units.

Rule 9. Not a Principal Aquifer (NAPA)

9a. Wells deriving water from clastic bedrock units are most likely tapping Class IIb, low yield (< 50 gpm) bedrock aquifers. At present, well data does not include daily well yields or flow rates, however, if such data becomes available, it should be checked in order to verify this classification.

9b. Wells located within confining units (Ph) are Class III.

9c. Several unit names and descriptions are too vague to base a Pettyjohn classification on. Wells deriving water from the MZPZs and PZs units are classified as Unknown, since the information available does not separate these units into "clastics vs. carbonates".

9d. Wells within the Mancos shale outcrop (Km) most likely derive water from the subcrop of the Dakota-Glen Canyon aquifer system. Wells in the Mancos shallower than 50 ft are Class IIc, because they derive water from bedrock, which is covered by only a thin layer of confining units.

9e. Wells within the Mancos shale outcrop (Km) deeper than 50 ft are Class III, due to the confining nature of the shale units.

9f. As discussed in rule 4, wells within the Dakota-Glen Canyon aquifer outcrop belt may derive water from the underlying Coconino-DeChelly aquifer. The same is true and perhaps more likely for wells located within the outcrop belt of the overlying Chinle and Moenkopi Formations (TRc, TRcs, and TRm) which are considered to be part of the NAPA group. Wells located in these outcrop belts are Class IIc if their depth is shallower than 50 ft, because the aquifer they derive water from is covered by < 50 ft of impermeable material.

9g. Wells located in the outcrop belts of the Chinle and Moenkopi Formations and deeper than 50 ft are Class III. Even if a well does not reach the deep subcrops of the Coconino-DeChelly system, it derives water from an aquifer confined by the impermeable Chinle or other units.

9h. Wells located within the outcrop belts of the Kaibab Limestone and Toroweap Formations (Pkt) are Class Ib if the depth of the well is <1200 ft. The Kaibab limestone unit, like most carbonates, has a relatively high potential for karst and increased porosity due to dissolution.

9i. Wells within the outcrop belts of the Kaibab Limestone and Toroweap Formations and deeper than 1200 ft are Class III. The value of 1200 ft is based on thickness estimates reported in the text accompanying USGS map MF-2343 (Billingsley, 2000).

Sole Source Aquifers

Arizona contains two EPA-designated sole-source aquifers: The Upper Santa Cruz and Avra Basin aquifer in Santa Cruz, Pima, and Pinal Counties (49 FR 2948) and the Bisbee-Naco aquifer in Cochise County (53 FR 38337). Both of these sole-source aquifers are contained within the coverage of the Basin and Range aquifers and are not differentiated in Figure 1. Inclusion of the sole-source aquifers within the larger Basin and Range aquifers does not affect the Pettyjohn classification of wells within the sole-source aquifers.

Metadata Sources References

Billingsley, George H. 2000. Geologic Map of the Upper Parashant Canyon and Vicinity, Mohave County, Northwestern Arizona. Report to Accompany US Geological Survey Miscellaneous Field Studies Map 2343.

Hirschberg, D.M. and G.S. Pitts. 2000. Digital geologic map of Arizona: A digital database derived from the 1983 Printing of the Wilson, Moore, and Cooper 1:500,000-scale Map: U.S. Geological Survey open-File Report 00-409, 67 pp., https://pubs.usgs.gov/of/2000/0409/.

Irwin, J. H., P. R. Stevens, and M. E. Cooley. 1971. Geology of the Paleozoic Rocks, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah. US Geological Survey Professional Paper 521-C.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Robson, S.G. and E.R. Banta. 1995. Ground water atlas of the United States: Segment 2, Arizona, Colorado, New Mexico, Utah. Hydrologic Investigations Atlas 730-C, U.S. Geological Survey, Reston, VA, 34 pp.

Rules for Applying the Pettyjohn Classification Scheme in Arkansas

16 March 2018

Introduction

The Arkansas aquifer boundaries were created on the basis of the areal distribution of geologic units as depicted in the digital representation of the Geologic Map of Arkansas. Thus, the aquifers are shown in outcrop extent only. Aquifer subcrops must be interpreted from the geologic map and other available information. The discussion of the aquifers of Arkansas and the classification rules below are derived largely from information in Renken (1998), Kresse et al. (2014) and the previously published DW USA reports (RSPA, 2002). The available data sets included:

1. Wells: location, depth, casing depth, source aquifer, source formation
2. Bedrock and surficial geology

Classification of all wells should be based on the shallowest sourced interval in the well. However, because screen depth data is not currently available for the state of Arkansas, the classification of wells is based on their casing depth and the source information provided. The source information provided with the wells lists all the aquifers that provide water for the well. To be conservative the most sensitive aquifer listed is used in determining the Pettyjohn classification. The maximum depth at which the classification changes is based upon the maximum thickness of each aquifer. The aquifer thicknesses were determined from the measurements and figures provided in Renken (1998) and Kresse et al. (2014). The objective is to identify the wells that most likely have an error in at least one of the parameters of location, depth, or source.

The following aquifers of Arkansas were distinguished for this work:

1. Surficial
    - Mississippi River Valley Alluvial
    - Stream-Valley Alluvial
2. Mississippi Embayment
    - Claiborne
    - Wilcox
    - McNairy-Nacatoch
3. Cretaceous
    - Tokio-Woodbine
    - Trinity
4. Ouachita Mountains
5. Western Interior Plains
6. Ozark Plateaus
    - Springfield Plateau
    - Ozark

Rule 1. Surficial aquifers (MISS, ALLU)

The Surficial aquifer system consists mainly of alluvial (gravel and sand) deposits with minor amounts of eolian sediments, including dune sands and loess. The deposition occurred during the

Quaternary within the floodplain of the Mississippi and other major rivers. These aquifers are generally characterized by a lower unit of sand and gravel covered by a confining unit of silt and clay.

Mississippi River Valley Alluvial aquifer (MISS): This aquifer generally ranges in thickness between 0 and 140 ft, reaching a maximum of 160 ft in two known locations. These high permeability sands and gravels are covered by the Mississippi River Valley confining unit of variable thickness but consistently 50 ft thick in many areas. Quaternary alluvial and deltaic deposits of the lower Mississippi River Valley generally are lithologically similar to and in good hydraulic connection with the underlying deposits of the coastal lowlands aquifer system and, therefore, are included in that system.

Stream-valley alluvial aquifers (ALLU): Locally important stream-valley alluvial aquifers include those of the Arkansas River (interior highlands), the Ouachita-Saline Rivers, and the Red River. These aquifers consist of terraced alluvial deposits of Pleistocene age and flood plain alluvial deposits of Holocene age. Most of these aquifers are thin due to pre-Pleistocene erosion and topography, with thicknesses usually not exceeding 100 ft.

1a. Wells deriving water from the outcrop of the Mississippi River Valley alluvial aquifer system, permeable facies (MISS_OUT) are <u>Class Id</u>, because these sediments are unconsolidated and contain high permeability sands and gravels. The majority of these sediments are covered by the Mississippi River Valley confining unit. Wells deriving water from this aquifer should be no deeper than 210 ft, based on a maximum thickness of 160 ft for the alluvial sediments plus 50 ft for the overlying confining unit.

1b. Wells deriving water from the outcrop of the Mississippi River Valley alluvial aquifer system (MISS_OUT) at depths greater than 210 ft are classified as unknown.

1c. Wells deriving water from the outcrop of the other alluvial aquifers (ALLU_OUT): Arkansas, Ouachita-Saline, and Red Rivers; are Class Id, because these sediments are unconsolidated and contain high permeability sands and gravels with an upper confining unit of silt and clay < 50 ft thick. Wells deriving water from this aquifer should be no deeper than 100 ft, based on the maximum thickness of these aquifers as described in Renken (1998).

1d. Wells deriving water from the outcrop of the Arkansas, Ouachita-Saline, and Red River alluvial aquifers (ALLU_OUT) at depths greater than 100 ft are classified as unknown.

Rule 2. Mississippi Embayment aquifers (CLAI, WILC, MCNA)

The Mississippi Embayment aquifer system is composed of several aquifers and aquitards Cretaceous to Eocene in age. The following hydrologic units in Arkansas can be distinguished based on the surface geologic coverage (listed youngest to oldest): Jackson Group (Tj) confining unit; Claiborne aquifer *(CLAI);* Wilcox aquifer *(WILC);* Midway Group (Tm) and Arkadelphia Marl (Kad) confining units; and McNairy-Nacatoch aquifer *(MCNA).*

These geologic units are an interbedded sequence of poorly consolidated deposits. The aquifers are permeable sands and are effectively separated by extensive confining units. The confining units are considered as part of the aquifer they overlie and are identified in the rules by their geologic formation.

Claiborne aquifer (CLAI): The Claiborne aquifer in Arkansas comprises the Cockfield formation (upper Claiborne), the Sparta Sand, and the Memphis Sand (the combined formations of the Sparta Sand, the Cane River Formation, and the Carrizo Sand). Confining units separate the middle Claiborne from overlying and underlying aquifers in most places. The overlying confining unit comprises the Jackson Group, also known as the Vicksburg-Jackson confining unit, and it separates the Claiborne aquifer from the Quaternary alluvial deposits. The Jackson Group is a sequence of largely unconsolidated clays with rare, interbedded siltstone and sandstone units.

Wilcox aquifer (WILC): In Arkansas, the lower confining unit of the Claiborne is missing, and the lower Claiborne and upper Wilcox function together as a single aquifer in the Wilcox Group. The Wilcox Group also includes the middle Wilcox and the lower Wilcox aquifers. The lower Claiborne-upper Wilcox includes all sand beds below the clay beds of the lower Claiborne group. The middle Wilcox includes irregular and discontinuous sand beds that are interbedded with layers of clay, silt, and lignite. The lower Wilcox includes thin, interbedded layers of lignitic sands and clays.

McNairy-Nacatoch aquifer (MCNA): The Midway Group (Tm) is a thick clay sequence underlain in some areas by another confining unit, the Arkadelphia Marl (Kad). The Midway Group serves as a lower confining unit for the Wilcox aquifer and, where present, the Arkadelphia Marl serves as an upper confining unit for the McNairy-Nacatoch aquifer. The McNairy Sand does not occur in Arkansas, so the McNairy-Nacatoch is often referred to as the Nacatoch aquifer. The Cretaceous-age Nacatoch Sand is predominantly composed of unconsolidated sands with local lenses and beds of sandy limestone.

- 2a. Wells deriving water from the Claiborne aquifer (CLAI_OUT) and located in the Jackson Group (Tj) confining unit of the Mississippi Embayment aquifer system are Class Id, because these are semi-consolidated sediments of unknown thickness.
- 2b. Wells deriving water from the Claiborne aquifer (CLAI_OUT) or the Wilcox aquifer (WILC_SUB) and located in the outcrop belt of the Claiborne aquifer (CLAI) are Class Ic, because the fluvial sediments are semi-consolidated.
- 2c. Wells deriving water from the Wilcox aquifer outcrop (WILC_OUT) are Class Ic, because these are semi-consolidated sediments.
- 2d. All other wells deriving water from the Claiborne aquifer (CLAI_SUB) or Wilcox aquifer (WILC_SUB) are Class Id, because there are semi-consolidated sediments of unknown thickness and are covered by <50 ft of impermeable material.
- 2e. Wells deriving water from the McNairy-Nacatoch aquifer (MCNA_OUT) and located in the Midway Group (Tm) and Arkadelphia Marl (Kad) confining units of the Mississippi Embayment aquifer system are Class III, because these are semi-consolidated sediments overlain by > 50 ft of impermeable material.
- 2f. All other wells deriving water from McNairy-Nacatoch (MCNA_OUT) aquifer are Class Ia, because the Nacatoch Sand consists of unconsolidated deltaic sediments.

2g. Wells deriving water from the subcrop of the McNairy-Nacatoch aquifer (MCNA_SUB) are Class III, because there is usually a confining unit 120-160 ft thick that overlies the Nacatoch Sand.

Rule 3. Cretaceous aquifers (TOKI, TRIN)

The Cretaceous aquifer system in Arkansas consists of two aquifers, the upper Cretaceous Tokio-Woodbine aquifer and the lower Cretaceous Trinity aquifer. The upper part of the Tokio-Woodbine aquifer consists of the Tokio Formation, which is a sequence of cross-bedded sand, gravel, and lignitic clay that grades down-dip to sand and shale. The lower part of the aquifer comprises the Woodbine Formation, which is a red and gray clay-rich unit that includes a massive, cross-bedded sand and gravel deposit where the formation extends into the shallow subsurface.

The Trinity aquifer extends to the states of Texas and Oklahoma. The Cretaceous aquifers are equivalent in age and facies with the Southeastern Coastal Plain aquifers.

3a. Wells deriving water from Trinity and the Tokio-Woodbine (TOKI_OUT, TRIN_OUT, TRIN_SUB) and located in the outcrop belts of the Trinity and the Tokio-Woodbine aquifers (TRIN, TOKI) are Class IIa, because these fluvial sediments are consolidated rocks.

3b. Wells deriving water from the Tokio aquifer (TOKI_OUT) and located in the Marlbrook Marl (Km), Ozan Formation (Ko), or Brownstown Marl (Kb) are Class III, because the marls are considered to be low permeability sediments up to 250 ft thick that confine the underlying Trinity or Tokio-Woodbine formations.

3c. Wells deriving water from the Tokio aquifer subcrop (TOKI_SUB) and located in the permeable minor alluvial aquifer system (ALLU) are Class IIc, because these are consolidated sandstones with large volumes of water yield and are covered by <50 ft of impermeable material.

3d. Wells deriving water from the subcrops of the Tokio aquifer (TOKI_SUB) or the Trinity aquifer (TRIN_SUB) and located in the outcrop belt of any other aquifer not specified in the other rules above are Class III, because there are multiple low permeability confining units up to 250 ft thick overlying these subcrops.

Rule 4. Ouachita Mountains aquifer (OUAC)

A thick sequence of Paleozoic rock formations in the Ouachita Mountains aquifer is composed mostly of shale, sandstone, and chert beds Cambrian to Pennsylvanian in age that were deposited in deep marine environments. The coarsest sediments are turbidity-current or debris-flow deposits. In the Ouachita Mountains, high-permeability fracture zones have formed along bedding-plane partings, but are best developed where folding has caused differential movement along contacts between shale and sandstone beds. Fault zones, which often contain milky quartz veins, also function as local conduits for ground-water flow. The system extends from Oklahoma into Arkansas.

4a. Wells deriving water from the Ouachita Mountains aquifer outcrop (OUAC_OUT) are Class IIb, because these are consolidated rocks with low yields (less than 50 gpm, USGS Ground Water Atlas, Segment 5, Renken, 1998, p. F27).

4b. Wells deriving water from the Ouachita aquifer subcrop (OUAC_SUB) are Class III, because these are consolidated sandstones with low yields, covered by low permeability units with thicknesses greater than 50 ft.

Rule 5. Western Interior Plains aquifer (WEST)

The Western Interior Plains aquifer is part of a widespread, thick, geologically complex, sedimentary sequence of Mississippian-Pennsylvanian age that extends eastward from the Rocky Mountains to western Missouri and northern Arkansas. Regionally designated as a confining system, the Western Interior Plains comprises 11 different predominantly clastic (sand, siltstone, shale) and relatively impermeable formations. Locally, however, individual geologic units or parts of units within the confining system yield as much as 19 gallons per minute to wells, mainly from the overlying weathered zone and partly from fractured bedrock. The Western Interior Plains system is, therefore, considered to be a minor aquifer with yields lower than 50 gpm.

5a. Wells deriving water from the Western Interior Plains aquifer outcrop (WEST_OUT) are classified as Class IIb.

5b. Wells deriving water from the Western Interior Plains aquifer subcrop (WEST_SUB) are Class III, because the source aquifer is a confining unit and there are likely other confining units above the subcrop.

Rule 6. Ozark Plateau aquifers (OZAR, SPRI)

The Ozark Plateaus aquifers contain two aquifers that crop out in northern Arkansas: the Ozark aquifer (OZAR) of Ordovician-Devonian age and the Springfield Plateau aquifer (SPRI) of Mississippian age. The aquifer system consists of a thick sequence of lithified, flat-lying to southward dipping limestone and dolomite that contains some beds of sandstone, shale and chert. Dissolution of limestone and dolomite rocks of the Ozark Plateaus aquifer system has resulted in the development of karst terrain in much of northern Arkansas. Karstic features that have developed on rocks of hydrologic significance include sinkholes, conduit springs and caves. Solution features are hydrologically important because they serve as the principal conduits for concentrated groundwater flow and, thus, account for much of the permeability within the Ozark Plateaus aquifer system.

The Boone Formation comprises the Springfield Plateau aquifer which has a thickness of about 200-400 ft throughout northern Arkansas. The beds of the Springfield Plateau aquifer dip southward beneath the Western Interior Plains confining system and extend to depths of more than 4,000 ft below sea level (Fig. 98, USGS Ground Water Atlas, Segment 5, Renken, 1998, page F22).

6a. Wells deriving water from the Springfield Plateau aquifer outcrop belt (SPRI_OUT) and deriving water from depths of 400 ft or less are Class Ib, because the Boone Formation has limestone members and solution openings.

6b. Wells deriving water from the Springfield Plateau aquifer outcrop belt (SPRI_OUT) and deriving water from depths greater than 400 ft are UNK, because these depths are below the Ozark confining unit.

6c. Wells deriving water from Springfield Plateau aquifer subcrop (SPRI_SUB) and located in the outcrop belt of the Pitkin Limestone (Mpfb) or the Moorefield Formation (Mm) in the Western Interior Plains aquifer (WEST) are Class Ib, because these are paleokarst formations with limestone members and solution openings.

6d. Wells deriving water from Springfield Plateau aquifer subcrop (SPRI_SUB) and located in the outcrop belt of the Western Interior Plains aquifer (WEST) are Class III, because there is a marked contrast between the high permeability of the karst limestone of the Springfield Plateau aquifer and the low fracture porosity in the Western Interior Plains confining system which impedes the flow of water to and from the underlying Springfield Plateau aquifer (Kresse et al., 2014).

6e. Wells deriving water from the subcrop of the Springfield Plateau aquifer (SPRI_SUB) and located in the outcrop belt of any aquifer other than those mentioned above are Class Ib because the source is likely to be the Boone Formation which has limestone members and solution openings.

6f. Wells deriving water from the Ozark aquifer outcrop (OZAR_OUT) are Class Ib if the source code is the Everton Dolomite or Powell Dolomite, because these formations are carbonate rocks with solution openings. Wells with unidentified source codes deriving water from the Ozark aquifer outcrop are also given this class because the source is most likely karstic.

6g. Wells deriving water from the Ozark aquifer outcrop (OZAR_OUT) are Class IIa if the source code is: Roubidoux Formation or Gunter Sandstone, because these are consolidated, permeable sandstone and carbonate units with high yields of water (100-300 gpm, USGS Ground Water Atlas, Segment 5, Renken, 1998, p. F22).

6h. Wells deriving water from the Ozark aquifer outcrop (OZAR_OUT) are Class IIb if the source code is the Jefferson City Dolomite or Cotter Dolomite, because these are consolidated rock formations with low yield (USGS Ground Water Atlas, Segment 5, Renken, 1998, p. F22).

6i. Wells deriving water from the Ozark aquifer outcrop (OZAR_OUT) and located in the outcrop belt of the Chattanooga Shale (MDcp) and deriving water from the Everton Dolomite or Powell Dolomite formations are Class Id, because these are soluble carbonate formations covered by less than 50 ft of impermeable material.

6j. Wells deriving water from the Ozark aquifer outcrop (OZAR_OUT) and located in the outcrop belt of the Chattanooga Shale (MDcp) and deriving water from the Cotter Dolomite, Jefferson City Dolomite, or Roubidoux Formations, are Class IIc, because these are confined consolidated rock formations covered by less than 50 ft of impermeable material.

6k. Wells that derive water from the Ozark aquifer subcrop (OZAR_SUB) and located in the outcrop belt of the Springfield aquifer (SPRI) are classified as Class Id, because these are potentially cavernous (karst) carbonate rocks covered by the Ozark confining unit (as shown in the stratigraphic column of Fig. 97 in the USGS Ground Water Atlas, Segment 5, Renken, 1998, p. F22), which has a thickness less than 50 ft.

6l. Wells located in any other areas and deriving water from the Ozark aquifer subcrop (OZAR_SUB) are Class III, because there are multiple impermeable layers that overlie the dolomite aquifer.

Metadata Sources References

Kresse, T.M., P.D. Hays, K.R. Merriman, J.A. Gillip, D.T. Fugitt, J.L. Spellman, A.M. Nottmeier, D.A. Westerman, J.M. Blackstock and J.L. Battreal. 2014. Aquifers of Arkansas—Protection, management, and hydrologic and geochemical characteristics of groundwater resources in Arkansas: U.S. Geological Survey Scientific Investigations Report 2014–5149, 334 p., http://dx.doi.org/10.3133/sir20145149.

Renken, R.A. 1998. Ground water atlas of the United States: Segment 5, Arkansas, Louisiana, Mississippi. Hydrologic Investigations Atlas 730-F, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in California

20 May 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-L (also called Ground Water Atlas of the United States, Segment 1; Planert and Williams, 1995), California's Groundwater Update 2013 (Brown et al., 2015) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules for California included:

1. Well Location
2. Well Screen Depth
3. Bedrock Geology

The geology of California was categorized into five aquifer systems:

1. Alluvial
2. Carbonate rock
3. Volcanic rock
4. Sandstone
5. Crystalline

Rule 1. Alluvial aquifers (ALLU)

The Alluvial basins of California are highly variable in their geologic origin, physical and hydrogeological characteristics, horizontal and vertical distribution, production properties, and water quality (Brown et al., 2015). Because of the high variability, Brown et al. (2015) divided California's alluvial aquifers into four principal aquifer systems: Central Valley aquifer system; coastal aquifers; Northern California basin-fill aquifers; and Basin and Range basin-fill aquifers. Brown et al. (2015) supplied information for individual basins within the four alluvial aquifer systems about the degree of consolidation of the aquifer within that basin and whether or not the aquifer is confined at a certain depth interval. This information, in combination with the distribution of well depths for wells within a given basin, permitted the establishment of a depth cutoff for rule making. Descriptions of the four major alluvial aquifer systems are below.

The Central Valley aquifer system is a structural trough that generally includes the valley portion of the Sacramento River, San Joaquin River, and Tulare Lake hydrologic regions. These aquifers are comprised primarily of sand, gravel, and clay deposits and exist under both unconfined and confined conditions. Although the Central Valley is filled with tens of thousands of feet of unconsolidated sediments, most of the fresh groundwater is found at depths of less than 2,500 ft. The Central Valley contains a single heterogeneous aquifer system that contains water under unconfined, or water-table, conditions in the upper few hundred feet; these conditions grade into confined conditions with depth. The confinement is the result of numerous overlapping lens-shaped clay beds. The most extensive clay bed is the Corcoran Clay Member of the Tulare Formation that underlies much of the San Joaquin Valley and forms a nearly impermeable barrier. The Corcoran clay is as much as 150 ft thick and occurs at depths of 250-800 ft.

The coastal aquifers include several basins located adjacent to the Pacific Ocean. Many of the coastal basins are characterized as structural depressions formed by folding and faulting and are subsequently filled by marine and alluvial sediments. Groundwater typically occurs under unconfined to confined conditions, with many basins consisting of two or more aquifers separated by fine-grained sediments of variable thickness and extent. The depth to confinement varies greatly among the different basins.

The Northern California basin-fill aquifers consist of unconsolidated alluvial sediments in valleys drained by tributaries or main stems of the Klamath and Sacramento Rivers. The northern basins of the Sacramento River have been included in the Central Valley aquifer system as described above.

The Basin and Range basin-fill aquifers are comprised of unconsolidated gravel, sand, silt, and clay of Pliocene to Holocene age deposited as alluvial fans, alluvial slopes, and playas. Holocene-age sediments were deposited in modern or ancestral stream beds. The basin fill aquifer contains water predominately under unconfined conditions.

1a. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the San Joaquin Valley of the Central Valley basin (BASIN 5-022) with well screen depths less than or equal to 800 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

1b. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the San Joaquin Valley of the Central Valley basin (BASIN 5-022) with well screen depths greater than 800 ft are Class III because the unconsolidated deposits in this aquifer are covered by more than 50 ft of impermeable material.

1c. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the East Side aquifer of the Salinas Valley (BASIN 3-004.02) with well screen depths less than or equal to 600 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

1d. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the East Side aquifer of the Salinas Valley (BASIN 3-004.02) with well screen depths greater than 600 ft are Class Id because the unconsolidated deposits in this aquifer are covered by less than 50 ft of impermeable material.

1e. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Monterey and Seaside areas of the Salinas Valley (BASIN 3-004.08 and 3-004.10) with well screen depths less than or equal to 550 ft are Class Ia,because the unconsolidated deposits in this aquifer are unconfined.

1f. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Monterey and Seaside areas of the Salinas Valley (BASIN 3-004.08 and 3-004.10) with well screen depths greater than 550 ft are Class III because the unconsolidated deposits in this aquifer are covered by more than 50 ft of impermeable material.

1g. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Paso Robles area of the Salinas Valley (BASIN 3-004.06) with well screen depths less than or equal to 130 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

1h. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Paso Robles area of the Salinas Valley (BASIN 3-004.06) with well screen depths greater than 130 ft are Class III because the unconsolidated deposits in this aquifer are covered by more than 50 ft of impermeable material.

1i. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Llagas area of the Gilroy-Hollister Valley (BASIN 3-003.01) with well screen depths less than or equal to 125 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

1j. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Llagas area of the Gilroy-Hollister Valley (BASIN 3-003.01) with well screen depths greater than 125 ft are Class IIa because the sediments in this aquifer are consolidated and unconfined.

1k. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Oxnard areas of the Santa Clara River Valley (BASIN 4-004.02) with screen depths less than or equal to 200 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

1l. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Oxnard areas of the Santa Clara River Valley (BASIN 4-004.02) with screen depths greater than 200 ft are Class III because the unconsolidated deposits in this aquifer are covered by more than 50 ft of impermeable material.

1m. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Owens Valley of the Basin and Range aquifers (BASIN 6-012) with screen depths less than or equal to 180 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined to semi-confined.

1n. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Owens Valley of the Basin and Range aquifers (BASIN 6-012) with screen depths greater than 180 ft are Class III because the unconsolidated deposits in this aquifer are covered by more than 50 ft of impermeable material.

1o. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Borrego Valley of the Basin and Range aquifers (BASIN 7-024) with screen depths less than or equal to 260 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

1p. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Borrego Valley of the Basin and Range aquifers (BASIN 7-024) with screen depths greater than 260 ft are Class Ic because the sediments in this aquifer are semiconsolidated and unconfined.

1q. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Warren Valley of the Basin and Range aquifers (BASIN 7-012) with screen depths less than or equal to 800 ft are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

1r. Wells that are located within the Alluvial aquifer outcrop (ALLU) and in the Warren Valley of the Basin and Range aquifers (BASIN 7-012) with screen depths greater than 800 ft are Class IIa,because the sediments in this aquifer are consolidated and unconfined.

1s. Wells that are located within the Alluvial aquifer outcrop (ALLU) and outside of the basin areas mentioned in rules 1a – 1r are Class Ia because the unconsolidated deposits in this aquifer are unconfined.

Rule 2. Carbonate rock aquifer (CARB)

The consolidated rocks of the Carbonate rock aquifer that underlie the alluvial basins of the Basin and Range outcrop in southeastern California. Carbonate rocks also outcrop in the eastern Klamath Mountains. The carbonate rocks are Paleozoic to Mesozoic in age, with some late Precambrian rocks in Death Valley. They are comprised of an upper sequence of limestone and minor dolomite interbedded with shale and sandstone and a lower sequence of limestone and dolomite that contains little clastic material. The aquifer may be greater than 15,000 ft in thickness and is highly fractured and locally brecciated. The aquifer contains water under unconfined conditions.

2. Wells located within the Carbonate rock aquifer outcrops (CARB) are Class Ib because the aquifer is comprised of soluble carbonate rocks.

Rule 3. Volcanic rock aquifer (VOLC)

The Volcanic rock aquifer consists of welded ash flows, bedded ash flows, and lava flows. The aquifer contains water under unconfined conditions, which is hosted in fractures and locally in intergranular spaces in porous tuffs.

3. Wells located within the Volcanic rock aquifer outcrop (VOLC) are conservatively Class Ib because they possibly tap into highly fractured igneous units.

Rule 4. Sandstone aquifer (SAND)

Sandstone rocks outcrop in California mainly between the Central Valley and Coastal basins. These rocks have minimal primary and secondary permeability and are thus not principal sources of groundwater. Groundwater is stored within fractures or other void spaces.

4. Wells located within the Sandstone Aquifer outcrop (SAND) are Class IIa because the aquifer is consolidated and unconfined.

Rule 5. Crystalline aquifer (CRYS)

The Crystalline aquifer consists of metamorphic, metavolcanic, igneous intrusive, and plutonic rocks. These rocks surround and underlie the coastal basins and the Central Valley, outcropping mainly on the eastern side of the Central Valley. These rocks are almost impermeable, and flow through them is not significant. Groundwater is stored within fractures or other void spaces.

5. Wells located within the Crystalline Aquifer outcrop (CRYS) are Class IIa because the aquifer is consolidated and unconfined.

Metadata Sources References

Brown Jr., Edmund G., John Laird, and Mark Cowin. 2015. California's Groundwater Update 2013: A Compilation of Enhanced Content for California Water Plan Update 2013.

Planert, M. and J.S. Williams. 1995. Ground water atlas of the United States: Segment 1, California and Nevada. Hydrologic Investigations Atlas 730-B, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Colorado

13 November 2018

Introduction

The rule set below is based on information published in the Ground Water Atlas of Colorado (Topper et al., 2003), the USGS Hydrologic Investigations Atlas 730-C, Segment 2 (Robson and Banta, 1995) and the previously published DW USA reports (RSPA, 2002). The data available for Colorado included:

1. Wells: location, screen depth, source
2. Bedrock aquifers
3. Bedrock geology

The following aquifers of Colorado were distinguished for this work:

1. Alluvial
2. Rio Grande
3. High Plains
4. Dawson
5. Denver
6. Arapahoe
7. Laramie-Fox Hills
8. Eagle Basin
9. Colorado Plateaus
10. Carbonate and basaltic rock aquifers
11. Crystalline and igneous rock aquifers
12. Not a principal aquifer

The Ground Water Atlas of Colorado (Topper et al., 2003) distinguishes 13 principal aquifer basins in Colorado. For the purposes of this report, these have been categorized into six aquifer systems: Rio Grande, High Plains, Denver Basin, Eagle Basin, Colorado Plateaus, plus a broad region considered as not a principal aquifer (NAPA). The Denver Basin aquifer system has been further divided into four separate aquifers according to Topper et al. (2003): Dawson aquifer, Denver aquifer, Arapahoe aquifer, and Laramie-Fox Hills aquifer.

Another important source of groundwater is the Dakota-Cheyenne Basin. However, a boundary for this aquifer is not included in the Ground Water Atlas of Colorado. Aquifers in this region were delineated using the bedrock geology coverage (updated in 2005). The geologic formations were grouped into three aquifer types: carbonate and basaltic rock; crystalline and igneous; and not a principal aquifer, which includes sandstone rock and confining units.

Rule 1. Alluvial aquifers (ALLU)

Unconsolidated Quaternary deposits of alluvial gravel, sand, silt, and clay or Quaternary deposits of Aeolian sand and silt are present in many parts of Colorado and generally compose the shallowest aquifers in the state. Collectively, these deposits are referred to as Surficial aquifers.

The alluvial and Aeolian deposits of the South Platte River Valley and the Arkansas River Valley are moderately thick and extensive and contain the two major Surficial aquifers in Colorado. Other Surficial aquifers in lesser stream valleys are generally small and isolated from each other. Shallow aquifers are also present in alluvial deposits of the Rio Grande Basin. However, these aquifers are considered part of the deeper and more extensive Rio Grande aquifer system, which is discussed below. All Surficial aquifers contain water primarily under unconfined or water-table conditions. The hydraulic conductivity of these aquifers is variable, depending on the sorting of the materials and the amount of silt and clay present, but generally it is high. Accordingly, Surficial aquifers are considered to be susceptible to contamination. Surficial aquifers in Colorado are thickest in the South Platte River Valley where they reach a maximum thickness of about 200 ft (Robson and Banta, 1995). Transmissivity of the Surficial aquifers can reach more than 100,000 ft squared per day in these areas where the aquifers are especially thick. An aquifer of large transmissivity can yield large volumes of water to wells.

1a. Wells less than or equal to 200 ft deep that derive water from surficial Quaternary unconsolidated sand and gravel aquifers (ALLU_OUT) and are located in Aeolian formations (Qe, Qeo) in the bedrock geology are <u>Class Id</u> because these formations include low permeability loess deposits less than 50 ft thick.

1b. Wells that derive water from surficial Quaternary unconsolidated sand and gravel aquifers (ALLU_OUT) excluding those found in Aeolian formations (Qe, Qeo) in the bedrock geology are <u>Class Ia</u> if well depth is less than or equal to 200 ft, because these aquifers can have high hydraulic conductivity and contain water primarily under unconfined or water-table conditions.

1c. Wells that derive water from surficial Quaternary unconsolidated sand and gravel aquifers (ALLU_OUT) at depths greater than 200 ft are <u>Class UNK</u>.

Rule 2. Rio Grande aquifer system (RIOG)

Tertiary and Quaternary basin-fill deposits along the Rio Grande Valley and surrounding valleys constitute the Rio Grande aquifer system. The portion of this aquifer system in Colorado consists of broad basin-fill deposits in the San Luis Valley in south-central Colorado. There are two major hydrogeologic units in the San Luis Valley: the upper unconfined aquifer and the lower confined aquifer, predominantly within the Alamosa Formation (Topper et al., 2003). A series of clay layers in the upper Alamosa Formation forms the confining layer between the two aquifers. Depth to the confining clay layers varies from about 100 ft in the northern part of the basin to about 40 ft in the southern part of the basin.

The unconfined aquifer consists of Quaternary alluvial fan deposits with some well-sorted Aeolian sands and the uppermost sandy layers of the Alamosa Formation. The alluvial deposits are underlain, in most areas, by the Alamosa Formation which is composed of fine dark sands interbedded with discontinuous blue, gray, and green clays and silts. The geologic materials comprising the upper portions of the confined aquifer vary with location within the valley. In the northern and central part of the San Luis Valley, this unit consists of unconsolidated sand and gravels of the lower Alamosa Formation. At the western edge of the valley, in the Monte Vista Graben and on the Alamosa Horst, the confined aquifer consists of unconsolidated sands and gravels of the Los Pinos Formation, and in the Baca Graben, it is composed of unconsolidated to semi-consolidated sands and sandstone of the Santa Fe Formation.

2a. Wells that derive water from unconsolidated sand and gravel aquifers in the Rio Grande aquifer system (RIOG_OUT) at depths less than or equal to 100 ft that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class Id, because they are covered by less than 50 ft of low permeability loess deposits.

2b. Wells that derive water from the Rio Grande aquifer system (RIOG_OUT) at depths less than or equal to 100 ft excluding those found in Aeolian formations (Qe, Qeo) in the bedrock geology are Class Ia, because these aquifers can have high hydraulic conductivity and contain water primarily under unconfined or water-table conditions.

2c. Wells that derive water from the Rio Grande aquifer system (RIOG_OUT) at depths greater than 100 ft are Class III, because these aquifers are confined by overlying clay layers.

Rule 3. High Plains aquifer (HIGH)

Near-surface Tertiary and Quaternary deposits of unconsolidated or partly consolidated gravel, sand, silt, or clay underlie the Great Plains of eastern Colorado and compose the High Plains aquifer. The High Plains aquifer extends across an area of about 174,000 square miles in parts of eight western states, including eastern Colorado. The boundary of the aquifer approximates the boundary of the Great Plains Physiographic Province. Tertiary geologic units include the White River Group, the Arikaree Formation, and the Ogallala Formation. Quaternary deposits include alluvial deposits, loess, dune sand, and valley-fill deposits. In eastern Colorado, saturated Quaternary sediments are generally thin and discontinuous. Loess deposits are generally impermeable and do not form aquifers.

The Ogallala Formation is the principle water-bearing geologic unit in the High Plains aquifer in eastern Colorado. It consists of an unconsolidated sequence of gravel sand, silt, and clay. The Ogallala was deposited by ancient streams that flowed eastward from the Rocky Mountains. The aggrading streams deposited fluvial sediments in stream valleys that were eventually filled and buried and thick deposits of Ogallala sediments extended over a vast area. The underlying Arikaree Formation consists of massive, very fine-to-fine sandstone and localized beds of volcanic ash, siltstone, claystone, and marl. Wells completed in the Arikaree Formation generally do not yield large volumes of water. The Brule Formation of the White River Group underlies the Arikaree Formation. It is relatively impermeable and not part of the High Plains aquifer except in areas where the rock has been extensively fractured. The bedrock formations underlying the High Plains aquifer consist primarily of impermeable shale. The unconfined portion of the High Plains aquifer in Colorado ranges from less than 50 ft thick along the western, eroded outcrop edge to more than 500 ft thick in the paleo-river valleys of Washington County (Topper et al., 2003).

3a. Wells less than or equal to 500 ft deep that derive water from and are located within unconsolidated sand and gravel deposits, primarily the Ogallala Formation, of the High Plains aquifer (HIGH_OUT) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class Id, because they are covered by less than 50 ft of low permeability loess deposits.

3b. Wells that derive water from and are located in the High Plains aquifer (HIGH_OUT) excluding those found in Aeolian formations (Qe, Qeo) in the bedrock geology are Class Ia if well depth is less than or equal to 500 ft, because these deposits can have high hydraulic conductivity and contain water primarily under unconfined or water-table conditions.

3c. Wells that derive water from and are located in the High Plains aquifer (HIGH_OUT) are Class III if well depth is greater than 500 ft, because wells deeper than 500 ft are presumed to be sampling water from a confined aquifer.

Denver Basin aquifers

The Denver Basin is an elongated, asymmetrical structural depression underlying the plains of Colorado just east of the Rocky Mountains. The structure and overall shape of the basin are the result of the uplift of the Rocky Mountains. Five geologic formations form a layered Upper Cretaceous to Eocene sequence of sedimentary rocks in the upper part of the basin and constitute the Denver Basin aquifer system. The Denver Basin aquifer system consists of a layered sequence of four aquifers in beds of permeable water-yielding conglomerate, sandstone, and siltstone interlayered with beds of non-water yielding mudstone and shale. Layers of relatively impermeable shale separate the aquifers and impede vertical movement of ground water between them.

The geologic formations that compose the Denver Basin aquifer system are, from oldest to youngest, the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, Denver Formation, and Dawson Arkose. The Paleocene to Eocene Dawson Arkose contains the Dawson aquifer and is the uppermost and least extensive water-yielding formation in the Denver Basin. This aquifer is considered unconfined to a depth of 840 ft. The maximum thickness of the Dawson aquifer is 1,200 ft. The Upper Cretaceous to Paleocene Denver Formation contains the Denver aquifer. Although the Denver aquifer yields usable quantities of water to wells, claystone and shale are prevalent in this unit and tend to form a leaky confining unit between the overlying Dawson aquifer and the underlying Arapahoe aquifer. The maximum thickness of the Denver aquifer is 1,000 ft. The Upper Cretaceous Arapahoe Formation contains the Arapahoe aquifer, which is the most permeable of the Denver Basin aquifers and may yield as much as 700 gallons per minute to wells. The maximum thickness of the Arapahoe aquifer is 700 ft. The Arapahoe aquifer is underlain by the Laramie confining unit. The Upper Cretaceous Fox Hills Sandstone and sandstones in the lower part of the Laramie Formation form the Laramie-Fox Hills aquifer. The maximum thickness of the Laramie-Fox Hills aquifer is 800 ft. This aquifer is underlain by the nearly impermeable Pierre Shale, which forms the base of the aquifer system.

In their outcrop areas, the Denver Basin aquifers are under unconfined conditions, while in the deeper parts of the basin, the aquifers become confined. Wells in the PWS database with source attributed to “DENVER” could be deriving water from any of the Denver Basin aquifers.

Rule 4. Dawson aquifer (DAWS)

4a. Wells deriving water from and located in the Dawson aquifer (DAWS_OUT) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology with screen depths less than or equal to 840 ft are presumed to be sampling a bedrock aquifer covered by less than 50 ft of low permeability material and are Class IIc.

4b. Wells deriving water from and located in the Dawson aquifer (DAWS_OUT) excluding those found in Aeolian formations (Qe, Qeo) in the bedrock geology with screen depths less than or equal to 840 ft are Class IIa, because they are sourcing unconfined sandstone aquifers.

4c. Wells deriving water from and located in the Dawson aquifer (DAWS_OUT) with screen depths greater than 840 ft and less than 1,200 ft are Class III, because the Dawson aquifer is confined at this depth.

4d. Wells deriving water from and located in the Dawson aquifer (DAWS_OUT) with screen depths greater than 1,200 ft and PWS source is DENVER or DENVER/DAWSON are Class III, because they could be sourcing aquifers below the Dawson aquifer.

4e. Wells deriving water from and located in the Dawson aquifer (DAWS_OUT) with screen depths greater than 1,200 ft and PWS source is not DENVER or DENVER/DAWSON are Class UNK, because this is deeper than the known maximum thickness of the Dawson aquifer.

Rule 5. Denver aquifer (DENV)

5a. Wells deriving water from and located in the Denver aquifer (DENV_OUT) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage with screen depths less than or equal to 1,000 ft are presumed to be sampling a bedrock aquifer covered by less than 50 ft of low permeability material and are Class IIc.

5b. Wells deriving water from and located in the Denver aquifer (DENV_OUT) excluding those found in Aeolian formations (Qe, Qeo) in the bedrock geology with screen depths less than or equal to 1,000 ft are Class IIa, because they are sourcing unconfined sandstone aquifers.

5c. Wells deriving water from and located in the Denver aquifer (DENV_OUT) with screen depths greater than 1,000 ft and PWS source is DENVER are Class III, because they could be sourcing aquifers below the Denver aquifer.

5d. Wells deriving water from the confined Denver aquifer subcrops (DENV_SUB) and located within the overlying Dawson aquifer are Class III.

Rule 6. Arapahoe aquifer (ARAP)

6a. Wells deriving water from and located in the Arapahoe aquifer (ARAP_OUT) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage with screen depths less than or equal to 700 ft are presumed to be sampling a bedrock aquifer covered by less than 50 ft of low permeability material and are Class IIc.

6b. Wells deriving water from and located in the Arapahoe aquifer (ARAP_OUT) excluding those found in Aeolian formations (Qe, Qeo) in the bedrock geology with screen depths less than or equal to 700 ft are Class IIa, because they are sourcing unconfined sandstone aquifers.

6c. Wells deriving water from and located in the Arapahoe aquifer (ARAP_OUT) with screen depths greater than 700 ft and PWS source is DENVER are Class III, because they could be sourcing aquifers below the Arapahoe aquifer.

6d. Wells deriving water from and located in the Arapahoe aquifer (ARAP_OUT) with screen depths greater than 700 ft and PWS source is not DENVER are Class UNK because this is deeper than the known maximum thickness of the Arapahoe aquifer.

6e. Wells deriving water from the confined Arapahoe aquifer subcrops (ARAP_SUB) and located within the overlying Denver Basin aquifers are Class III.

Rule 7. Laramie-Fox Hills aquifer (LARA)

7a. Wells deriving water from and located in the Laramie-Fox Hills aquifer (LARA_OUT) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage with screen depths less than or equal to 800 ft are presumed to be sampling a bedrock aquifer covered by less than 50 ft of low permeability material and are Class IIc.

7b. Wells deriving water from and located in the Laramie-Fox Hills aquifer (LARA_OUT) excluding those found in Aeolian formations (Qe, Qeo) in the bedrock geology with screen depths less than or equal to 800 ft are Class IIa, because they are sourcing unconfined sandstone aquifers.

7c. Wells deriving water from and located in the Laramie-Fox Hills aquifer (LARA_OUT) with screen depths greater than 800 ft are Class UNK because this is deeper than the known maximum thickness of the Laramie-Fox Hills aquifer.

7c. Wells deriving water from the confined Laramie-Fox Hills aquifer subcrops (LARA_SUB) and located within the overlying Denver Basin aquifers are Class III.

Rule 8. Eagle Basin aquifer (EAGL)

The Eagle Basin underlies approximately 1,500 square miles in north-central Colorado along the western flank of the Continental Divide. The Eagle, Roaring Fork, and Colorado Rivers form the primary surface water drainages in the basin, with the headwaters of those rivers located along the Continental Divide. The Eagle Basin developed in Middle Pennsylvanian time, concurrent with the uplift of the ancestral Rocky Mountains, and is generally regarded as a sub-basin of the Colorado trough. As such, the geology is dominated by carbonate rocks, near-shore sands, and evaporitic sequences. The primary Eagle Basin aquifers are found in the Permian and Pennsylvanian sandstones and the Mississippian and Devonian carbonates.

8. Wells deriving water from and located in the Eagle Basin aquifer (EAGL_OUT) are sampling a carbonate-dominated bedrock aquifer and are Class Ib.

Rule 9. Colorado Plateaus aquifers (COLO)

In the Colorado Plateaus region of western Colorado, a thick Permian to Oligocene sequence of poorly to well-consolidated conglomerate, sandstone, and shale form the Colorado Plateaus aquifers. Structural deformation and faulting, associated with uplift of the Rocky Mountains, and lateral changes in the lithology of the rocks have produced a complex sequence of water-yielding layers. Uplift of the Colorado Plateaus steepened stream gradients and accelerated the downcutting of the Colorado River. Broad structural basins were developed between some of the uplifted areas. The thickness and hydraulic characteristics of the geologic units that compose the aquifers vary greatly. Thickness of aquifers generally increases toward the central parts of basins.

The principal aquifers of the Colorado Plateaus aquifers are the Uinta-Animas aquifer, Mesaverde aquifer, Dakota-Glen Canyon aquifer system, and Coconino-De Chelly aquifer. Relatively impermeable confining units separate each of the four principal aquifers. The two thickest of these confining units are the Mancos Shale (Km), which underlies the Mesaverde aquifer, and the Chinle-Moenkopi confining unit (including the Dolores Formation, TRd), which underlies the Dakota-Glen Canyon aquifer system. Other confining units include the Lewis Shale (Kls) and the Wasatch Formation (Two), which overlie the Mesaverde aquifer in the San Juan Basin and Piceance Basin, respectively.

The Uinta-Animas aquifer is primarily composed of Lower Tertiary beds of sandstone, conglomerate, and siltstone in the Duchesne River, Uinta, Green River, Nacimiento, and Animas Formations. The Mesaverde aquifer comprises water-yielding units, primarily sandstone with interbedded shale and coal, in the Upper Cretaceous Mesaverde Group. The Dakota-Glen Canyon aquifer system consists of water-yielding Jurassic and Cretaceous rocks, which underlie most of the Colorado Plateaus area. The geologic units that form the bulk of these aquifers are the Dakota Sandstone, the lower part of the Morrison Formation, the Entrada Sandstone, and the Glen Canyon sandstone. Sandstone, conglomerate, and conglomeratic sandstone are the principal water-yielding rocks. Low-permeability layers of mudstone, claystone, siltstone, shale, and limestone form confining units that separate individual aquifers in the Dakota-Glen Canyon aquifer system. The Coconino-De Chelly aquifer consists of water-yielding Permian rocks that underlie the southern part of the Colorado Plateaus. In Colorado, the Cutler Formation, which consists of arkosic sandstone, siltstone and conglomerate, forms the bulk of this aquifer. All of these aquifers are considered higher-yield bedrock aquifers.

9a. Wells deriving water from and located in the Colorado Plateaus aquifers (COLO_OUT) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are <u>Class IIc</u>, because they are presumed to be sampling bedrock aquifers covered by less than 50 ft of low permeability material.

9b. Wells deriving water from and located in the Colorado Plateaus aquifers (COLO_OUT) that also fall within the low-permeability confining units Km, Kls, Two, and TRd, are presumed to derive water from the underlying aquifers (Dakota-Glen Canyon and Mesaverde). Wells within the coverage of these formations with screen depths less than or equal to 50 ft are <u>Class IIc</u>.

9c. Wells deriving water from and located in the Colorado Plateaus aquifers (COLO_OUT) that also fall within the low-permeability confining units Km, Kls, Two, and TRd, are presumed to derive water from the underlying aquifers (Dakota-Glen Canyon and Mesaverde). Wells within the coverage of these formations with screen depths greater than 50 ft are <u>Class III</u>.

9d. Wells deriving water from and located in the Colorado Plateaus aquifer (COLO_OUT) excluding those found in the units described in rules 9a. and 9b. are Class IIa because they are sampling bedrock aquifers conservatively assumed to be higher yield.

Rule 10. Carbonate and basaltic rock aquifers (CARB)

Carbonate and evaporite units may contain solution cavities and other karst features. Basalt flow units commonly can be highly permeable as they contain open spaces associated with fractures and joints, rubble zones and vesicular basalt at the top and bottom of flows, and unconsolidated-deposit interbeds.

10a. Wells deriving water from and located in the carbonate and basaltic rock aquifers (CARB_OUT) are Class Ib because of the potential for high permeability and porosity.

10b. Wells deriving water from the carbonate and basaltic rock aquifer subcrops (CARB_SUB) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class Id, because they are covered by less than 50 ft of low permeability loess deposits.

10c. Wells deriving water from the carbonate and basaltic rock aquifer subcrops (CARB_SUB) excluding those that fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class Ib.

Rule 11. Crystalline and igneous rock aquifers (CRYS)

Colorado's crystalline rocks represent a unique and expansive aquifer system. The crystalline rocks are Precambrian aged igneous and metamorphic rocks, composed mostly of granites, gneisses, and schists, and Tertiary aged volcanic and igneous intrusive rocks. These rock types occupy approximately 19 percent of the state's total surface area, and represent the fractured, crystalline-rock aquifers that supply much of the domestic water supply needs in the mountainous portion of Colorado. Fractures provide the only significant porosity and flow conduits within the unweathered crystalline rocks of Colorado. Well yields from Precambrian rocks are generally only a few gallons per minute, although wells that penetrate extensively fractured zones, fault zones, or shear zones may produce up to 50 gpm (Topper et al., 2003).

11a. Wells deriving water from and located in the crystalline and igneous rock aquifers (CRYS_OUT) are Class IIb because of the lower yield from these bedrock units.

11b. Wells deriving water from the subcrops of the crystalline and igneous rock aquifers (CRYS_SUB) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class IIc, because they are covered by less than 50 ft of low permeability loess deposits.

11c. Wells deriving water from the subcrops of the crystalline and igneous rock aquifers (CRYS_SUB) excluding those that fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class IIb.

Rule 12. Not a principal aquifer (NAPA)

The outcrop belts of some rock units in Colorado are designated as ‘not a principal aquifer’ (Segment 2 atlas, Figure 11; Robson and Banta, 1995). This includes areas where aquifers either do not exist, yield too little water to be significant, or yield sufficient water to supply only local requirements, but are not extensive enough to be considered major aquifers. The region consists of higher-yield sandstone bedrock units such as the Dakota Sandstone, the Glen Canyon Sandstone, the Fox Hills Sandstone, and the Cliff House Sandstone, and low-permeability confining units such as the Mancos Shale (Km), Pierre Shale (Kp, Kpl, Kpm, Kpu), and Laramie Formation (Kl).

12a. Wells deriving water from and located in the Mancos, Lewis, and Pierre Shales (Kl, Km, Kp, Kpl, Kpm, Kpu) of the NAPA region (NAPA_OUT) with screen depths less than or equal to 50 ft are Class IIc, because these shales are low-permeability units.

12b. Wells deriving water from and located in the Mancos, Lewis, and Pierre Shales (Kl, Km, Kp, Kpl, Kpm, Kpu) of the NAPA region (NAPA_OUT) with screen depths greater than 50 ft are Class III because, at this thickness, these shales act as confining units.

12c. Wells deriving water from the higher-yield sandstones of the NAPA region (NAPA_OUT) are Class IIa.

12d. Wells deriving water from the subcrops of the higher-yield sandstones of the NAPA region (NAPA_SUB) that also fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class IIc, because they are covered by less than 50 ft of low permeability loess deposits.

12e. Wells deriving water from the subcrops of the higher-yield sandstones of the NAPA region (NAPA_SUB) excluding those that fall within the Aeolian map formations (Qe, Qeo) in the bedrock geology coverage are Class IIa.

Metadata Sources References

Paschke, S.S. (ed.). 2011. Groundwater availability of the Denver Basin aquifer system, Colorado: U.S. Geological Survey Professional Paper 1770, 274 p.

Robson, S.G. and E.R. Banta. 1995. Ground water atlas of the United States: Segment 2, Arizona, Colorado, New Mexico, Utah. Hydrologic Investigations Atlas 730-C, U.S. Geological Survey, Reston, VA, 34 pp.

Topper, R., K.L. Spray, W.H. Bellis, J.L. Hamilton and P.E. Barkmann. 2003. SP-53 Ground Water Atlas of Colorado. Special Publications, SP-53. Denver, CO: Colorado Geological Survey, Division of Minerals and Geology, Department of Natural Resources.

Rules for Applying the Pettyjohn Classification Scheme in Connecticut

22 August 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-M, also called Ground Water Atlas of the United States, Segment 12 (Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The available data sets included:

1. Well location
2. Bedrock geology
3. Surficial geology

The aquifer boundaries were generated using bedrock geology, the surficial aquifer potential coverage, and the Segment 12 Atlas (Olcott, 1995) as a guide.

Due to the lack of source or depth data, classification of all wells is based solely on the location of the well within the aquifer coverage. There are five principal aquifers in the state of Connecticut:

1. Alluvial and Outwash*
2. Paleozoic Carbonate
3. Mesozoic Sandstone
4. Crystalline
5. Not a principal aquifer

* The Alluvial and Outwash aquifer was constructed using the "Surficial_Aquifer_Potential" feature class and is a combination of both glacial and fluvial deposition.

The aquifer features were constructed from the bedrock geology features (BGEO) and the surficial aquifer potential features (SURFICAL_AQUIFER_POTENTIAL).

Rule 1. Alluvial and Outwash aquifer (ALLU)

The unconsolidated sediments of the Alluvial and Outwash aquifer are present throughout the major river valleys of the state of Connecticut. The aquifer predominantly consists of sand and gravel from glacial outwash and modern alluvial deposition. The aquifer ranges in thickness from less than 50 ft to more than 400 ft. The Alluvial and Outwash Aquifer is predominantly used in the flood plains of the Connecticut and Farmington Rivers where it commonly obtains a thickness of greater than 200 ft. The aquifer is generally unconfined and is underlain by the Paleozoic Carbonate aquifer in northwest Connecticut, the Mesozoic Sandstone aquifer in central Connecticut and the Crystalline aquifer throughout the remainder of the state.

1a. Wells located within the outcrop boundary of the Alluvial and Outwash aquifer (ALLU) are <u>Class Ia</u> because these unconsolidated sand gravel deposits are predominantly under unconfined conditions.

Rule 2. Paleozoic Carbonate aquifer (CARB)

The consolidated carbonate rocks of the Paleozoic Carbonate aquifer outcrop along the western border of Connecticut. These are comprised mostly of limestone, dolomite and marble, and are Cambrian to Ordovician in age. The deformation of these carbonate beds has caused parting along bedding planes and has created joints, fractures and faults which are the major water yielding openings in the rock. The Carbonate Aquifer is bound on the west by quartz-mica schist and on the east by quartzite, granite-biotite gneiss and micaceous schist. The aquifer is generally unconfined in the upper 200 ft.

2a. Wells located within the outcrop boundary of the Paleozoic Carbonate aquifer (CARB) are Class Ib because these wells derive water from rocks that are soluble and fractured.

Rule 3. Mesozoic Sandstone aquifer (SAND)

The consolidated siliciclastic sedimentary rocks of Mesozoic Sandstone Aquifer are found in a thick band in the central portion of Connecticut. The rocks are comprised of mostly red sandstone, shale, siltstone, conglomerate, and are Triassic and Jurassic in age. The water in the Mesozoic Sandstone aquifer primarily moves through secondary openings such as joints, fractures and bedding planes. Bedding planes are believed to produce the largest quantity of water. On average, wells sourcing the Mesozoic sandstone produce an average yield of 34 gallons per minute and have an average depth of 203 ft.

3a. Wells located within the outcrop boundary of the Mesozoic Sandstone aquifer (SAND) are Class IIb because these wells derive water from rocks that are consolidated and unconfined.

Rule 4. Crystalline aquifer (CRYS)

The consolidated crystalline rocks of the Crystalline Aquifer system are found throughout most of the state of Connecticut. The rocks are comprised of mostly granite, schist, gneiss, and quartzite, and are Pre-Cambrian to Devonian in age. The Crystalline Aquifer primarily moves through secondary openings such as joints, fractures, and bedding or cleavage planes. These openings decrease with depth therefore most wells are drilled no deeper than 600 ft. The volume water stored in these fractures is generally small therefore an average yield of only a few gallons per minute is common in wells sourcing the Crystalline aquifer.

4a. Wells located within the outcrop boundary of the Crystalline aquifer (CRYS) are Class IIb because these wells derive water from rocks that are consolidated and for the most part unconfined.

Rule 5. Not a principal aquifer (NAPA)

The consolidated crystalline rocks in the northwest corner of Connecticut do not produce enough water to be considered significant therefore they receive the ‘not a principal aquifer’ (NAPA) designation. The outcrop predominantly consists of schists of Cambrian and Ordovician age.

5a. Wells located within the outcrop boundary of not a principal aquifer (NAPA) are Class IIb because these wells derive water from rocks that are consolidated and unconfined.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Delaware

12 March 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-L (also called Ground Water Atlas of the United States, Segment 11; Trapp and Horn, 1997) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Screen depth
4. Source aquifer
5. Pump rate
6. Surficial geology
7. Aquifer boundaries

The aquifer boundaries were generated using surface geology and the Segment 11 Atlas (Trapp and Horn, 1997) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are six principal aquifers in Delaware:

1. Surficial
2. Chesapeake*
3. Castle Hayne-Aquia*
4. Severn-Magothy*
5. Potomac*
6. Piedmont

*The Chesapeake, Castle Hayne-Aquia, Severn-Magothy, and Potomac aquifers comprise the Northern Atlantic Coastal Plain Aquifer System.

Rule 1. Surficial aquifer (ALLU)

The unconsolidated sediments of the surficial aquifer are exposed at the land surface across the coastal plain of Delaware, and consist of locally gravelly sand, mostly of Quaternary age. The average thickness of the surficial aquifer in Delaware is generally 50 ft or less, and the aquifer contains water predominately under unconfined conditions. The aquifer is defined as a principal aquifer where it is capable of yielding at least 50 gallons of water per minute.

1a. Wells that derive water from the surficial aquifer and located within the surficial aquifer outcrop (ALLU_OUT) are <u>Class Ia</u>, because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

Rule 2. Chesapeake aquifer (CHPK)

The unconsolidated sediments of the Chesapeake aquifer outcrop across the lower coastal plain of Delaware plain, lying stratigraphically below the surficial aquifer. The Chesapeake aquifer consists of shelly sand, silty sand, and shell beds, and fine to medium phosphatic sand of Miocene age. The maximum thickness of the aquifer is about 600 ft, and the average thickness is about 300 ft. The aquifer underlies the surficial aquifer and contains an upper and lower confining unit. The upper confining unit is truncated in the northwest Delmarva Peninsula, so only the lower Chesapeake aquifer, found at depths exceeding 250 ft is considered confined.

2a. Wells sourcing the Chesapeake aquifer and located within the aquifer outcrop (CHPK_OUT), with depths less than or equal to 250 ft or with no depth information are Class Ia, because the aquifer is unconfined and consists of unconsolidated sediments.

2b. Wells sourcing the Chesapeake aquifer and located within the aquifer outcrop (CHPK_OUT), with depths greater than 250 ft are Class III, because the aquifer is confined.

Rule 3. Castle Hayne-Aquia aquifer (CHAQ)

The unconsolidated to semi-consolidated sediments of the Castle Hayne-Aquia aquifer outcrop in a narrow band in the upper coastal plain of Delaware, and subcrops to the east, lying stratigraphically below the Chesapeake aquifer. The Castle Hayne-Aquia aquifer is confined, except where it outcrops, and consists of a highly productive upper unit of limestone, sandy marl, and fine to coarse limey sand and a less productive lower unit of fine to medium glauconitic sand with thin beds of shell and limestone. The total average thickness of the aquifer is about 140 ft.

3a. Wells sourcing the Castle Hayne-Aquia aquifer and located within the aquifer outcrop (CHAQ_OUT) are Class Ia, because the aquifer unit is unconsolidated and unconfined.

3b. Wells sourcing the Castle Hayne-Aquia aquifer subcrop (CHAQ_SUB) are Class III, because the Castle Hayne-Aquia aquifer is overlain by a confining unit.

Rule 4. Severn-Magothy aquifer (SVMG)

The semi-consolidated sediments of the Severn-Magothy aquifer outcrop in a narrow band in the upper coastal plain of Delaware, and subcrop to the east, lying stratigraphically below the Castle Hayne-Aquia aquifer. The Severn-Magothy aquifer is separated from the Castle Hayne-Aquia aquifer by a confining unit, and is comprised of fine to medium glauconitic sand with minor shell material and calcareous sandstone beds in the upper unit, and fine to medium sand with lenses of coarse sand and clay in the lower unit, all of Late Cretaceous age. The maximum thickness of the aquifer is about 385 ft; the average is about 185 ft.

4a. Wells sourcing the Severn-Magothy aquifer and located within the aquifer outcrop (SVMG_OUT) are Class Ic, because the aquifer is semi-consolidated and unconfined.

4b. Wells sourcing the Severn-Magothy aquifer subcrop (SVMG_SUB) are Class III, because the aquifer is overlain by confining units.

Rule 5. Potomac aquifer (PTMC)

The semi-consolidated sediments of the Potomac aquifer outcrop in a narrow band in the upper coastal plain of Delaware, onlapping the crystalline rocks of the Piedmont, and lying stratigraphically below the Severn-Magothy aquifer. The Potomac aquifer is separated from the Severn-Magothy aquifer by a confining unit of clay and sandy clay, and is composed of fine to medium sand interbedded with clay in the upper unit, and fine to medium sand with a few beds of coarse sand and limestone in the lower unit, all of Lower Cretaceous age. The maximum thickness of the aquifer is about 4,500 ft, and the average thickness is about 1,600 ft.

5a. Wells sourcing the Potomac aquifer outcrop (PTMC_OUT) are Class Ic, because the aquifer is semi-consolidated and unconfined.

5b. Wells sourcing the Potomac aquifer subcrop (PTMC_SUB) are Class III, because the Potomac aquifer is confined.

Rule 6. Piedmont aquifer (PIED)

The consolidated igneous and metamorphic rocks and local sedimentary rocks of the Piedmont aquifer outcrop in northern Delaware. Water is obtained from the regolith and/or fractures in these crystalline rocks, implying unconfined conditions. The aquifer consists of a complex of low- to medium-grade metamorphic rocks and intrusive igneous rocks of Precambrian to Jurassic age.

6a. Wells sourcing the Piedmont aquifer outcrop (PIED_OUT) that source the Cockeysville formation are Class Ib, because the aquifer is comprised of soluble carbonate rocks.

6b. All other wells sourcing the Piedmont aquifer outcrop (PIED_OUT) with pump rate less than or equal to 50 gallons of water per minute are Class IIb, because the aquifer is consolidated and the wells are lower yield.

6c. All other wells sourcing the Piedmont aquifer outcrop (PIED_OUT) with pump rate greater than 50 gallons of water per minute or with no pump rate information are Class IIa, because the aquifer is consolidated and the wells are higher yield.

Metadata Sources References

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Trapp, Jr., H. and M.A. Horn, 1997. Ground water atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. Hydrologic Investigations Atlas 730-L, U.S. Geological Survey, Reston, VA, 32 pp.

Rules for Applying the Pettyjohn Classification Scheme in Florida

10 August 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-G, (Miller, 1997), and Florida Aquiver Vulnerability Assessment (FAVA): Contamination Potential of Florida's Principal Aquifer Systems (Arthur et al., 2005) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Source aquifer
4. Bedrock geology
5. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology, the national aquifer coverage, and the USGS Hydrologic Investigations Atlas 730-G, Segment 6 atlas (Miller, 1997) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are five principal aquifers in the state of Florida:

1. Sand and Gravel*
2. Surficial
3. Biscayne
4. Intermediate
5. Floridan

* The Sand and Gravel Aquifer is referred to as the Coastal Lowlands Aquifer in Texas, Louisiana and Mississippi.

The aquifer features were constructed from the bedrock geology features (BGEO) and the national aquifer features (aquifrp025).

Rule 1. Sand and gravel aquifer (SAND)

The unconsolidated to semi-consolidated sediments of the Sand and Gravel aquifer outcrop in the westernmost Florida Panhandle. As the name implies, the aquifer predominantly consists of sand and gravel with interbedded silt and clay deposited from the middle Miocene to the Holocene in a deltaic environment. In most locations, the aquifer contains two permeable zones, the upper "surficial zone" and the lower "main producing zone" separated by a less permeable sand and clay unit. In Florida, the lower "main producing zone" is the predominant source of water supply (Miller, 1997). At the Florida/Alabama border the Sand and Gravel Aquifer has a maximum thickness of approximately 700 ft and decreases considerably to the East until the underlying clay unit is no longer present and the aquifer is in direct contact with the Upper Floridan aquifer. Because the aquifer's confined areas cannot be distinguished from the unconfined areas, for the purpose of applying the Pettyjohn classification, the aquifer is treated as semiconfined because most of the groundwater is known to be withdrawn from the lower "main producing zone" (Miller, 1997).

1a. Wells sourcing the Sand and Gravel aquifer outcrop (SAND_OUT) with a well depth less than or equal to 700 ft are <u>Class Id</u> because most of the groundwater withdrawn from the aquifer in Florida is from the lower semi-confined "main producing zone." Note: The Sand Gravel aquifer boundary was created using the national aquifers features due to its inability to be distinguished from the Surficial aquifer based on surficial geology alone.

1b. Wells sourcing the Sand and Gravel aquifer outcrop (SAND_OUT), with a well depth greater than 700 ft are <u>Class UNK</u> because the depth is greater than the maximum depth for the Sand and Gravel Aquifer in Florida.

Rule 2. Surficial aquifer (SURF)

The unconsolidated to semi-consolidated sediments of the surficial aquifer system are exposed at the surface across the peninsula of Florida and across a large portion of the eastern panhandle of Florida. The aquifer consists of mostly shell, shelly sand and sand. In some locations especially across the southwest coast of Florida, limestone beds form a highly permeable section of the aquifer. In other locations clay beds divide the system into multiple aquifers. Complex interbedding of fine and course grained rocks are common throughout the surficial aquifer system. The average thickness of the surficial aquifer is 50 ft, but in some locations such as in Indian River County the aquifer can be as thick as 400 ft.

2a. Wells sourcing the Surficial aquifer outcrop (SURF_OUT) with a well depth less than or equal to 400 ft are <u>Class Ia</u> because the aquifer is unconfined and consists of unconsolidated, surficial shell and sand deposits.

2b. Wells sourcing the Surficial aquifer outcrop (SURF_OUT) with a well depth greater than 400 ft are <u>Class UNK</u> because the depth is greater than the maximum depth for the Surficial aquifer in Florida.

Rule 3. Biscayne aquifer (BSCN)

The predominantly Pleistocene age highly permeable limestone of Biscayne aquifer underlies an area of approximately 4,000 square miles and outcrops in the Southeast corner of the peninsula of Florida. The aquifer as a whole contains more limestone and calcareous sandstone in the south and west and is sandier in its northern and eastern sections where it is poorly differentiated from the surficial aquifer. The aquifer is wedge shaped and slopes seaward where it reaches a maximum thickness of 240 ft. A sequence of low permeability, mostly clayey deposits approximately 1,000 ft thick are the confining unit between the Biscayne Aquifer and the Floridan aquifer.

3a. Wells sourcing the Biscayne aquifer outcrop (BSCN_OUT) with a well depth less than or equal to 240 ft are Class Ib because the aquifer predominantly consists of karstic limestone.

3b. Wells sourcing the Biscayne aquifer outcrop (BSCN_OUT) with a well depth greater than 240 ft are Class UNK because the depth is greater than the maximum depth for the Biscayne aquifer.

3c. Wells sourcing the Biscayne aquifer subcrop (BSCN_SUB) are Class Ib because the aquifer predominantly consists of karstic limestone.

Rule 4. Intermediate aquifer (INMD)

The semiconsolidated sediments and karstic limestone lenses of the Intermediate aquifer system outcrop where the surficial confining unit is not present in southwest Florida. The Intermediate aquifer is the main source of water in Sarasota, Charlotte and Lee Counties of the southwest peninsular Florida (Barr, 1996). The aquifer slopes to the south-southwest.

4a. Wells sourcing the Intermediate aquifer outcrop (INMD_OUT) located in the predominantly clastic formation (unit code: Thp - Hawthorn Group, Peace River Formation) are Class Ic because the sediments in this formation are predominantly semiconsolidated clay and phosphatic silts and sands.

4b. Wells sourcing the Intermediate aquifer outcrop (INMD_OUT) located in the predominantly carbonate formations (unit codes: Tha - Hawthorn Group, Arcadia Formation; Thpb – Hawthorn Group, Bone Valley Member) are Class Ib because karstic solution cavities may exist.

4c. Wells sourcing the Intermediate aquifer subcrop (INMD_SUB) are Class III because the Intermediate aquifer is overlain by a confining unit.

Rule 5. Floridan aquifer (FLOR)

The predominantly Eocene age karstic limestone of the Floridan aquifer system underlies the entire state of Florida but only outcrops from Tampa Bay north around the Big Bend and into the northern Panhandle regions of Florida. The Floridan aquifer thickens dramatically from north to south. South of Lake Okeechobee the Floridan aquifer is brackish to saline, and at that point is no longer used as a main water source (Williams and Kuniansky, 2016).

5a. Wells sourcing the Floridan aquifer outcrop (FLOR_OUT) are Class Ib because the aquifer predominantly consists of karstic limestone.

5b. Wells sourcing the Floridan aquifer subcrop (FLOR_SUB) with a well depth less than 100 ft are Class Id because the aquifer is likely overlain by less than 50 ft of low permeability material.

5c. Wells sourcing the Floridan aquifer subcrop (FLOR_SUB) with a well depth greater than 100 ft are Class III because the Floridan aquifer is overlain by a confining unit most likely more than 50 ft in thickness.

Rule 6. Not a principal aquifer (NAPA)

The Miocene and Pliocene-age low permeability sandy clays and clayey sands that receive the not a principal aquifer designation outcrop in the central and eastern Panhandle of Florida as well as in a band running north-south near the west coast of the peninsula of Florida. From a stratigraphic stand point, these units make up the confining unit between the Surficial aquifer and the Floridan aquifer. The Claiborne Formation is also considered to be a non-principal aquifer in Florida due to its very limited use and presence only in the very northern panhandle underlying the Floridan aquifer.

6a. Wells sourcing the non-principal aquifer subcrop (NAPA_SUB) are Class III because these wells are sourcing aquifers overlain by more than 50 ft of low permeability confining material.

Metadata Sources References

Arthur, J., A. Baker, J. Cichon, A. Wood, and A. Rudin. 2005. Florida Aquifer Vulnerability Assessment (FAVA): Contamination potential of Florida's principal aquifer systems, Division of Resource Assessment and Management. Florida Geological Survey, Tallahassee, FL.

Barr, G.L. (eds.). 1996. Hydrogeology of the Surficial and Intermediate Aquifer Systems in Sarasota and Adjacent Counties, Florida. USGS Water-Resources Investigations Report 96-4063. U.S. Geological Survey, Tallahassee, FL.

Miller, J. 1997. Ground water atlas of the United States: Segment 6, Alabama, Florida, Georgia South Carolina. Hydrologic Investigations Atlas 730-G, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Williams, L.J. and E.L. Kuniansky. 2016. Revised hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama, and South Carolina (ver 1.1, March 2016): U.S. Geological Survey Professional Paper 1807.

Rules for Applying the Pettyjohn Classification Scheme in Georgia

20 May 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-G (also called Ground Water Atlas of the United States, Segment 6; Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Well location
2. Bedrock geology
3. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology and the Segment 6 Atlas (Olcott, 1995) as a guide.

Due to the lack of source or depth data, classification of all wells is based solely on the location of the well within the aquifer coverage.

There are ten aquifers in the state of Georgia:

1. Surficial
2. Floridan
3. Pearl River
4. Chattahoochee River
5. Black Warrior River
6. Piedmont and Blue Ridge
7. Valley and Ridge Carbonate
8. Valley and Ridge Siliciclastic
9. Appalachian Plateaus and Interior Low Plateaus
10. Not a principal aquifer

The aquifer features were constructed from the bedrock geology features (BGEO).

Rule 1. Surficial aquifer (SURF)

The unconsolidated to semi-consolidated sediments of the Surficial aquifer are present throughout southeast Georgia, south of the Fall Line. Near the coastline the Surficial aquifer is composed of Quaternary age sandy shoreline complexes. Sediments that make up the Surficial aquifer are also found within the major river valleys of Georgia such as the Oconee, Flint, Chattahoochee and Savannah rivers as well as in the broad plains throughout southern Georgia where the sediment is Neogene in age and composed of clay, semi-consolidated sandstone and gravel. The aquifer is unconfined throughout the entire state of Georgia.

1. Wells located within the Surficial aquifer outcrop (SURF) are conservatively <u>Class Ia</u> because these sediments are predominantly unconsolidated under unconfined conditions.

Rule 2. Floridan aquifer (FLOR)

The consolidated carbonate rocks of the Floridan Aquifer outcrop in a northeast trending band across southeast Georgia terminating in the central portion of the state. In Georgia, the Floridan aquifer consists of Eocene to Oligocene age limestone and residuum and is unconfined throughout the state except in areas where it is overlain by Miocene clays.

2. Wells located within the Floridan aquifer outcrop (FLOR) are <u>Class Ib</u> because the aquifer predominantly consists of karstic limestone containing possible solution cavities.

Rule 3. Pearl River aquifer (PEAR)

The predominantly unconsolidated sediments of the Pearl River aquifer outcrop in a northeast trending band across southwest and central Georgia. The Pearl River aquifer consists of thick sequences of sand with minor sandstone, gravel, limestone and marl beds of Paleocene to Eocene age. The aquifer grades laterally and is hydrologically connected to the Floridan aquifer. The Chattahoochee River aquifer underlies the Pearl River aquifer.

3. Wells located within the Pearl River aquifer outcrop (PEAR) are <u>Class Ia</u> because the sediments are unconsolidated and the water is under unconfined or water table conditions.

Rule 4. Chattahoochee River aquifer (CHAT)

The unconsolidated to semi-consolidated sediments of the Chattahoochee River aquifer outcrop in a northeast trending band across southwest and central Georgia. The Chattahoochee River aquifer consists of sand beds with thin clay lenses and locally glauconitic sand and limestone deposited in marine environments of Cretaceous to Paleocene age. The aquifer is overlain by the Chattahoochee River confining unit and underlain by the Black Warrior River confining unit.

4. Wells located within the Chattahoochee River aquifer outcrop (CHAT) are conservatively <u>Class Ia</u> because these sediments are predominantly unconsolidated sands under unconfined conditions.

Rule 5. Black Warrior River aquifer (BLAC)

The unconsolidated to semi-consolidated sediments of the Black Warrior River aquifer outcrop in a in a northeast trending band across western Georgia. The Black Warrior River aquifer consists of sand and clay deposited in fluvial deltaic and marine environments during the Cretaceous period. The aquifer is overlain by the Black Warrior confining unit and is underlain by crystalline basement rock.

5. Wells located within the Black Warrior River aquifer outcrop (BLAC) are conservatively <u>Class Ia</u> because these sediments are predominantly unconsolidated and under unconfined conditions.

Rule 6. Piedmont aquifer and Blue Ridge aquifers (PIED)

The consolidated igneous and metamorphic rocks of the Piedmont and Blue Ridge aquifer outcrop throughout the northern half of Georgia with the exception of the northwest portion of the state. The Piedmont aquifer consists of predominantly low to medium grade metamorphic rocks such as schist, quartzite, marble, and gneiss; and intrusive igneous rocks such as granite and gabbro. These rocks are of Precambrian to Devonian age. Water is most commonly obtained from highly fractured contact zones between crystalline rock types.

6a. Wells located within the Piedmont aquifer outcrop (PIED) located in marble (m1) are Class Ib because the aquifer is potentially karstic and may contain solution cavities.

6b. Wells located within the Piedmont aquifer outcrop (PIED) excluding those located in marble (m1) are Class IIa because the aquifer is consolidated and generally unconfined.

Rule 7. Valley and Ridge Carbonate aquifer (VALC)

The consolidated carbonate rocks of the Valley and Ridge Carbonate aquifer outcrop in northeast trending bands across the northwest corner of the state. The Valley and Ridge Carbonate aquifer consists of limestones, dolomites and chert of Cambrian to Mississippian age. These carbonate rocks are most productive where solution cavities have developed along valley floors which are favorable areas for recharge.

7. Wells located within the Valley and Ridge Carbonate aquifer outcrop (VALC) are Class Ib because the aquifer consists of karstic limestone containing solution cavities.

Rule 8. Valley and Ridge Siliciclastic aquifer (VALS)

The consolidated siliciclastic rocks of the Valley and Ridge Siliciclastic aquifer outcrop in northeast trending bands across the northwest section of the state. The Valley and Ridge Siliciclastic aquifer consists of primarily sandstones, mudstones and shales of Cambrian to Pennsylvanian age. Much of the water in the Valley and Ridge Siliciclastic aquifer is obtained from fractures in the Red Mountain Formation and the Rome Formation.

8. Wells located within the Valley and Ridge Siliciclastic aquifer outcrop (VALS) are Class IIa because the aquifer is consolidated and generally unconfined.

Rule 9. Appalachian Plateaus and Interior Low Plateaus aquifer (APPA)

The consolidated siliciclastic rocks of the Appalachian Plateaus and Interior Low Plateaus Aquifer outcrop in the plateau region of extreme northwest Georgia. In Georgia, the Appalachian Plateaus and Interior Low Plateaus Aquifer consists of predominantly sandstones and shales of Permian age. Water is obtained from fractures in the sandstone beds of the Gizzard Formation.

9. Wells located within the Appalachian Plateaus and Interior Low Plateaus Aquifer outcrop (APPA) are Class IIa because the aquifer is consolidated and generally unconfined.

Rule 10. Not a principal aquifer (NAPA)

The semi-consolidated low permeability sediments of the Not a Principal aquifer predominantly outcrop throughout central and southern Georgia, south of the Fall Line. The Not a Principal aquifer consists of clay, silt, and marl of Paleocene to Miocene age. These sediments make up the confining units between the Surficial, Floridan, Pearl River and Chattahoochee aquifers.

10a. Wells located within the Not a Principal aquifer outcrop (NAPA) located in the Hawthorn Formation (MIh) are Class Ib because the dolostone component of the formation has dissolution potential.

10b. Wells located within the Not a Principal aquifer outcrop (NAPA) excluding those located in the Hawthorn Formation (MIh) are conservatively Class Id because they are overlain by a low permeability clay, silt or marl.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Hawaii

31 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-M (also called Ground Water Atlas of the United States, Segment 13; Miller et al., 1999) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Bedrock geology
2. Aquifer boundaries
3. Well location

The aquifer boundaries were generated using aquifer extents received from the state and the Segment 13 Atlas (Miller et al., 1999) as a guide.

There are two principal aquifers in the state of Hawaii:

1. Sedimentary
2. Volcanic

The aquifer coverage was created using the "TYPEA" field in the AQUIFER layer. This process is further explained in the "Aquifer coverage guidelines: Hawaii" document.

Rule 1. Sedimentary aquifer (SEDE)

The unconsolidated sediments and consolidated rock of the Sedimentary aquifer are present in basins between volcanic deposits and along coastlines throughout the Hawaiian Islands. The sediments and rock are primarily comprised of sand, sandstone and limestone of Pliocene to Quaternary age. The consolidated rocks are predominantly found in coastal areas in the form of sandstone and limestone. These aquifers are usually brackish in nature due to good hydraulic connection to the ocean and slow recharge. The unconsolidated sediments are found along beaches, in lagoonal settings. The sedimentary deposits thicken toward the coast but because of the increased salinity seaward, are used less often as a potable aquifer than the volcanic rocks further inland.

1a. Wells located within the Sedimentary aquifer outcrop (SEDE), are Class Ia because the state provided aquifer coverage does not distinguish between unconsolidated sediments and consolidated rock, therefore, all wells within the Sedimentary aquifer outcrop are conservatively assumed to be sourcing unconsolidated, unconfined deposits.

Rule 2. Volcanic aquifer (VOLC)

The predominantly consolidated rocks of the Volcanic aquifer outcrop across all eight major islands of Hawaii. The rocks are comprised mostly of basaltic lava flows, basanite, dike complexes and breccia of Pliocene to Quaternary age. These aquifers are the most extensive and productive aquifers in the Hawaiian Islands. The most productive aquifers are formed by sequences of highly fractured, permeable, basaltic lava flows where no dikes are present. These aquifers vary in thickness from island to island but the largest freshwater lenses are almost always located in the center of each island.

2a. Wells located within the Volcanic aquifer outcrop (VOLC) are Class Ib because these wells are sourcing potentially highly fractured, highly permeable volcanic rock associated with intergranular and conduit porosity.

Metadata Sources References

Miller, J.A., R.L. Whitehead, D.S. Oki, S.B. Gingerich, and P.G. Olcott. 1999. Ground Water Atlas of the United States: Segment 13, Alaska, Hawaii, Puerto Rico, and the US Virgin Islands (No. 730-N, pp. N1-N36). Geological Survey, Reston, VA, 33 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Idaho

17 April 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-H (Whitehead, 1994) and the previously published DW USA reports (RSPA, 2002). The available data set included:

1. Wells: location
2. Bedrock geology

Because information regarding source aquifer or source depth is unavailable, classification of wells is based on the shallowest aquifer that could potentially be sampled. If source data become available, well classifications could change.

Codes used below to identify bedrock geology map formations refer to those used in the digital representation of the Idaho state geologic map (Johnson and Raines, 1996).

The following aquifers of Idaho were distinguished for this work:

1. Unconsolidated sand and gravel
2. Pliocene and younger basaltic rock
3. Miocene basaltic rock
4. Volcanic and sedimentary rock
5. Carbonate rock
6. Pre-Miocene rocks

Rule 1. Unconsolidated sand and gravel aquifers (QUAT)

Unconsolidated Quaternary deposits extend over large areas of Idaho and form the most widespread and prolific aquifers in the state. These include the Pacific Northwest basin-fill aquifers in the western Snake River Plain and other valley and lowland areas adjacent to the Snake River Plain, unconsolidated-deposit aquifers of the Northern Rocky Mountains Intermontane Basins aquifer system, which fill narrow basins between rugged mountain ranges in the central mountainous portion of the state, and the Basin and Range basin-fill aquifers in the southeast portion of the state (Whitehead, 1994). In this report, these aquifers are combined and referred to as the unconsolidated sand and gravel aquifers. The unconsolidated sand and gravel aquifers are prevalent along present and ancestral stream valleys and in lowlands that are associated with structural or erosional basins. The deposits consist of younger coarse-grained material of chiefly stream or glacial origin and older, fine-grained deposits of chiefly lake, volcanic, or eolian origin (loess). Well-sorted alluvial and glacial outwash deposits of sand and gravel constitute the principal aquifers. Fine-grained deposits and poorly sorted deposits, such as glacial till, generally form confining units. The thickness of unconsolidated deposits along present stream valleys is generally less than 250 ft in larger basins formed by faulting or erosion, unconsolidated deposits may be as much as 5,500 ft thick. However, the uppermost 500 ft is generally the most permeable, because the deposits are increasingly compacted with depth. Permeability of the unconsolidated deposits is variable. Sand and gravel commonly yield from 20 to 2,000 gallons per minute to wells. Coarser deposits along major streams and deposits of glacial outwash yield from 500 to 2,500 gallons per minute to wells (Whitehead, 1994).

1a. Wells that derive water from surficial Quaternary unconsolidated sand and gravel aquifers (= unconsolidated-deposit aquifers) are Class Ia, because these aquifers can have high hydraulic conductivity and contain water primarily under unconfined or water-table conditions.

1b. Wells in the unconsolidated sand and gravel aquifers coverage that also fall within the coverages of the following formations in the bedrock geology coverage are Class Id because these units represent deposits of low permeability, unconsolidated material, such as glacial till, lacustrine, and loess deposits:

- Qw – Quaternary wind-blown deposits; most commonly a loess mantle east of the Snake Plain.
- Qpc, Qpt – Pleistocene till, outwash, moraines and similar unsorted glacial debris.
- Qpmd – Middle Pleistocene lava-dammed Snake Plain lake beds of silt, clay and diatomite.

Rule 2. Pliocene and younger basaltic-rock aquifers (PLIO)

Volcanic rocks in Idaho range in composition from basaltic to silicic and in age from Eocene to Recent. Some basalt flows on the Snake River Plain are less than 2,000 years old. Pliocene and younger basaltic rocks are present chiefly in the Snake River Plain and adjacent areas in southern Idaho. They consist of multiple thin flows of basaltic rocks interbedded with unconsolidated deposits of basaltic ash, cinders, and sand. Most were extruded as lava flows from numerous vent and fissures concentrated along rift or major fault zones in the Snake River Plain. These flows and associated interbeds form the Pliocene and younger basaltic-rock aquifers, which include the aquifers of the Snake River Plain aquifer system. The Pliocene and younger basaltic rocks are from 1,000 to 2,000 ft thick over broad areas of the eastern Snake River Plain and exceed 3,000 ft thick near the central part of the eastern plain. Although hydraulic properties of these volcanic rocks are highly variable, they can be highly permeable, as they contain open spaces associated with lava tubes, pillow basalts, vesicles, fractures, faults, and porous interflow zones. Yields of wells completed in the Pliocene and younger basaltic-rock aquifers in the eastern Snake River Plain are among the largest in the nation and yield as much as 7,000 gallons per minute (Whitehead, 1994).

2. Wells that derive water from Pliocene and younger basaltic-rock aquifers of the Snake River Plane aquifer system and adjacent areas in southern Idaho are Class Ib, because portions of these volcanic rocks may be highly permeable as they contain open spaces associated with lava tubes, pillow basalts, vesicles, fractures, faults, and porous interflow zones. Generally, the regional aquifer system in the eastern Snake River Plain is an unconfined system. Rain and snowmelt on the plain infiltrate quickly to the water table because of many surface or near-surface openings in the Pliocene and younger basaltic-rocks; similar openings at depth provide conduits for water movement.

Rule 3. Miocene basaltic rock aquifers (MIOC)

Miocene basaltic rocks commonly are thick, flood-type basaltic lava flows that were extruded from major fissures. They form productive aquifers in west-central Idaho and include basalts of the Columbia River Basalt Group that form the Columbia Plateau aquifer system (Whitehead, 1994). Similar to the Pliocene and younger basaltic-rock aquifers, the Miocene basaltic rocks can be highly permeable, as they contain open spaces associated with fractures and joints, rubble zones and vesicular basalt at the top and bottom of flows, and unconsolidated-deposit interbeds. Aquifers in the eastern part of the Columbia Plateau in Idaho generally are discontinuous and isolated. Wells yield from 1 to 2,000 gallons per minute, though small yields are more common.

3a. Wells located within the coverage of the Columbia Plateau aquifer system in west-central Idaho sample water from basaltic lava flows and some interbedded sedimentary units of the Miocene Columbia River Basalt group. Miocene basaltic-rocks also form productive aquifers in parts of southern Idaho. All wells that derive water from Miocene basaltic-rock aquifers are <u>Class Ib</u>, because these volcanic rocks can be highly permeable as they contain open spaces associated with fractures and joints, rubble zones and vesicular basalt at the top and bottom of flows, and unconsolidated-deposit interbeds.

3b. Wells in the Miocene basaltic-rock aquifer coverage that also fall within the coverages of the formation Qpw (Pleistocene wind-blown loess of Northern Idaho) in the bedrock geology coverage are <u>Class Id</u>, because this low permeability loess deposit overlies the Miocene basaltic-rock aquifer.

Rule 4. Volcanic and sedimentary rock aquifers (VOLC)

Tertiary and Quaternary silicic volcanic rocks are present chiefly in southern Idaho, where they consist of thick flows interspersed with unconsolidated deposits of volcanic ash and sand. These rocks in combination with semiconsolidated sand and gravel eroded mostly from volcanic rocks form the volcanic and sedimentary rock aquifers. These aquifers are not as productive as the Quaternary unconsolidated sand and gravel aquifers, Pliocene and younger basaltic-rock aquifers, or the Miocene basaltic rock aquifers. However, portions of the volcanic rocks can be highly permeable, as they contain open spaces associated with fractures, faults, and porous interflow zones. Wells deriving water from volcanic and sedimentary rock aquifers can yield up to several thousand gallons per minute, though most wells yield less than 100 gallons per minute. Silicic volcanic rocks in northeastern Idaho are extremely permeable in places, as indicated by the large springs that issue from these rocks (cf. Figure 41, Whitehead, 1994).

4. Volcanic and sedimentary rock aquifers consist of a variety of volcanic and sedimentary rocks. Volcanic and sedimentary rock aquifers in Idaho include silicic volcanic rocks in southern Idaho, including unconsolidated volcanic ash and cinder deposits and semi-consolidated sand and gravel eroded mostly from volcanic rocks. Permeability of these rocks is extremely variable. These aquifers are not as productive as the Quaternary unconsolidated sand and gravel aquifers, Pliocene and younger basaltic-rock aquifers, or the Miocene Columbia River Basalt group aquifers. However, portions of the volcanic rocks may be highly permeable as they contain open spaces associated with fractures, faults, and porous interflow zones. Thus, these wells are <u>Class Ib</u>.

Rule 5. Carbonate rock aquifers (CARB)

Precambrian to Triassic limestones and dolomites crop out within the mountain ranges of the Basin and Range Physiographic Province in southeastern Idaho and in areas of central Idaho. The hydrologic properties of these rocks are not well known. However, they are potentially moderately to highly permeable in areas where they have been subjected to fracturing and dissolution. In this report, these rocks are referred to as the carbonate-rock aquifers.

5. Carbonate aquifers in Idaho consist primarily of the Basin and Range carbonate-rock aquifers that form mountain ranges between the basins of the Basin and Range aquifer system in southeastern Idaho. A few scattered carbonate-rock aquifers also occur in central Idaho. Wells that derive water from carbonate rocks are <u>Class Ib</u>, because these units may contain solution cavities and other karst features.

Rule 6. Pre-Miocene rock aquifers (PREM)

Precambrian to Tertiary undifferentiated volcanic rocks, undifferentiated consolidated sedimentary rocks, and undifferentiated intrusive-igneous and metamorphic rocks are found principally in the mountainous areas of central and eastern Idaho. Collectively, these are referred to as the aquifers in pre-Miocene rocks. In the pre-Miocene volcanic rocks water is present primarily in joints and fractures as in the Pliocene and younger and the Miocene basaltic-rock aquifers. The undifferentiated pre-Miocene intrusive-igneous, metamorphic, and sedimentary rocks are generally dense and contain few fractures. The aquifers in all rock types generally yield only from 1 to 100 gallons per minute of water to wells.

6a. Wells located within the coverage of aquifers in Pre-Miocene rocks sample water from undifferentiated volcanic rocks, undifferentiated consolidated sedimentary rocks, and undifferentiated intrusive igneous and metamorphic rocks, principally in the mountainous areas of central and eastern Idaho. The aquifers in all rock types generally yield only from 1 to 100 gpm of water to wells. Thus, all wells in aquifers in pre-Miocene rocks are <u>Class IIb</u>.

6b. In the pre-Miocene volcanic rocks, water is present primarily in open spaces associated with joints and fractures, as in the Pliocene and younger and Miocene basaltic-rock aquifers. Because of these potential high-permeability zones, wells in the coverage of aquifers in pre-Miocene rocks that also fall within the volcanic formations Tevf, Tevi, and Tevr in the bedrock geology coverage are <u>Class Ib</u>.

Sole source Aquifers

Idaho contains three EPA-designated sole source aquifers. These are the Spokane Valley Rathdrum Prairie aquifer in Kootenai and Bonner Counties, the Lewiston Basin aquifer in Nez Perce County, and the Eastern Snake River Plain aquifer in southern Idaho. Each of these sole source aquifers is contained within one or more of the larger principal aquifers or aquifer systems described above.

The Spokane Valley Rathdrum Prairie aquifer *(SVRP_SSA)* is contained within the unconsolidated sand and gravel aquifers. Any wells deriving water from this aquifer will be assigned a classification based on rule 1a. The Lewiston Basin aquifer *(LEWI_SSA)* is contained within the

Miocene basaltic-rock aquifers. Any wells deriving water from this aquifer will be assigned a classification based on rule 3a. The Eastern Snake River Plain aquifer *(ESRP_SSA)* is contained largely by the Pliocene and younger basaltic-rock aquifers. Any wells deriving water from this aquifer will be assigned a classification based on rule 2.

Metadata Sources References

Johnson, B.R. and G.L. Raines. 1996. Digital representation of the Idaho State geologic map, U.S. Geological Survey Open-File Report 95-690. 24 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Whitehead, R.L. 1994. Ground water atlas of the United States: Segment 7, Idaho, Oregon and Washington. Hydrologic Investigations Atlas 730-H, U.S. Geological Survey, Reston, VA, 33 pp.

Rules for Applying the Pettyjohn Classification Scheme in Illinois

4 June 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-K (referred to as Segment 10 atlas; Lloyd, Jr. and Lyke, 1995) and the previously published DW USA reports (RSPA, 2002). The available data set included:

1. Wells: location, source, depth
2. Geology: surficial, bedrock, alluvial thickness, and drift thickness

The aquifer boundaries were created on the basis of the areal distribution of geologic units as depicted in the digital representation of the Geologic Map of Illinois. Thus, the aquifers are shown in outcrop extent only. Aquifer subcrops must be interpreted from the geologic map and other available information. The following discussion of the aquifers of Illinois is derived largely from information in Lloyd and Lyke (1995).

The following aquifers of Illinois were distinguished for this work:

1. Alluvial and Glacial
2. Mississippi Embayment
3. Pennsylvanian
4. Mississippian
5. Devonian-Silurian
6. Ordovician- Cambrian
7. Mahomet Sole Source

Rule 1. Alluvial and glacial aquifer systems (ALLU)

The most productive aquifers consist of Quaternary sand and gravel deposits. These Quaternary deposits primarily are either river alluvium material or glacial deposits. Even the Holocene alluvium present in some river valleys is mostly derived from reworked glacial deposits. The glacial till sediments are a poorly sorted mixture of clay, silt, sand and boulders deposited directly by the ice; they have low permeability and usually are confining units. Sediments deposited by glacial meltwater consist of coarse sand and gravel that are productive aquifers. The alluvial sediments usually have high permeability and are located in river valleys, primarily in the Mississippi River valley and along its tributaries.

The alluvial and glacial aquifer boundary is not included in the aquifer coverage because most of the state is covered by these sediments. The source information included in the well database will be used to determine whether or not a well is deriving water from these sediments, as will information regarding the thickness of alluvial and glacial sediments.

1a. Wells that derive water from unconsolidated alluvium (ALLU_OUT) anywhere in Illinois are <u>Class Ia</u>. These wells are deriving water from surficial sands and gravels, or buried

Pleistocene sands that occur within major mapped alluvial valleys (as defined in the SEDTHICK feature class by a value of 2). This classification is in some cases conservative, such as instances in which a layer of till, loess, or lacustrine sediments greater than 50 ft thick separates the underlying Pleistocene aquifer from the overlying alluvial valley sediments. A disclaimer is made that it is possible that the two permeable units may be separated by an impermeable layer greater than 50 ft thick, thus those wells would be Class III. However, data describing the thickness of such subsurface confining units is not available, so all wells are considered Class Ia.

1b. Wells that derive water from unconsolidated sediments (ALLU_OUT) are Class Id if they are located within areas of till thicknesses less than or equal to 50 ft thick (as defined in the DRIFT feature class by a value of 1).

1c. Wells are Class III if they derive water from unconsolidated sediments (ALLU_OUT) and are located within areas of till thicknesses greater than 50 ft thick (as defined in the DRIFT feature class by a value of 2). Wells in this case most likely derive water from buried Pleistocene valley aquifers, which are usually overlain by confining layers of younger till (some of these wells are artesian in nature).

Rule 2. Mississippi Embayment aquifers (MSEM)

The aquifers in the Mississippi Embayment consist mostly of semi-consolidated sediments that range in age from Late Cretaceous through Paleocene. Only a relatively small portion of the McNairy-Nacatoch and Wilcox aquifers extend into the territory of Illinois in its southwestern margin. The two aquifers are separated by the Midway confining unit. The extensive and massive sands of the aquifers pinch out along the updip limit of the Mississippi Embayment and they thicken toward the center of the embayment.

2. Wells within the outcrop belt of the Mississippi Embayment aquifer system (MSEM_OUT) that derive water from the Cretaceous McNairy-Nacatoch or Tertiary Wilcox aquifer systems are Class Ic. These aquifers are semi-consolidated and have no overlying impermeable till.

Rule 3. Pennsylvanian aquifers (PNAQ, PNCU)

Sandstone and limestone beds of Pennsylvanian age that are aquifers in Illinois lie beneath the Glacial or Alluvial aquifers in most areas. The Pennsylvanian limestones and sandstones are parts of repeating sequences of beds deposited during multiple sedimentary cycles. An ideal complete cycle consists of the following sequence of beds, listed from bottom to top: basal sandstone, sandy shale, limestone, underclay, coal, gray shale, limestone, black platy shale, limestone, and silty gray shale. Small or moderate supplies of water are obtained from the Pennsylvanian aquifers in places where little water is available from the overlying Quaternary deposits.

Our aquifer coverage contains two Pennsylvanian units, the Pennsylvanian aquifer (PNAQ) and the overlying Pennsylvanian confining unit (PNCU). The Pennsylvanian confining unit is not a source aquifer and therefore has no rules.

3a. Wells located within the outcrop belt of the Pennsylvanian aquifers (PNAQ_OUT) and deriving water from Pennsylvanian rocks are conservatively called Class IIc despite the possibility of internal confining units.

3b. Wells located anywhere and sourcing subcrops of the Pennsylvanian units (PNAQ_SUB) are Class III because of the presence of overlying confining shales.

Rule 4. Mississippian aquifers (MSAQ)

Mississippian rocks that are aquifers in Illinois lie beneath Quaternary deposits and Pennsylvanian rocks, cropping out in the Mississippi valley and southern and eastern Illinois. Generally, thick-bedded limestones and sandstones constitute the aquifers. Although small amounts of water can be obtained from nearly all of the Mississippian rocks, the most productive water-yielding rocks are limestones and sandstones.

4a. Wells deriving water from Mississippian aquifers (MSAQ_OUT) and located in the area where glacial till is less than or equal to 50 ft thick (as defined in the DRIFT feature class by a value of 1) are Class Id because these aquifers consist of covered limestones, dolomites, or sandstones.

4b. Wells that derive water from the Mississippian units (MSAQ_OUT) in areas in which till thicknesses are greater than 50 ft thick (as defined in the DRIFT feature class by a value of 2) are Class III because of the confining units within the till.

4c. Wells that derive water from the Mississippian units (MSAQ_OUT) and are located in unglaciated areas should be Class Ib, because there is no overlying impermeable material.

4d. Wells located anywhere and deriving water from the subcrops of the Mississippian units (MSAQ_SUB) are Class III because of the presence of overlying confining shales.

Rule 5. Devonian-Silurian aquifers (DECU, DESI)

Dolomites and limestones of Devonian and Silurian age constitute the principal aquifers in this unit. Sandstone formations are also present in places. The Devonian-Silurian aquifer, which is present in northern Illinois, lies beneath Upper Devonian shales, Mississippian rocks or Quaternary deposits.

Our aquifer coverage contains two Devonian-Silurian units: the Devonian-Silurian aquifer (DESI) and the overlying Devonian confining unit (DECU). The Devonian confining unit is not a source aquifer and therefore has no rules.

5a. Wells deriving water from Devonian-Silurian (DESI_OUT) aquifers and are in the area where glacial till is less than or equal to 50 ft thick (as defined in the DRIFT feature class by a value of 1) are Class Id, because these aquifers consist of covered limestones, dolomites, or sandstones.

5b. Wells that derive water from Devonian-Silurian (DESI_OUT) units in areas in which till thicknesses are greater than 50 ft thick (as defined in the DRIFT feature class by a value of 2) are Class III because of the confining units within the till.

5c. Wells that derive water from Devonian-Silurian (DESI_OUT) units and are located in unglaciated areas should be classified as Class Ib, because there is no overlying impermeable material.

5d. Wells located anywhere and deriving water from the subcrops of the Devonian-Silurian units (DESI_SUB) are Class III because of the presence of confining shales.

Rule 6. Ordovician-Cambrian aquifers (MACU, ORCA)

The aquifers in rocks of Ordovician and Cambrian age and the confining units that separate and overlie them are collectively called the Ordovician-Cambrian aquifer system. This aquifer system is complex and multilayered; major aquifers are separated by leaky confining units. Cambrian and Ordovician rocks consist primarily of sandstone in the lower part and sandstone and shale interbedded with limestone or dolomite in the upper part. Where this aquifer system is buried beneath Devonian and Silurian rocks, it is separated from the overlying Devonian-Silurian aquifer by the Maquoketa confining unit, which consists of Upper Ordovician shale, dolomite and dolomitic shale. Where the Maquoketa confining unit is removed by erosion, the Ordovician-Cambrian aquifer is overlain by the surficial Glacial or Alluvial aquifer system, or it is exposed at the land surface (in northern Illinois).

The Maquoketa confining unit boundary is differentiated from the Ordovician-Cambrian aquifer in our aquifer coverage and is designated by MACU. The Maquoketa confining unit in Illinois consists of several formations: Maquoketa Group, Galena Group, Platteville Group, and upper part of the Ancell Group. The Maquoketa confining unit can be a source of groundwater.

6a. Wells located anywhere and deriving water from the Maquoketa confining unit (MACU_OUT, MACU_SUB) are Class III.

6b. Wells located in the outcrop belt of sandstones of the Ordovician-Cambrian aquifer system (ORCA_OUT) in northern Illinois that derive water from these units and are in the area where glacial till is less than or equal to 50 ft thick (as defined in the DRIFT feature class by a value of 1) are Class IIc covered bedrock aquifers.

6c. Wells that derive water from the Ordovician-Cambrian units (ORCA_OUT) in areas in which till thicknesses are greater than 50 ft thick (as defined in the DRIFT feature class by a value of 2) are Class III because of the confining units within the till.

6d. Wells that derive water from the Ordovician-Cambrian units (ORCA_OUT) and are located in the unglaciated areas should be classified as Class IIa, because they are high-yield sandstone aquifers.

6e. Wells located in the subcrop belt of sandstones of the Ordovician-Cambrian aquifer are Class III because of the presence of confining units overlying these subcrops.

Rule 7. Mahomet sole source aquifer (MAHO_SSA)

Illinois contains one EPA-designated sole source aquifer, the Mahomet aquifer. The Mahomet aquifer consists of sand and gravel deposited during the pre-Illinois Glacial Episode by meltwater flowing westward along the Mahomet Bedrock Valley. This bedrock valley, incised mostly into Pennsylvanian shales, forms the western part of the Teays-Mahomet Bedrock Valley System that extends into Illinois from Indiana and possibly Ohio and West Virginia. Most of the sand and gravel of the Mahomet aquifer belongs to the Mahomet Sand Member, the lithostratigraphic unit that comprises the lower half of the Banner Formation. The rest of the Banner Formation consists mostly of the Hillery and overlying Tilton Members, two till units that overlie and form the confining unit for the Mahomet. The Mahomet aquifer is covered by drift from the most recent glaciation.

7a. Wells deriving water from the Mahomet soul source aquifer (MAHO_SSA) and in the area where glacial till is less than or equal to 50 ft thick (as defined in the DRIFT feature class by a value of 1) are <u>Class Id</u>.

7b. Wells deriving water from the Mahomet soul source aquifer (MAHO_SSA) and in the area where glacial till is greater than 50 ft thick (as defined in the DRIFT feature class by a value of 2) are <u>Class III</u>.

Metadata Sources References

Lloyd Jr., O.B. and W.K. Lyke. 1995. Ground water atlas of the United States: Segment 10, Illinois, Indiana, Kentucky, Ohio, Tennessee. Hydrologic Investigations Atlas 730-K, U.S. Geological Survey, Reston, VA, 32 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Indiana

1 May 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-K (referred to as Segment 10 atlas, Lloyd and Lyke, 1995) and the previously published DW USA reports (RSPA, 2002). The available data set included:

1. Wells: location
2. Aquifer systems: unconsolidated and bedrock
3. Geology: surficial and bedrock

Because information regarding source aquifer or source depth is unavailable, classification of wells are based on the shallowest aquifer that could potentially be sampled. If source data become available, well classifications could change. The aquifer boundaries were created on the basis of the areal distribution of geologic units as depicted in the digital representation of the Geologic Map of Indiana. Thus, the aquifers are shown in outcrop extent only. Aquifer subcrops must be interpreted from the geologic map and other available information. The discussion of the aquifers of Indiana is derived largely from information in Lloyd and Lyke (1995).

The following aquifers of Indiana were distinguished for this work:

1. Alluvial
2. Glacial till
3. Glacial aquifer complexes
4. Glacial outwash
5. Thinly covered buried valley bedrock
6. Unglaciated, dissected till, and till veneer
7. St. Joseph Aquifer System and Tributary Valleys Sole Source

Rule 1. Alluvial aquifer systems (ALLU, ALLC)

The most productive aquifers consist of Quaternary sand and gravel deposits. These deposits supply the majority of the fresh ground water. The Quaternary deposits primarily are material of glacial origin and alluviums. Even the Holocene alluvium present in some river valleys mostly is derived from reworked glacial deposits. The alluvial aquifers are mapped along modern river systems, such as the Kankakee River, Wabash River, White River, and the East Fork White River, where the floodplain is greater than one-eighth mile in width and total thickness of deposits are greater than 25 ft.

The materials in this aquifer system come from two major sources. One source is alluvium deposited by the streams along with colluvium eroded from the valley walls and upland areas. The second source is glaciolacustrine sediment, which accumulated in bodies of relatively stagnant lake water. These silts and clays were deposited when the valleys of the White, Wabash, and Ohio

Rivers were choked with coarser material carried by glacial meltwater that effectively dammed tributary streams, creating lakes. Few wells are completed in the glaciolacustrine system.

1a. Wells located in the alluvial aquifer systems (ALLU) are Class Ia, because they likely derive water from highly permeable unconsolidated fluvial sands. This classification is somewhat conservative given the likelihood of local confining units being present within alluvial floodplains. Typically, a maximum depth of 200 ft is the cutoff for this rule, but the lack of well depth information makes this untenable.

1b. Wells located in regions where the alluvial aquifers are capped by less than 50 ft of either lacustrine clay or till (ALLC) are Class Id.

Rule 2. Glacial till aquifers (TILL)

The till sediments are a poorly sorted mixture of clay, silt, sand and boulders deposited directly by the ice; they have low permeability and usually are confining units. Wells within the extensive till plains that cover most of Indiana may derive water from isolated pockets of gravel or outwash within the till, or from buried, and in most cases confined, Paleozoic units below. As shown in Figures 11 and 14 of the Segment 10 Atlas, p. K6, only a small portion of the till covered areas in northern Indiana is recognized as a significant source of groundwater. Throughout the rest of the state, sand and gravel aquifers within the glacial cover are difficult to locate.

2. Wells located in the thinner (less than 100 ft thick) central and southern till plains are Class III, because the wells are most likely tapping bedrock aquifers overlain by more than 50 ft of impermeable material.

Rule 3. Glacial aquifer complexes (COMP)

This system is typically mapped in areas of multiple glacial sequences. Aquifer complexes commonly occur adjacent to a till aquifer system; however, the number of aquifers, thickness, and yield are greater than till aquifer systems. The glacial aquifer complexes consist of unconsolidated sand and gravel interbedded with clay and till and are typically confined by overlying till.

3. Wells located in the glacial complex are Class Id, because these aquifers are often confined by variably thick clay or till sequences.

Rule 4. Glacial outwash aquifers (OUTW, OUTC)

In places, meltwater streams deposited large volumes of sand and gravel in the stream valleys. These areas are mapped as the outwash aquifer system and are characterized by excellent groundwater availability. Outwash fans and plains are generated by multiple glacial periods. Wells located within these regions are most likely deriving water from these thick, highly permeable sand and gravel deposits.

4a. Wells located within the outwash fans and plains (OUTW) generated by multiple glacial periods are most likely deriving water from these thick, highly permeable sand and gravel deposits and are categorized as Class Ia. Normally, a maximum depth rule would apply, but in the absence of well depth information, depth cut-offs for any rule are not possible.

4b. Wells located in regions of till capped outwash (OUTC) could be Class III or Class Id, depending on the thickness of the overlying till. With the data that is presently available, there is no way to differentiate between thick and thin till caps. Therefore, the most conservative approach is taken, and these wells are assigned Class Id.

Rule 5. Thinly covered, buried valley bedrock aquifers (VALL)

These areas consist of a known bedrock valley that underlies a shallower mapped system, with supporting data showing some deep aquifer potential; although the deep aquifer is not typically used as the main aquifer source because of overlying aquifers. In southern Indiana, there is limited aquifer potential and most wells are completed in bedrock.

5a. Wells deriving water from the subcrops of Mississippian-Devonian carbonate formations (Blue River Group, Muscatatuck Group, Sanders Group) and Silurian and Ordovician limestone units (Bainbridge Group, Lexington Formation, Salina Group) are Class Id, because these are covered carbonate units with some potential for karst.

5b. Wells within the covered Mississippian Borden, Buffalo Wallow, Stephensport, and West Baden Groups are Class IIc, covered bedrock aquifers, because these are low yield sandstones, shales and limestones covered by a till of variable thickness (Lloyd and Lyke, 1995) It should be noted that according to Indiana Geological Survey Bulletin 59, the Buffalo Wallow Group includes the Tar Springs Sandstone, a known aquifer unit.

5c. Wells located within the thinly till-capped subcrops of the Mississippian-Devonian New Albany Shale formation or the shale-dominated sandy limestone units within the Ordovician Dillsboro and Kope Formations (Maquoketa Group) are Class III due to the confining nature of the shale.

5d. Wells located in areas of thinly capped Pennsylvanian Strata (Raccoon Creek Group, Carbondale Group, and Patoka and Shelborn Formations) are *Class III, because of the high probability of confining units being present within the strata (Lloyd and Lyke, 1995).*

Rule 6. Unglaciated, dissected till, and till veneer aquifers (UNGL)

These systems are similar in composition and have little potential for groundwater production. The Dissected Till and Residuum Aquifer System includes areas where pre-Wisconsin and/or Wisconsin till is thin and dissected due to deep down-cutting by streams and other areas where soils have formed directly from bedrock due to weathering. The Till Veneer Aquifer System encompasses areas where the unconsolidated material is predominantly thin till overlying bedrock; chiefly the product of the deposition of glacial till over an uneven, eroded bedrock surface rather than erosion of till by younger streams. The Unglaciated Southern Hills and Lowlands Aquifer System is mapped within areas of nonglaciation, beyond the southern limit of older glacial deposits. Wells located in these areas are classified according to the lithology of the Paleozoic units present.

6a. Wells located within the outcrop belts of the Mississippian-Devonian carbonate formations (Blue River Group, Muscatatuck Group, Sanders Group) and Silurian and Ordovician limestone units (Bainbridge Group, Lexington Formation, Salina Group) are Class Ib, due to the potential for solution cavities along fractures and joints within the limestone.

6b. Wells in the outcrop belts of Mississippian mixed sandstones, shales and limestones strata are Class IIb, low yield bedrock aquifers (includes Stephensport, West Baden, Borden, and Buffalo Wallow Groups).

6c. Wells located within the thinly till-capped subcrops of the Mississippian-Devonian New Albany Shale formation or the shale-dominated sandy limestone units within the Ordovician Dillsboro and Kope Formations (Maquoketa Group) are Class III due to the confining nature of the shale.

6d. Wells in the outcrop belts of the Pennsylvanian strata are Class III, because of the high probability of confining units being present within the strata (includes Raccoon Creek Group, Carbondale Group*, and Patoka and Shelborn Formations).*

Rule 7. St. Joseph Aquifer System and Tributary Valleys sole source aquifer (STJO)

Indiana contains one EPA-designated sole source aquifer, the St. Joseph aquifer system and tributary valleys. This sole source aquifer is an outwash plain consisting of fine to medium sand with local layers of coarse sand and gravel, interspersed with numerous thin layers of clay.

7. Wells deriving water from the St. Joseph aquifer system are most likely deriving water from the thick, highly permeable sand and gravel deposits of the outwash plain and are categorized as Class Ia. As in rule 4a, a maximum depth rule would usually be applied, but in the absence of well depth information, depth cut-offs for any rule are not possible.

Metadata Sources References

Lloyd Jr., O.B. and W.K. Lyke. 1995. Ground water atlas of the United States: Segment 10, Illinois, Indiana, Kentucky, Ohio, Tennessee. Hydrologic Investigations Atlas 730-K, U.S. Geological Survey, Reston, VA, 32 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Iowa

25 September 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-J, also called Ground Water Atlas of the United States, Segment 9 (Olcott, 1992) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Casing depth
4. Pump rate
5. Source aquifer
6. Surficial geology
7. Aquifer boundaries

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are six principal aquifers in Iowa:

1. Alluvial
2. Cretaceous
3. Pennsylvanian
4. Mississippian
5. Silurian-Devonian
6. Cambrian-Ordovician

Rule 1. Alluvial aquifer (ALLU)

The unconsolidated sediments of the alluvial aquifer are exposed at the land surface throughout Iowa, including the Mississippi and Missouri river valleys. The aquifer is comprised primarily of alluvial sediments of Quaternary age deposited within river and stream valleys in Iowa, including the Mississippi and Missouri Rivers. The lithology of the aquifer is a combination of alluvial sand, gravel, and clay. The thickness of the alluvial aquifer in Iowa is commonly 200-400 ft, but may reach thicknesses of 600 ft and contains water predominately under unconfined conditions. Yields from wells sourcing the alluvial aquifer commonly yield up to 500 gallons per minute, particularly along the Mississippi and Missouri Rivers.

1a. Wells that derive water from the alluvial aquifer, occur within the alluvial aquifer outcrop (ALLU_OUT), derive water from less than 600 ft depth, and are covered by glacial loess deposits are <u>Class Id</u> because here the alluvial aquifer is covered.

1b. Wells that derive water from the alluvial aquifer, occur within the alluvial aquifer outcrop (ALLU_OUT), and derive water from less than 600 ft depth are <u>Class Ia</u> because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

1c. All other wells that derive water from the alluvial aquifer, occur within the surficial aquifer outcrop (ALLU_OUT), and are deeper than 600 ft are Class UNK because the depth is greater than the maximum depth for the alluvial aquifer.

Rule 2. Cretaceous aquifer (CRET)

The consolidated siliciclastic sedimentary rocks of the Cretaceous aquifer outcrop in northwestern Iowa and subcrop to the south. These rocks are composed mostly of sandstone and are Lower Cretaceous in age. The thickness of the aquifer ranges from 90-160 ft and contains water under confined conditions. Yields of wells completed in the Cretaceous aquifer range from less than 100 gallons per minute to over 100 gallons per minute and average 250 gallons per minute.

2a. Wells sourcing the Cretaceous aquifer and located within the aquifer outcrop (CRET_OUT), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

2b. Wells sourcing the Cretaceous aquifer and located within the aquifer outcrop (CRET_OUT), with a pump rate less than 50 gpm are Class IIb because they are unconfined and lower yield.

2c. Wells sourcing the Cretaceous aquifer subcrop (CRET_SUB), where the aquifer forms the bedrock surface and is overlain by the alluvial aquifer, with a pump rate greater than 50 gpm, are Class IIa because they are unconfined and higher yield.

2d. Wells sourcing the Cretaceous aquifer subcrop (CRET_SUB), where the aquifer forms the bedrock surface and is overlain by the alluvial aquifer, with a pump rate less than or equal to 50 gpm, are Class IIb because they are unconfined and lower yield.

2e. Wells sourcing the Cretaceous aquifer subcrop (CRET_SUB), where the aquifer does not form the bedrock surface, are Class III because the aquifer is consolidated and confined.

Rule 3. Pennsylvanian aquifer (PENN)

The consolidated siliciclastic sedimentary rocks of the Pennsylvanian aquifer outcrop in southern and western Iowa. These rocks are composed mostly of sandstone, with subordinate shale, and contain water under confined conditions. The thickness of the aquifer is generally less than 300 ft and yields from wells completed in the aquifer are typically less than 100 gallons of water per minute.

3a. Wells sourcing the Pennsylvanian aquifer and located within the aquifer outcrop (PENN_OUT), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

3b. Wells sourcing the Pennsylvanian aquifer and located within the aquifer outcrop (PENN_OUT), with a pump rate less than 50 gpm are Class IIb because they are unconfined and lower yield.

3c. Wells sourcing the Pennsylvanian aquifer subcrop (PENN_SUB), where the aquifer forms the bedrock surface and is overlain by the alluvial aquifer, with a pump rate greater than 50 gpm, are Class IIa because they are unconfined and higher yield.

3d. Wells sourcing the Pennsylvanian aquifer subcrop (PENN_SUB), where the aquifer forms the bedrock surface and is overlain by the alluvial aquifer, with a pump rate less than or equal to 50 gpm, are Class IIb because they are unconfined and lower yield.

3e. Wells sourcing the Pennsylvanian aquifer subcrop (PENN_SUB), where the aquifer does not form the bedrock surface, are Class III because the aquifer is consolidated and confined.

Rule 4. Mississippian aquifer (MISS)

The consolidated sedimentary rocks of the Mississippian aquifer outcrop in central Iowa, and subcrop to the south and east, where the aquifer is confined. The lithology of the aquifer is principally limestone and dolomite with subordinate sandstone and siltstone. The aquifer thickness ranges from less than 100 ft to over 600 ft in Iowa. Yields from wells completed in the aquifer range from 900-1000 gallons per minute.

4a. Wells sourcing the Mississippian aquifer, located within the aquifer outcrop (MISS_OUT) are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

4b. Wells sourcing the Mississippian aquifer subcrop (MISS_SUB), where the aquifer forms the bedrock surface and is overlain by the alluvial aquifer, are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

4c. Wells sourcing the Mississippian aquifer, located within the aquifer subcrop (MISS_SUB), where the aquifer does not form the bedrock surface, are Class III because the aquifer unit is confined.

Rule 5. Silurian-Devonian aquifer (SILD)

The consolidated sedimentary rocks of the Silurian-Devonian aquifer outcrop in eastern Iowa, and the aquifer subcrop extends over much of the state, where the aquifer is confined. The lithology of the aquifer is mostly limestone and dolomite, with minor shale and evaporate beds. The aquifer thickness ranges from 300-400 ft and yields from wells completed in the aquifer range from 100 to 500 gallons per minute.

5a. Wells sourcing the Silurian-Devonian aquifer, located within the aquifer outcrop (SILD_OUT) are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

5b. Wells sourcing the Silurian-Devonian aquifer subcrop (SILD_SUB), where the aquifer forms the bedrock surface and is overlain by the alluvial aquifer, are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

5c. Wells sourcing the Silurian-Devonian aquifer, located within the aquifer subcrop (SILD_SUB), where the aquifer does not form the bedrock surface, are Class III because the aquifer unit is confined.

Rule 6. Cambrian-Ordovician aquifer (CORD)

The consolidated sedimentary rocks of the Cambrian-Ordovician aquifer outcrop in northeastern Iowa, and the aquifer subcrop extends over much of the state, where the aquifer is confined. The Cambrian-Ordovician aquifer includes the Upper Carbonate aquifer. The lithology of the aquifer is primarily dolomite and sandstone, with subordinate shale. The aquifer thickness ranges from 50-150 ft.

6a. Wells sourcing the Cambrian-Ordovician aquifer, located within the aquifer outcrop (CORD_OUT), are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

6b. Wells sourcing the Cambrian-Ordovician aquifer subcrop (CORD_SUB), where the aquifer forms the bedrock surface and is overlain by the alluvial aquifer, are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

6c. Wells sourcing the Cambrian-Ordovician aquifer, located within the aquifer subcrop (CORD_SUB), where the aquifer does not form the bedrock surface, are Class III because the aquifer unit is confined.

Metadata Sources References

Olcott, P.G. 1992. Ground water atlas of the United States: Segment 9, Iowa, Michigan, Minnesota, Wisconsin. Hydrologic Investigations Atlas 730-J, U.S. Geological Survey, Reston, VA, 33 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Kansas

12 February 2018

Introduction

The rule set below is based primarily on information published in the USGS Hydrologic Investigations Atlas 730-D (Miller and Appel, 1997) and the previously published DW USA reports (RSPA, 2002). The data available for Kansas included:

1. Wells: location, source, depth, screen depth
2. Bedrock geology

In most cases, the aquifer coverages used were provided by the USGS. In some cases, the aquifer boundaries were generated using surficial geology and the Segment 3 atlas (Miller and Appel, 1997) as a guide. Classification of all wells should be based on the shallowest sourced interval in the well.

The following aquifers of Kansas were distinguished for this work:

1. Alluvial
2. Glacial
3. High Plains
4. Dakota
5. Ozark Plateaus
6. Not a principle aquifer

Rule 1. Alluvial aquifers (ALLU)

The Alluvial aquifers consist of narrow bands of fluvial and alluvial sediments, which fill or partly fill the valleys of meandering to braided streams that have eroded shallow channels into glacial deposits, older unconsolidated alluvium, or bedrock. The Alluvial aquifers are composed of mostly unconfined, unconsolidated, surficial sand and gravel deposits in hydraulic continuity with the water table. The sediments are of Holocene age but locally include sediments of Pleistocene age. Important water sources occur in the alluvium of the larger rivers, such as the Kansas and Missouri rivers and their tributaries (e.g., Big Blue and Republican) and the Arkansas, Neosho, and Cimarron Rivers. The average thickness of the aquifers is about 90 to 100 ft, but locally they are as much as 160 ft thick. An additional 40 ft was added for alluvial aquifers to allow for uncertainty in the measurement of well depth, resulting in the estimated maximum thickness of 200 ft.

1a. Wells located within the mapped Alluvial aquifers (alluvial valleys) that derive water from depths <200 ft are Class Ia.

1b. Wells deriving water from the mapped Alluvial aquifers (alluvial valleys) that are covered in loess are Class Id.

1c. Wells deriving water from depths greater than 200 ft are classified as unknown.

Rule 2. Glacial aquifers (GLAC)

The glacial sediments include the tills of the Kansan Stage and Nebraskan Stage located in northeastern Kansas. The Nebraskan Stage includes the sediments genetically related to the first major cycle of Pleistocene glaciation. Nebraskan glacial sediments are distributed discontinuously over the state and are only exposed in extreme northeastern Kansas. The subsequent Kansan Stage contains the Atchison formation, the Kansas till, and the Meade formation which includes the Grand Island sand and gravel member at the base and the Sappa member with the Pearlette volcanic ash bed. Kansas till includes the deposits made directly by the Kansan glacier and some water-laid sediments interstratified with the till. The Atchison formation includes the pro-glacial silts, sands, and gravels deposited in front of the advancing glacier, and the Meade formation includes the outwash deposits from the retreating glacier. Most of these sediments were laid down directly by the ice and are fine grained, poorly sorted and, therefore, yield only small amounts of water to wells. However, meltwater created an extensive stream network in front of the advancing ice and the streams deposited gravel, sand and finer sediments as alluvium along the courses of periglacial bedrock valleys. The thickness of glacial drift generally is 100 to 200 ft but locally is greater than 400 ft in northeastern Kansas. Water generally is obtained from sand beds that range from 20 to 40 ft in thickness.

- 2a. Wells within the glacial coverage are conservatively classified as a <u>Class Ia</u> if they derive water from depths shallower than 50 ft, because of the patchy nature of till permeability.
- 2b. Wells that occur outside of the mapped alluvial valleys (Alluvial aquifers) but are within the boundaries of the glacial coverage in the northeastern corner of the state are <u>Class III</u> if they are deeper than 50 ft, regardless of water source, because of the high likelihood of impermeable Pleistocene glacial material confining the aquifers. These wells may derive their water from buried Pleistocene valley aquifers, which are usually overlain by confining layers of younger till.
- 2c. Pleistocene-sourced wells that occur within major, mapped alluvial valleys (created by third order or higher streams) in the northeastern glacial region (glacial aquifer coverage) are probably <u>Class Id</u>, because the confining unit separating the Holocene and Pleistocene sands would have been mostly eroded away.

Rule 3. High Plains aquifer (HIGH)

The High Plains aquifer is named from the High Plains Physiographic Province, an area of flat to gently rolling topography, which is part of a vast plain that slopes gently eastward from the Rocky Mountains and was deposited by a network of streams. Subsequent uplift and erosion have partly dissected the plain. In places, extensive areas of windblown silt and sand that were derived from channel deposits of the streams are at the land surface. The aquifer underlies an area of 30,500 square miles in central and western Kansas. The aquifer overlies rocks of Late Cretaceous age in Kansas, where it generally is less than 250 ft thick. The High Plains, is an unconsolidated, unconfined aquifer. The High Plains aquifer consists of all or parts of several geologic units of Quaternary and Tertiary age. The oldest sediments of the High Plains aquifer are as old as Oligocene. The deposits include alluvial sand, silt and gravel; and eolian sands and silts.

The High Plains aquifer includes the Ogallala aquifer and is the most important water source for much of western and central Kansas. In the subsurface, the Ogallala aquifer largely consists of sands and gravel that are interlayered with silt and clay beds that are mostly unconsolidated, or not naturally cemented together. Younger (Pleistocene) sediments of the High Plains aquifer that are similar to the Ogallala include the Equus Beds aquifer and the Great Bend Prairie aquifer. In places along the Arkansas River in the southwestern part of the state and in the south-central region, overlying unconsolidated deposits of Quaternary age are saturated and in hydraulic continuity with the underlying Ogallala Formation. Where this is the situation, the combined Quaternary/Miocene deposits (alluvium) are referred to as the High Plains aquifer. The depth to water in the High Plains aquifer is less than 200 ft in most of Kansas.

3a. Wells located within the outcrop belt of the Miocene/Pliocene Ogallala formation, which is part of the High Plains aquifer, that derive water from that aquifer are typically Class Ic, because this aquifer is composed of semi-consolidated sediments and has a high yield of ground water.

3b. In places along the Arkansas River in the southwestern part of the state and in the south-central region, overlying unconsolidated deposits of Quaternary age are saturated and in hydraulic continuity with the underlying Ogallala Formation and are thus referred to as the High Plains aquifer. Where the water is derived from these Quaternary sediments, the well is Class Ia (see rule 1).

3c. In many areas, the High Plains aquifer is overlain by wind-blown loess, an impermeable silt deposit. Where the loess is present, wells that derive water from the high plains aquifer at depths greater than or equal to 50 ft are Class III. Wells that derive water from depths less than 50 are Class Id.

Rule 4. Dakota aquifer (DAKO)

Formations of the Great Plains aquifer crop out in northcentral Kansas. The rocks were deposited during the early part of the Cretaceous period in an oscillating sea, resulting in repeated, abrupt shifts from marine to marginal marine to non-marine depositional environments. Regionally, the Great Plains aquifer system is composed of two sandstone aquifers separated by a shale confining unit. The upper aquifer is the Dakota Sandstone. In Kansas, the term "Dakota aquifer" refers to the entire Great Plains aquifer system. It consists of loosely cemented, medium- to fine-grained sandstone bodies encapsulated in shales in the Cheyenne Sandstone, Kiowa Formation, and Dakota Formation. The sands were deposited in ancient rivers, deltas, and beaches and form lens-shaped bodies. Typically, the most productive sandstone aquifers are up to 100 ft thick. Some deeper water bearing units like the Dakota aquifer contain consolidated (e.g., sandstone) layers, and may be separated from the surface by confining layers impermeable enough so that the deep water can be under pressure. In most of Kansas, the aquifer system is buried to depths of 1,000 ft or less below land surface. The Upper Cretaceous aquitard (part of the Great Plains confining system) overlies the Dakota aquifer in Kansas and is a major factor that exerts control on the flow of the upper Dakota aquifer (Macfarlane, 1995).

4a. Wells located in the outcrop belt of the Dakota Sandstone that derive water from that unit are Class IIa, because this is a high yield sandstone aquifer exposed at the land surface.

4b. Wells located in the outcrop belt of the Kiowa Shale and Cheyenne Sandstone that derive water from that unit are Class III, because although this is a high yield sandstone aquifer near the land surface, it is confined by the Kiowa shale. This unit also goes by the name of Apishapa aquifer and is the lowermost of the two units that make up the Great Plains aquifer system in Kansas. Figure 76 of the segment 3 atlas (Miller and Appel, 1997) illustrates the difficulty in separating the Cheyenne sandstone from the Dakota. In this figure, the Cheyenne is included as part of the Dakota, whereas surface geology maps show the two units individually. Most likely, however, the Cheyenne sandstone is extremely thin in this area.

4c. Wells located outside of the outcrop belt of the Dakota Sandstone that derive water from that unit are Class III, because the Dakota Sandstone is overlain by the Great Plains confining system.

Rule 5. Ozark Plateaus aquifer (OZAR)

The Ozark Plateaus aquifer system extends from Missouri into southeastern Kansas. Several formations compose each of the aquifers that are separated by confining units. The water-yielding formations are mostly limestone and dolomite but locally include sandstone and chert. The confining units are shale primarily, but also consist of limestone, dolomite and sandstone, all of which have minimal permeability. The Ozark Plateaus Aquifer System in Kansas consists of karst and fractured carbonate rock units and has been subdivided into the Springfield Plateau (Mississippian), Ozark, and St. Francois regional aquifers. These regional aquifers are separated by one or more confining, low-permeability stratigraphic units. The Ozark Plateaus aquifer system is confined above by a sequence of Pennsylvanian shales and limestones and below by rocks of Precambrian age.

5a. Wells located within the outcrop belt of the Mississippian Ozark Plateaus aquifer (e.g., Warsaw and Keokuk Limestones) in the southeastern portion of Cherokee County (southeast corner of the state) that derive water from the carbonates are Class Ib, because these limestones contain solution cavities.

5b. Wells that derive water from the Ozark Plateaus aquifer anywhere in the state outside of the outcrop belt are Class III, because these rocks are overlain by a major confining unit (Pennsylvanian shales).

Rule 6. Not a principle aquifer (NAPA)

In addition to the aquifer regions provided by the Kansas Geological Survey, a non-principle aquifer region (NAPA) has been added to allow for the classification of wells not located in the existing aquifer coverages. The wells sourcing the NAPA region are classified according to the geological units present at the surface as shown in the bedrock geology dataset. The wells are classified as follows:

6a. Wells sourcing the NAPA region and in the Douglas (including the Stranger formation), Dakota, or Shawnee groups are Class IIa. The Dakota sandstone is confirmed as a high yield bedrock aquifer; small outcrops of which have been included in the NAPA region as a result of the scale at which the aquifer regions were defined. The Douglas and Shawnee group are less well known, and are included in this class as a matter of conservatism. These are predominately sandstones with little known information relating to well yield.

6b. Wells sourcing the NAPA region and within the Kansas City Group, Lansing Group, Pleasanton Group, Marmaton Group, Nippewalla (including the Salt Plain formation), Sumner Group, and Wabaunsee Group are Class IIb, low yield bedrock aquifers.

6c. Wells sourcing the NAPA region and within the Admire Group, Chase Group, Council Grove Group, loess, Cheyenne Sandstone, and Kiowa Formation are Class III, confined aquifers. Each of these units includes at least 50 ft of impermeable material between the aquifer and the ground surface.

6d. Wells sourcing the NAPA region and sourcing the Belleville formation are Class III, confined aquifer. The Belleville formation is composed of sand, gravel, and silt deposited by streams in and near the ancestral Republican River Valley and yields abundant supplies of good water to wells. This unit is overlain by loess, an impermeable silt deposit.

6e. Wells sourcing the NAPA region and sourcing the Colorado Group and its members (Carlile Shale, Codell Sandstone, and Niobrara Chalk) are Class III, confined aquifers.

6f. Wells sourcing the NAPA subcrop region (outside of the outcrop belt of the associated surface bedrock geologic units) are Class III because these rocks are overlain by confining units.

6g. Wells sourcing the NAPA subcrop region at depths of 50 ft or less and covered by glacial drift, a low permeability, unconsolidated material, are Class IIc.

Metadata Sources References

Macfarlane, P.A. 1995. The effect of river valleys and the Upper Cretaceous aquitard on regional flow in the Dakota aquifer in the central Great Plains of Kansas and southeastern Colorado. 238. 11-30.

Miller, J.A. and C.L. Appel. 1997. Ground water atlas of the United States: Segment 3, Kansas, Missouri, and Nebraska. Hydrologic Investigations Atlas 730-D, U.S. Geological Survey, Reston, VA, 26 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Kentucky

21 August 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-K (referred to as Segment 10 atlas; Lloyd, Jr. and Lyke, 1995) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Source aquifer
4. Surficial geology
5. Aquifer boundaries

The aquifer boundaries were generated using surface geology and the Segment 10 Atlas (Lloyd, Jr. and Lyke, 1995) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are five principal aquifers in Kentucky:

1. Surficial
2. Paleozoic sandstone
3. Paleozoic carbonate
4. Mississippi embayment
5. Not a principal

Rule 1. Surficial aquifer (SURF)

The unconsolidated sediments of the surficial aquifer are exposed at the land surface within river and stream valleys in Kentucky, and in the western portion of the state. The aquifer is comprised primarily of alluvial sediments of Quaternary age deposited along the Ohio and Mississippi Rivers. Subordinate glacial deposits located in northern Kentucky and loess deposits located in western Kentucky form the remainder of the aquifer. The lithology of the aquifer is a combination of alluvial sand, gravel, and clay; glacial sand, gravel, and clay; and loess deposits of windblown silt. The thickness of the surficial aquifer in Kentucky is commonly 25-200 ft, but may reach thicknesses of 300 ft, and contains water predominately under unconfined conditions. Yields from wells sourcing the surficial aquifer that are completed in finer grained units range from 25 to 50 gallons per minute, while those completed in sand and gravel units commonly yield 100 to 500 gallons per minute, but can exceed 1000 gallons of water per minute near the Ohio and Mississippi Rivers.

1a. Wells that derive water from the surficial aquifer, occur within the surficial aquifer outcrop (SURF_OUT), and derive water from less than 300 ft depth are <u>Class Ia</u> because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

1b. All other wells that derive water from the surficial aquifer, occur within the surficial aquifer outcrop (SURF_OUT), and are deeper than 300 ft are Class UNK because the depth is greater than the maximum depth for the surficial aquifer.

Rule 2. Paleozoic Sandstone aquifer (PSSA)

The consolidated siliciclastic sedimentary rocks of the Paleozoic sandstone aquifer outcrop in the Appalachian Plateau and Interior Low Plateau physiographic provinces of Kentucky. These rocks are composed mostly of sandstone, with subordinate conglomerate, shale, limestone, and coal, and are Devonian to Permian in age. Permeable units are tilted in the Appalachian Plateau province, but are relatively flat-lying in the Interior Low Plateau province. Yields of wells completed in Pennsylvanian sandstones of the Interior Low Plateau province range from 0.5 to 150 gallons per minute and average 25 gallons per minute, while wells deriving water from Mississippian and Pennsylvanian sandstones of the Appalachian Plateau province range from 5 to 50 gallons per minute.

2a. Wells sourcing the Paleozoic sandstone aquifer and located within the aquifer outcrop (PSSA_OUT) are Class IIa because these wells derive water from rocks that are consolidated and unconfined.

Rule 3. Paleozoic Carbonate aquifer (PCOA)

The consolidated carbonate rocks of the Paleozoic carbonate aquifer outcrop in the Appalachian Plateau and Interior Low Plateau physiographic provinces of Kentucky. These rocks are composed mostly of limestone and dolomite and are Ordovician to Mississippian in age. Permeable units are tilted in the Appalachian Plateau province, but are relatively flat-lying in the Interior Low Plateau province.

3a. Wells sourcing the Paleozoic carbonate aquifer and located within the aquifer outcrop (PCOA_OUT) are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

3b. Wells sourcing the Paleozoic carbonate aquifer subcrop (PCOA_SUB) within FM code QTcl are Class Id because here the Paleozoic carbonate aquifer is covered by less than 50 ft of low permeability material.

3c. All other wells sourcing the Paleozoic carbonate aquifer subcrop (PCOA_SUB) are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

Rule 4. Mississippi embayment aquifer (MSEA)

The unconsolidated sediments of the Mississippi embayment aquifer outcrop in western Kentucky. The aquifer is comprised of seven permeable units, and two impermeable confining units. These units range in age from Late Cretaceous to Quaternary. The lithology of the aquifer is principally sand, with subordinate gravel, silt, and clay. The aquifer thickens to the west of its outcrop area, attaining a thickness in excess of 1000 ft. Yields from wells completed in the aquifer range from 5-100 gallons per minute.

4a. Wells sourcing the Mississippi embayment aquifer, located in either the outcrop or subcrop, with well depth less than 400 ft are Class Ia because the aquifer is unconsolidated and unconfined.

4b. Wells sourcing the Mississippi embayment aquifer, located in either the outcrop or subcrop, with well depth greater than 400 ft are Class III because the aquifer is confined.

4c. Wells sourcing the Mississippi embayment aquifer, located in either the outcrop or subcrop, completed in the McNairy aquifer are Class III because the aquifer is confined.

Metadata Sources References

Lloyd Jr., O.B. and W.K. Lyke. 1995. Ground water atlas of the United States: Segment 10, Illinois, Indiana, Kentucky, Ohio, Tennessee. Hydrologic Investigations Atlas 730-K, U.S. Geological Survey, Reston, VA, 32 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Louisiana

12 February 2018

Introduction

The rule set defined below is based primarily on information published in the USGS Hydrologic Investigations Atlas 730-F (Renken, 1998), the previously published DW USA reports (RSPA, 2002) and the Guide to Louisiana's Groundwater Resources (referred to as Stuart et al., 1994). The data available for Louisiana included:

1. Wells: location, source, well depth
2. Bedrock geology

In addition to Pettyjohn classifications, most rules include a maximum depth at which well classification becomes "unknown." At outcrop locations, this is based on maximum aquifer thickness as published in Stuart et al. (1994) and/or cross sections from Renken (1998). In subcrop, this usually is based on the cross sections and isopach maps in Segment 5 atlas, Renken (1998). In some cases, an additional buffer of 50 to 200 ft is added to the published depth numbers; when this is done, it is noted in the rule. The addition of a buffer accommodates uncertainty in the measurement of well depth, local changes in the depth to the aquifer, and local changes in aquifer thickness. Total dissolved solids (TDS) concentration contours were also used to evaluate the maximum well depth for any given aquifer. It was assumed that groundwater with TDS concentrations greater that 10,000 parts per million is saline. Lastly, maximum depths stated here are based on the down dip portions of the units discussed.

In much of the area of the coastal parishes, including the entire modern Mississippi delta (Plaquemines Parish), and northward in a band up the Atchafalaya River to central Iberville Parish, the aquifers contain only salt water. Therefore, these areas are eliminated from this study (i.e., there are no community wells in that region). See Figs. 4 and 29 of Stuart et al. (1994). Classification of all wells is based on the shallowest interval in the well from which water is derived when source information is available.

The following aquifers of Louisiana were distinguished for this work:

1. Alluvial
2. Chicot/Terraces
3. South East Louisiana
4. Evangeline
5. Miocene
6. Cockfield
7. Sparta Sand
8. Carrizo-Wilcox

Rule 1. Alluvial aquifers (ALLU)

The Alluvial aquifers are comprised of the flood plains of the Mississippi, Atchafalaya, and Red Rivers. The Mississippi Alluvial Plain is in the northern part of the Mississippi Embayment, a geologic structural trough in which the underlying crust of the Earth forms a deep valley. Large rivers, such as the Mississippi, Arkansas, and Ohio Rivers, have flowed through this region, carved the surface, and deposited clay, silt, sand, and gravel, collectively called alluvium. During the past 2 million years, up to 300 ft of alluvium has filled this valley. The alluvium can be grouped into three major units: the Pleistocene Prairie Complex, Pleistocene valley trains, and the Holocene alluvium.

The Prairie Complex is older than the Pleistocene valley trains and the Holocene alluvium. It is suggested that the Prairie Complex was deposited between about 120,000 years ago and the time of the greatest extent of the last glacier, about 18,000 years ago. The Pleistocene valley trains were mostly deposited during two time periods, between about 60,000 and 25,000 years ago and during the waning phase of the latest glacial period between 18,000 and 10,000 years ago. Glacial outwash (melting) flowing from north to south provided enough energy to cause a braided stream depositional environment to form in the Lower Mississippi River Valley during this time. By about 9,000 years ago, the rate of glacial outwash in the Lower Mississippi River Valley declined, and valley train deposition ceased. The braided stream depositional process of the Pleistocene epoch was replaced by the lower energy meander stream depositional process of the Holocene epoch near major rivers, such as the Mississippi and Arkansas.

The Pleistocene valley train deposits generally have a coarser grain size than the Holocene alluvium. Also, water well drillers' logs indicate that the clay and silt layer near the surface is thicker in the Holocene alluvium, whereas the underlying sand and gravel layer (alluvial aquifer) is thicker in the Pleistocene valley train deposits (Kleiss et al, 2000).

1a. Wells located within the boundary of the Pleistocene braided stream deposits deriving water from this aquifer are <u>Class Ia</u> and can be no deeper than 250 ft.

1b. When covered with loess, wells located within the boundary of the Pleistocene braided stream deposits are <u>Class Id</u> and can be no deeper than 300 ft, because the loess is an impermeable layer, usually less than 50 ft thick.

1c. Wells located within the flood plains of the Mississippi, Atchafalaya, and Red Rivers that derive water from the Quaternary deposits of the Alluvial aquifer system are <u>Class Id</u> if the upper confining unit (flood plain deposits <12,000 years old) is <50 ft thick. This aquifer system is comprised of permeable sands and gravels. Wells are Class Ia where the upper confining unit is missing. In a few areas, the upper confining unit may be >50 ft thick, in which case the wells are Class III. However, in the current model, the thickness of upper confining unit is unknown. Therefore, all wells are currently assigned Class Id, because the river valleys typically contain flood plain deposits and therefore it is probable that shallow, thin confining units exist.

1d. In general, wells deriving water from depths greater than 300 ft are <u>Class III</u>, because greater than 50 ft of confining units are highly probable within the alluvium. The maximum depth of the Alluvial aquifer is 500 ft, based on the thickness of alluvium published in Stuart et al. (1994).

Rule 2. Chicot/Terraces aquifer system (CHIC)

The Chicot/Terraces aquifer system ranges in age from Pliocene to Holocene and is composed of deltaic sands of permeable units A and B (Renken, 1998) in central and southwestern Louisiana, and fluvial terrace deposits in the central and northern portion of the state. The thickness of this system ranges from 250 ft in the north to a maximum thickness of greater than 5000 ft in the south.

The USGS Segment 5 atlas (Renken, 1998, page F15) states:

> *"Although permeable zone A is not overlain by a regional confining unit, ground water is contained within the deeper parts of the zone under confining conditions. This is due to abundant, but discontinuous, fine-grained beds of local extent that act as confining units, but cannot be traced over an area larger than several counties. Because these local confining units combine to retard the vertical movement of ground water, water in the aquifer at depths of a few hundreds of ft is under confined conditions in most locations."*

However, the Louisiana Department of Environmental Quality (Harold Fielding, pers. comm. 2000) stated that surficial clays in southern Louisiana were once thought to be an impermeable barrier to downward movement of water from the surface. However, faulting and fracturing associated with salt domes and secondary porosity created by sub-aerial weathering after deposition have resulted in vertical leakage, primarily from the surface. Because water levels in the 500-foot sand are lowest, water moves vertically through confining units from the 200-foot toward the 500-foot sand.

Because the aquifer ranges greatly in thickness and is of a wide geographic extent, it is not practical to speculate on a depth beyond which wells cannot possibly be deriving water from the Chicot/Terrace aquifer.

2a. Wells deriving water from the Chicot/Terraces system (outcrop and subcrop) that are screened at depths less than 1,000 ft are <u>Class Ia</u>, because this system is composed primarily of permeable unconsolidated sediments of fluvial and deltaic origins.

2b. Wells deriving water from depths greater than 1,000 ft are <u>Class III</u>, because of the high probability of confining units.

Rule 3. South East Louisiana aquifer system (SOUT)

The South East Louisiana aquifer (SOUT) system consists of up to thirteen different aquifers composed of Miocene to Holocene deltaic sands overlain, in some areas, by loess and alluvial deposits. The aquifer includes permeable units A, B, C and D of the Coastal Lowlands aquifer system. These units or portions of them are also known as the Chicot Equivalent, the Jasper Equivalent and the Evangeline Equivalent aquifer systems (Renken, 1998 and USGS Report 94-4085, 1994). In the Baton Rouge area, the aquifer, or portions of it, may be referred to as a series of individual sands named according to their depth (i.e., the "400 foot sand" and "1700 foot sand"; see Fig. 47, Renken, 1998). Subcrops of this aquifer system are treated the same as outcrops.

3a. Wells less than or equal to 300 ft deep that derive water from the South East Louisiana aquifer system and are located within Pleistocene terrace and Holocene alluvium outcrops are Class Ia, because these units are highly permeable unconsolidated sediments. Wells within these outcrops that are deeper than 300 ft are Class III, because of the high probability of confining units.

3b. Wells within the loess-covered portions of the Prairie, Intermediate, and High Terraces that derive water from the aquifer at depths less than or equal to 350 ft are Class Id, because loess deposits are low permeability sediments, commonly of a thickness less than 50 ft.

3c. Wells in the loess-covered areas and deeper than 350 ft are Class III, because of the high probability of confining units. The 300 ft cut off between Class Ia and Class III is reasonable given that even the thickest of deltaic deposits (delta mouth bar sands) are rarely over 200 ft thick in any one location.

3d. Wells deeper than 4000 ft do not derive water from the SOUT aquifer. This maximum depth is derived from the isopach maps and cross sections produced by the USGS (Figs. 46, 48, 49, and 50 of Renken, 1998) as well as thickness reported in Stuart et al. (1994). Figure 50 Renken's USGS Segment 5 atlas (1998) shows that beyond all other considerations, water derived from depths greater than 4000 ft are well within a zone containing concentrations of dissolved solids above 10,000 milligrams per liter. Therefore, 4000 ft is used as a reasonable maximum depth for the SOUT aquifer.

Rule 4. Evangeline aquifer (EVAN)

The Evangeline aquifer is comprised of unnamed Pliocene sands and the Pliocene-Miocene Blounts Creek member of the Fleming formation. The Blounts Creek consists of sands, silts, and silty clays, with some gravel and lignite. The sands of the aquifer are moderately well to well sorted and fine to medium grained with interbedded coarse sand, silt, and clay. The mapped outcrop corresponds to the outcrop of the Blounts Creek member, but downdip, the aquifer thickens and includes Pliocene sand beds that do not outcrop. The confining clays of the Castor Creek member (Burkeville aquiclude) retard the movement of water between the Evangeline and the underlying Miocene aquifer systems. The Evangeline is separated in most areas from the overlying Chicot aquifer by clay beds; in some areas the clays are missing and the upper sands of the Evangeline are in direct contact with the lower sands and gravels of the Chicot.

4a. Wells deriving water from depths less than or equal to 1000 ft within the Evangeline aquifer in the western portion of the state are Class Ia, because these are unconsolidated permeable sediments.

4b. Wells deriving water from the aquifer from depths greater than 1,000 ft are Class III due to the high probability of overlying confining units.

4c. Wells deriving water from the subcrop of the aquifer at depths of less than or equal to 2,400 ft are Class III.

4d. Wells can extend no deeper than 2400 ft and still derive water from the Evangeline aquifer based on maximum reported well depths in Stuart et al. (1994).

Rule 5. Miocene aquifer (MIOC)

The Miocene aquifer is comprised of the Jasper and Catahoula aquifers of the coastal lowland aquifer system. The Miocene aquifer is confined at the top by the Castor Creek confining unit and the bottom by the Vicksburg-Jackson confining unit. The Jasper and Catahoula aquifers are separated by the Lena confining unit.

Well depths within the outcrop of the Jasper or in areas where the Jasper is covered by the Alluvial aquifer can be no greater than about 2000 ft based on cross section 49 of the Segment 5 atlas, Renken, 1998. Well depths within the subcrops of the Jasper to the south and southeast (below only the Chicot/Terrace aquifer system or Chicot/Terrace and Alluvial aquifers combined) may reach depths up to approximately 3700 ft. This is based in part on USGS cross-sections (Figs. 49 and 50 in Renken, 1998) and published maximum well depths of 3500 ft (Stuart et al., 1994) plus a 200 ft buffer to be conservative.

Wells deriving water from the Catahoula subcrop to the south may have a range of depths up to and beyond 7000 ft, based on published cross sections (Figs. 49 and 50 in Renken's, 1998).

- 5a. Wells located in the outcrop belt of the Jasper aquifer (and equivalents) or within the Alluvial aquifer that derive water from Jasper are <u>Class Ic</u> if the depths are less than or equal to 1,000 ft.
- 5b. Wells located in the outcrop belt of the Catahoula (OGc) or within the Alluvial aquifer that derive water from the Catahoula are <u>Class Ic</u> if the water source is at depths less than or equal to 500 ft. Class Ic is used because these units are semi-consolidated.
- 5c. Wells located in areas where the Catahoula is covered with loess (OGc-l), deriving water from depths less than or equal to 550 ft are <u>Class Id</u>, because the loess is a layer of low permeability generally less than 50 ft thick.
- 5d. In all areas of the Catahoula outcrop (OGc, OGc-l), if a well derives water from either aquifer at depths greater than 500 ft (or 550 ft for areas covered with loess) it is unknown, because the maximum depth at which wells can be reliably said to derive water from the Catahoula in outcrop or where covered by only the Alluvial aquifer is 500 ft, based on a maximum thickness published in USGS Report 94-4085 (1994) of 450 ft, plus a 50 ft buffer.
- 5e. Wells within the Jasper or Catahoula outcrop belt with depths greater than 1,000 ft deep and less than 2000 ft are <u>Class III</u>, because of the presence of confining units. Well depths within the outcrop of the Jasper or in areas where the Jasper is covered by the Alluvial aquifer can be no greater than about 2000 ft based on cross section 49 of the Segment 5 atlas, Renken, 1998.
- 5f. Wells deriving water from the subcrop of the Jasper or Catahoula at depths of less than or equal to 3700 ft are <u>Class III</u>. If a well derives water from these subcrops at depths greater than 3700 ft, the classification is unknown.

Rule 6. Cockfield Formation (COCK)

The Eocene Cockfield Formation consists of sands, silts, and shales and minor amounts of lignite, bentonite, gypsum, and limestone. Individual sand units are extremely variable in thickness and permeability. The main source of fresh water from the Cockfield Formation is from areas with well-developed channel sand deposits, characteristic of deltaic and fluvial plain areas.

6a. Wells located in and deriving water from the outcrop or subcrop belt of the Cockfield Formation (also known as the upper Claiborne aquifer of the Mississippi embayment aquifer system) at depths less than or equal to 600 ft are <u>Class Ic</u>, because this aquifer is semi-consolidated sandstone.

6b. Wells in the Cockfield outcrop belt cannot exceed 600 ft total depth. This is based on a published thickness range for the Cockfield (Stuart et al., 1994).

6c. Wells deriving water from the subcrop belt of the Cockfield Formation and covered by impermeable loess or alluvium are <u>Class Id</u>.

6d. Wells deriving water from the Cockfield subcrop at depths greater than 600 ft are <u>Class III</u>.

6e. Wells deriving water from the Cockfield subcrop should not exceed 2000 ft in depth based on USGS cross sections (Fig. 68 in Renken, 1998) and published well depths (Stuart et al., 1994).

Rule 7. Sparta Sand (SPAR)

The Sparta Sand Formation makes up most of the Middle Claiborne Group, a hydrogeologic unit of the Mississippi Embayment. The sands were laid down as part of the ancient Gulf of Mexico beach system. The Sparta Sand consists of fine to medium sand interbedded with coarse sand, silty clay and lignite. The sands become (thicker) with depth of the aquifer. On both the west and east sides of the Mississippi embayment, the Sparta aquifer is exposed at the surface (outcrops) and is locally unconfined; it becomes confined as it dips toward the axis of the embayment, (generally corresponding with the Mississippi River) and southward toward the Gulf of Mexico where it is deeply buried in the subsurface (McKee and Hays, 2002). In north Louisiana, the Cane River Formation, predominantly marine clay, underlies the aquifer, and the Cook Mountain Formation overlies it. These confining units are composed of clay, mud, marl, and shale. For most of the Sparta aquifer in Louisiana, the altitude of the top ranges from 200 ft above sea level (recharge area) to 300 ft below sea level (freshwater/saltwater interface). The altitude of the base ranges from 150 ft above sea level (recharge area) to 1000 ft below sea level (freshwater/saltwater interface). The otherwise relatively smooth base is interrupted in places by domes created by intrusion of buried salt formations pushing overlying geological units upward. The thickness of the aquifer ranges from 50 ft (recharge area) to 500 ft (adjacent to recharge area), increasing to 700 ft (freshwater/saltwater interface).

7a. Wells located in the outcrop belt of the Sparta Sand or that occupy an arcuate band across the northwest part of the state, that derive water from this unit are <u>Class Ic</u> if the water source is less than or equal to 500 ft deep, because the producing horizons are semi-consolidated sandstones. Wells within the Sparta sandstone outcrop belt and deriving water from it may not exceed 500 ft in depth, based on USGS isopach maps (Fig. 71 in Renken, 1998).

7b. Wells deriving water from the subcrop are Class III, because the middle Claiborne aquifer is typically confined at top and bottom. These wells may have a range of depths depending on the cover type, described as follows. In areas covered by the Alluvial aquifer, the maximum depth is 1000 ft, based on an average Sparta sand thickness of 1000 ft (Fig. 71 in Renken, 1998). In areas with Chicot/Terrace material (in the northern portion of the state), the maximum depth of a well deriving water from the Sparta sandstone is 1250 ft, based on an average Sparta sand thickness of 900 ft (Fig. 71 in Renken, 1998), 250 ft of terrace alluvium, and 100 extra ft to be conservative. In areas with overlying Cockfield and Cook Mountain, the maximum well depth may be as much as 2500 ft, based on the cross section shown in Fig. 68 in Renken (1998).

Rule 8. Carrizo-Wilcox aquifer (CARR)

The Eocene Carrizo-Wilcox aquifer system consists of the Carrizo Sand of the Eocene Claiborne group and the undifferentiated Wilcox group of Eocene and Paleocene age. The Wilcox deposits, outcropping in northwestern Louisiana, are the oldest deposits in the state containing fresh water. The Carrizo is discontinuous and consists of well-sorted, fine to medium grained, crossbedded sands, with some silt and lignite. Well yields are restricted because the sand beds are typically thin, lenticular and fine textured. The system is confined downdip by the clays and silty clays of the overlying Cane River formation and the regionally confining clays of the underlying Midway group.

The maximum depths of occurrence of fresh water in the Carrizo-Wilcox range from 200 ft above sea level to 1,100 ft below sea level. The range of thickness of the fresh water interval in the Carrizo-Wilcox is 50 to 850 ft.

8a. Wells located in the outcrop or subcrop of the Carrizo-Wilcox aquifer that derive water from these units are Class Ic if the water source is less than or equal to 850 ft deep, because the producing horizons are semi-consolidated sandstones. Wells deriving water from the Carrizo-Wilcox system, in the outcrop belt, may not be deeper than 850 ft, based on aquifer thickness (Stuart et al., 1994).

8b. Wells deriving water from the subcrop belt of the Carrizo-Wilcox aquifer and covered by impermeable loess or alluvium are Class Id.

8c. Wells located in the geologic boundary of either the Cook Mountain Formation (Eocene; Middle Claiborne confining unit; EOcm) or the Cane River Formation (Eocene; Lower Claiborne confining unit; EOcr) that derive water from the subcrop of the Carrizo-Wilcox are Class III, because these formations are confining units. Wells deriving usable water from the subcrop of the Carrizo-Wilcox may not be deeper than 3700, based on the cross section shown in Fig. 68 in Renken (1998).

Metadata Sources References

Harold Fielding, pers. comm. 2000.

Kleiss, B.A., R.H. Coupe, G.J. Gonthier, and B.J. Justus. 2000. Water Quality in the Mississippi Embayment, Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky, 1995–98: U.S. Geological Survey Circular 1208, 36 pp.

McKee, P.W. and P.D. Hays. 2002. The Sparta Aquifer: A sustainable water resource? U.S. Geological Survey Fact Sheet FS-111-02, 4 pp.

Stuart, C.G., D.D. Knochenmus, and B.D. Mcgee. 1994. Guide to Louisiana's ground-water resources. Survey, U.S.G. and USGS Earth Science Information Center, O.F.R.S., 94-4085. pp.

Renken, R.A. 1998. Ground water atlas of the United States: Segment 5, Arkansas, Louisiana, Mississippi. Hydrologic Investigations Atlas 730-F, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Maine

12 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-M (Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Well location
2. Well total depth
3. Pump rate
4. Bedrock geology
5. Surficial geology
6. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology, surficial geology, and the USGS Hydrologic Investigations Atlas 730-M, Segment 12 Atlas (Olcott, 1995) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are three principal aquifers in the state of Maine:

1. Alluvial and Glacial Outwash
2. Paleozoic Carbonate
3. Crystalline

* The Alluvial and Glacial Outwash aquifer was constructed using the "CODE" field in the SGEO feature class and is a combination of both glacial and fluvial deposition.

The aquifer features were constructed from the bedrock geology features (BGEO) and the surficial geology (SGEO).

Rule 1. Alluvial and Glacial Outwash aquifer (GLAC)

The unconsolidated sediments of the Alluvial and Glacial Outwash aquifer are present throughout the glacial carved valleys of Maine. The aquifer predominantly consists of sand and gravel from glacial deposition and modern alluvial deposition. The aquifer ranges in thickness from less than 50 ft to more than 150 ft. The Alluvial and Glacial Outwash Aquifer is predominantly used in the glacial valleys throughout the state where surface resources do not yield enough water to sustain local populations. The aquifer is generally unconfined and is underlain by the Paleozoic Carbonate aquifer predominantly in the far northeast corner of Maine, and the Crystalline aquifer throughout the remainder of the state.

1a. Wells located within the Alluvial and Outwash aquifer outcrop (GLAC), with well depths less than or equal to 150 ft are Class Ia because these unconsolidated sand gravel deposits are predominantly under unconfined conditions.

1b. Wells located within the Alluvial and Outwash aquifer outcrop (GLAC), located in the Paleozoic Carbonate aquifer subcrop with depths greater than 150 ft are Class Ib because the wells are likely sourcing carbonate, potentially cavernous rock.

1c. Wells located within the Alluvial and Outwash aquifer outcrop (GLAC), located in the Crystalline aquifer subcrop with well depths greater than 150 ft with pump rates less than or equal to 50 gpm are Class IIb because they are unconfined, consolidated and lower yield.

1d. Wells located within the Alluvial and Outwash aquifer outcrop (GLAC), located in the Crystalline aquifer subcrop with well depths greater than 150 ft with pump rates greater than 50 gpm are Class IIa because they are unconfined, consolidated and higher yield.

Rule 2. Paleozoic Carbonate aquifer (CARB)

The consolidated carbonate rocks of the Paleozoic Carbonate aquifer outcrop predominantly in the northeast corner of Maine and in northeast trending bands across the state. These are comprised mostly of limestone and dolomite and are Pre-Cambrian to Silurian in age. The deformation of these carbonate beds has caused parting along bedding planes and has created joints, fractures and faults which are the major water yielding openings in the rock. The Paleozoic Carbonate aquifer is bound on the east and west by low to medium-grade metaphoric rocks. The aquifer is generally unconfined in the upper 200 ft.

2a. Wells located within the Paleozoic Carbonate aquifer outcrop (CARB) are Class Ib because these wells derive water from rocks that are soluble and fractured.

Rule 3. Crystalline aquifer (CRYS)

The consolidated crystalline rocks of the Crystalline Aquifer system are found throughout most of the state of Maine. The rocks are comprised of mostly granite, schist, gneiss, and quartzite, and are Pre-Cambrian to Jurassic in age. The Crystalline Aquifer primarily moves through secondary openings such as joints, fractures, and bedding or cleavage planes. These openings decrease with depth therefore most wells are drilled no deeper than 600 ft. The volume water stored in these fractures is generally small therefore an average yield of only a few gallons per minute is common in wells sourcing the Crystalline aquifer.

3a. Wells located within the Crystalline aquifer outcrop (CRYS) with pump rates less than or equal to 50 gpm are Class IIb because they are unconfined, consolidated and lower yield.

3b. Wells located within the Crystalline aquifer outcrop (CRYS) with pump rates greater than 50 gpm are Class IIa because they are unconfined, consolidated and higher yield.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Maryland

4 January 2019

Introduction

The rules below are based primarily on information published in the USGS Ground Water Atlas of the United States, Segment 11, Hydrologic Investigations Atlas 730-L (Trapp and Horn, 1997) and the previously published DW USA reports (RSPA, 2002). The Geologic map of Maryland (Cleaves et al., 1968), published by the Maryland Geological Survey, was also used in the classification work. The data available for Maryland included:

1. Well location
2. Bedrock geology

If source-aquifer data become available, well classifications could change. The following aquifers of Maryland were distinguished for this work:

1. Surficial
2. Northern Atlantic Coastal Plain
3. Sandstone
4. Carbonate rock
5. Crystalline rock

Rule 1. Surficial aquifers (SURF)

The surficial sediments are Quaternary in age and are grouped in four categories: upland deposits on the eastern coast and western coast, lowland deposits and a group of undifferentiated sediments. The upland sediments are cross-bedded, poorly sorted gravels and sands that contain silt and clay as well as boulders at their base. Their thickness is reported to be 0-90 ft (locally thicker in paleochannels) on the eastern shore and 0-50 ft on the western shore (Cleaves et al., 1968). The lowland deposits are composed of gravel, sand, silt and clay with estuarine and marine fauna in some areas. Their thickness is between 0-150 ft. The undifferentiated sediments are sand, gravel, lignitic silt and clay, with some boulders. The facies of these sediments vary through intercalated fluvial sands and marsh muds, dune sands, estuarine clays and silts, beach zone sands, and incised fluvial sands (Cleaves et al., 1968). This group of undifferentiated sediments is located in the southeastern portion of the state, from Dorchester county southward.

1. Wells located within and deriving water from the surficial aquifers are Class Ia, because these sediments are unconsolidated and highly permeable.

Rule 2. Northern Atlantic Coastal Plain aquifers (NACP)

The oldest member of the Coastal Plain sediments is the Potomac Formation of Cretaceous age. During this time, streams transported variegated clays and sand from the ancestral Appalachians. This process continued until late Cretaceous time and built a wedge of fluvial sediments. The Potomac Formation is overlain by the Magothy Formation (part of Severn-Magothy aquifer), which represents a transition from the non-marine to marine deposits. The Magothy is composed of white sands and lignitic black silts. Following the Magothy deposition, the sea encroached upon the land and a sequence of marine sediments was deposited: the Matawan and Monmouth Formations of the Severn-Magothy aquifer of late Cretaceous age and the Castle Hayne-Aquia aquifer of Paleocene-Eocene age. The Matawan and Monmouth Formations are composed of mostly dark gray, glauconitic fine-grained sand and silt. The Castle Hayne-Aquia aquifer is dark green to gray, well sorted fine to medium-grained sands, with some clay members and phosphatic pebbles.

The marine series is truncated by erosion and no Oligocene strata are present. During the Miocene, the marine sedimentation returned in the area of coastal Maryland and the Chesapeake aquifer sediments were deposited in a marine to fluvial environment. Interbedded fine-grained sands and silts are common, and locally, calcareous sandstone and gravel also occur.

The Potomac aquifer has two main water producing horizons, the Patuxent Formation and the overlying Patapsco Formation. According to the USGS Atlas, the Patuxent is confined by a 50-300 ft clayey unit. The bedrock geology coverage has only one unit (Kp) for the Potomac aquifer, therefore no distinction can be made between these two water-bearing units on the map.

2. Wells located within the Northern Atlantic Coastal Plain aquifers are Class Ia, because these aquifers consist of unconsolidated sand units.

Rule 3. Sandstone aquifers (SAND)

The sandstone aquifers include the low-yield sandstone units of the Triassic; the Paleozoic, water-yielding, sedimentary formations of the Valley and Ridge Physiographic Province; and the Paleozoic sandstones of the Appalachian Plateaus. This aquifer system also includes Devonian siltstone, shale and thin-bedded sandstones that locally yield sufficient water for domestic and commercial supplies, especially where the rocks are fractured.

3. Wells located within the consolidated sandstone aquifers are Class IIa.

Rule 4. Carbonate rock aquifers (CARB)

Limestone, dolomite, and marble of Paleozoic and Precambrian age form carbonate rock aquifers in western Maryland in the Appalachian Plateaus, Piedmont and Blue Ridge, and Valley and Ridge aquifer regions. Although these carbonate rocks are of small extent, they are significant local sources of water.

4. Because of the potential for high permeability associated with fracture and solution porosity, all wells in the carbonate rock aquifers are Class Ib.

Rule 5. Crystalline rock aquifers (CRYS)

The crystalline rocks are Precambrian, Cambrian, and Ordovician coarse-grained gneisses and schists of various mineral composition; however, fine-grained rocks, such as phyllite and metamorphosed volcanic rocks, are common in places. Most of the metamorphic rocks were originally sediments; some, however, were igneous rocks or volcanic tuff, ash, and lava flows.

Triassic intrusives (diabase sills and dikes) are also included in the crystalline rock aquifers. The crystalline rock aquifers consist of dense and almost impermeable bedrock that yields water primarily from secondary porosity and permeability provided by fractures.

5. Wells located within the crystalline rock aquifers are Class IIb, because these rocks have low porosity with wells yielding typically less than 50 gpm.

Sole source Aquifers

Maryland contains two EPA-designated sole source aquifers: the Maryland Piedmont aquifer (Montgomery, Howard, and Carroll Counties); and the Poolesville Area aquifer extension of the Maryland Piedmont aquifer. Both of these sole source aquifers are contained within the coverage of one of the larger principal aquifers described above and are not differentiated. Inclusion of the sole source aquifers within the larger principal aquifers of Maryland does not affect the Pettyjohn classification of wells within the sole source aquifers.

Metadata Sources References

Cleaves, E.T., J. Edwards, and J.D. Glaser. 1968. Geologic Map of Maryland: Maryland Geological Survey. Baltimore, Maryland, scale, 1(250,000).

Trapp, Jr., H. and M.A. Horn. 1997. Ground water atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. Hydrologic Investigations Atlas 730-L, U.S. Geological Survey, Reston, VA, 32 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Massachusetts

18 May 2018

Introduction

The rules set below is based primarily on the surface geology coverage and information of the USGS Ground Water Atlas of the United States, Segment 12, Hydrologic Investigations Atlas 730-M (Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The data available for Massachusetts included:

1. Well location
2. Surface geology
3. Bedrock geology
4. Well lithology

Overview

The surface geology coverage includes the following units: End moraines; fine-grained deposits; floodplain alluvium; large sand deposits; sand and gravel deposits; sandy till over sand; till or bedrock.

Four aquifers have been grouped from these geologic units:

1. Glacial permeable aquifer (large sand deposits, sand and gravel deposits and sandy till over sand);
2. Glacial confining aquifer (end moraines and fine-grained deposits);
3. Alluvial (floodplain alluvium);
4. Till or bedrock.

According to the USGS Atlas, three main bedrock aquifers occur in Massachusetts. These are carbonate rocks along the western boundary of the state, Triassic rift graben fill in the middle, and crystalline bedrock which underlies the rest of the state. Carbonate rock aquifers are present in the Housatonic River Valley and are composed of limestone, dolomite, and marble of the Cambrian and Ordovician ages and some limestones of the Precambrian age. These rocks have fractures, fissures and dissolution cavities that allow rapid water transport. As a result they would have a classification of Ib. Sedimentary rocks that are primarily sandstone of the Mesozoic age are present along the Connecticut River valley in central Massachusetts and in eastern Massachusetts, south of Boston. These are porous rocks and can yield significant amounts of water. The aquifer would have a classification of IIa. With the exception of Cape Cod and Martha's Vineyard the remainder of the state is covered by crystalline rock aquifers. These are low yield aquifers composed mostly of igneous or metamorphic rock. Movement of water through the rocks is totally dependent on the presence of secondary openings (Factures, faults, fissures, etc.). Intergranular porosity is so small as to be insignificant. Therefore, these aquifers would be classified as IIb. The till cover may contain permeable layers, or it can be totally impermeable. Depending on the thickness of the till, the underlying aquifers can be confined, partially confined or unconfined. Some of the wells have source information identifying whether it is sourcing bedrock, confined, semiconfined, or unconfined aquifers. When available this information will be used to help classify the well. When not available it is assumed that the well is sourcing the surficial geology and will be classified according to the features of that geology.

Rule 1. Glacial permeable aquifer (PERM)

Glacial permeable aquifers are composed of coarse-grained sand and gravel deposit. These are typically valley fill aquifers. It also includes the low preglacial topography at the terminus of the glaciers on Cape Cod. The glacial deposits there are as much as 1000 ft thick. The valley fill deposits are created by the meltwater streams draining away from glacial ice.

1a. Wells located in the Glacial permeable aquifer (PERM) that have a lithology of unconfined (UNCNF) or unknown (UNK) are Class Ia, because these wells are likely sourcing unconsolidated and highly permeable sediments.

1b. Wells located in the Glacial permeable aquifer (PERM) that have a lithology of semiconfined (SMCNF) are Class Id, because the source is in unconsolidated and highly permeable sediments that are partially confined.

1c. Wells located in the Glacial permeable aquifer (PERM) that have a lithology of confined (CNF) are Class III, because these are unconsolidated and highly permeable sediments that are completely confined.

1d. Wells located in the Glacial permeable aquifer (PERM) that have a lithology of bedrock (BDR) are Class Ib if they fall within the bedrock geology (BGEO_DESC) of Carbonate Rocks, because they likely source fractured and soluble bedrock aquifers. And the overlying aquifers are in hydraulic continuity with the bedrock aquifer.

1e. Wells located in the Glacial permeable aquifer (PERM) that have a lithology of bedrock (BDR) are Class IIa, if they fall within the BGEO_DESC of Basin Sedimentary because they likely source permeable consolidated sedimentary rock. The overlying aquifers are in hydraulic continuity with the bedrock aquifer.

1f. Wells located in the Glacial permeable aquifer (PERM) that have a lithology of bedrock (BDR) are Class IIb if they fall within the BGEO_DESC of Crystalline Rocks because they likely source a low yield crystalline bedrock aquifer. The overlying aquifers are in hydraulic continuity with the bedrock aquifer.

1g. Wells located in the Glacial permeable aquifer (PERM) that have a lithology of bedrock (BDR) are Class Ia if they fall within the BGEO_DESC of Unconsolidated Sediments, because they are part of the glacial permeable aquifer.

Rule 2. Glacial confining aquifer (CONF)

In valleys that either drained toward the glacial ice or in valleys that drained away from the glacial ice and were dammed by sediments, large lakes formed. Sediments deposited in the lakes were primarily silt, clay, and very fine sand. Along parts of Cape Cod and Martha's Vineyard, the glaciers depressed the land surface and large areas were inundated by the ocean and marine clay and silt were deposited over till. Since this was the southern extent of the last glacial period there are also areas of till from terminal moraines.

2a. Wells that derive water from the Glacial confining aquifer (CONF) and have a lithology of unconfined (UNCNF), semiconfined (SMCNF), or unknown (UNK) are Class Id, because these are unconsolidated and low permeable sediments of unknown thickness.

2b. Wells that derive water from the Glacial confining aquifer (CONF) and have a lithology of confined (CNF) are Class III, because they source unconsolidated and low permeable sediments that are completely confined.

Rule 3 Alluvial aquifer (ALLU)

After the glaciers retreated the land rebounded, base level was lowered and the streams began eroding the glacial deposits. The streams and rivers are now depositing alluvium that consists of reworked glacial material. These reworked coarse-grained outwash, ice-contact and alluvial deposits form productive surficial aquifer systems.

3a. Wells that derive water from the Alluvial aquifer (ALLU) and have a lithology of unconfined (UNCNF) or unknown (UNK) are Class Ia, because a large part of the alluvial sediments can be permeable.

3b. Wells that derive water from the Alluvial aquifer (ALLU) and have a lithology of semiconfined (SMCNF) are Class Id, because the alluvial sediments contain layers of low permeability fine grained sediments partially confining the source.

3c. Wells that derive water from the Alluvial aquifer (ALLU) and have a lithology of confined (CNF) are Class III, because the alluvial sediments contain layers of low permeability fine grained sediments confining the source.

3d. Wells located in the Alluvial aquifer (ALLU) that have a lithology of bedrock (BDR) are Class IIa, if they fall within the BGEO_DESC of Basin Sedimentary because they source permeable consolidated sedimentary rock. The overlying aquifers are in hydraulic continuity with the bedrock aquifer.

3e. Wells located in the Alluvial aquifer (ALLU) that have a lithology of bedrock (BDR) are Class IIb if they fall within the BGEO_DESC of Crystalline Rocks because they source a low yield crystalline bedrock aquifer. The overlying aquifers are in hydraulic continuity with the bedrock aquifer.

Rule 4. Till and bedrock aquifer (TILL)

The till sediments were plastered to the deeply eroded and glacially scoured bedrock surface under the advancing glacier. As the ice melted, the till generally remained in place, which left a relatively continuous sheet over the bedrock. Till yields little water because it is generally unsorted and unstratified and contains a large amount of fine-grained material.

4a. Wells that derive water from the Till and bedrock aquifer (TILL) and have a lithology of unconfined (UNCNF), semiconfined (SMCNF), or unknown (UNK) are Class Id, because these are unconsolidated and low permeable sediments of unknown thickness.

4b. Wells that derive water from the Till and bedrock aquifer (TILL) and have a lithology of confined (CNF) are Class III, because they are sourcing unconsolidated and low permeable sediments below a confining unit.

4c. Wells located in the Till and bedrock aquifer (TILL) that have a lithology of bedrock (BDR) are Class Id if they fall within the BGEO_DESC of Carbonate Rocks, because they source fractured and soluble bedrock aquifers. The overlying aquifer is an unconsolidated confining unit of unknown thickness.

4d. Wells located in the Till and bedrock aquifer (TILL) that have a lithology of bedrock (BDR) are Class IIc, if they fall within the BGEO_DESC of Basin Sedimentary because they are permeable consolidated sedimentary rock The overlying aquifers contain confining units of unknown thickness, so they are treated as if it was less than 50 ft.

4e. Wells located in the Till and bedrock aquifer (TILL) that have a lithology of bedrock (BDR) are Class IIc, if they fall within the BGEO_DESC of Crystalline Rocks, because they are a low yield crystalline bedrock aquifer. The overlying aquifers contain confining units of unknown thickness, so they are treated as if it was less than 50 ft.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Michigan

6 April 2018

Introduction

The guidelines for well classification outlined below are based primarily on information from the USGS Hydrologic Investigations Atlas 730-J, by Perry G. Olcott (1992), Digital maps of the Quaternary Geology of Michigan by Farrand and Bell (1982), bedrock geology maps by R.C. Reed and J. Daniels (1987), a revised stratigraphic column produced by the Michigan Department of Environmental Quality (Catacosinos et al., 2000) and the previously published DW USA reports (RSPA, 2002). Digital data available included:

1. Wells: location, casing depth, well depth
2. Surficial geology (digital version of Farrand and Bell, 1982)
3. Bedrock geology (digital version of Reed and Daniels, 1987)

The rules outlined here were designed to be used with an aquifer coverage constructed by PHMSA from the available digital geology maps. When no screen or case depth information is available in the well database, it is assumed that water is derived from the bottom half of the well and all depths are doubled.

The following aquifers of Michigan were distinguished for this work:

1. Permeable surficial region
2. Confining surficial region
3. Carbonate bedrock
4. Sandstone bedrock
5. Crystalline bedrock
6. Not a principal aquifer

Rule 1. Permeable surficial region (PERM)

The portion of the aquifer coverage labeled "PERM" or permeable surficial consists of sandy, generally stratified deposits of fluvial, lacustrine, eolian, and glacial-fluvial origins. The sediments are no older than the Pliocene; predominantly they are Pleistocene to Holocene in age. All sediments are unconsolidated. As noted on page J9 of the USGS atlas, Michigan's surficial aquifer system is by far the most widespread in the state and one of the most heavily used sources of groundwater. Wells completed within the permeable portion of the surficial aquifer system may produce at rates of 500 gallons per minute (gpm) or more (Olcott, 1992).

According to Farrand and Bell (1982), individual units of dune sand, lacustrine sands and gravels, and outwash deposits rarely exceed 30 meters (approx. 100 ft) in thickness. Whereas individual deposits may rarely exceed 100 ft in thickness, stacking of multiple generations of deposition brought about by numerous glacial stages has undoubtedly resulted in a complex stratigraphy, the thickness of which remains generalized and largely unknown. Permeable units may be deposited atop older, impermeable tills; therefore, the thicknesses reported for individual units by Farrand and Bell (1982) do not necessarily indicate the depth at which bedrock would be encountered.

Figure 30 of the USGS atlas shows a large region in the northern Lower Peninsula with thickness of glacial cover over 400 ft.

1a. Wells located within the PERM region are Class Ia if the screen or casing depth is shallower than 100 ft. This depth comes from the potential for a 100 ft thick section of permeable material. If only well depth is available then all of the depth values are doubled, assuming that water is being sourced from the bottom half of the well.

1b. Wells with screen or casing depths between 100 and 200 are Class Id. Till likely contains pockets of sands and gravels, therefore, the 200 ft cut-off is used. Conservatively, this means the sandy interval may not be covered with over 50 ft of impermeable material, hence the Id classification. If only well depth is available then all of the depth values are doubled, assuming that water is being sourced from the bottom half of the well.

1c. Wells screens or casings deeper than 200 ft are Class III, because it is more than likely they derive water from a confined source (bedrock or unconsolidated). If only well depth is available then all of the depth values are doubled, assuming that water is being sourced from the bottom half of the well.

Rule 2. Confining surficial region (CONF)

The portion of the aquifer coverage labeled “CONF” or confining surficial consists of tills, end moraines, lacustrine silts and clays, and regions of peat and muck. Just as with the permeable region, the sediments of the confining region are unconsolidated and relatively young (no older than Pliocene). However, all of the units that make up the region are dominantly fine-grained material with little porosity, or are such chaotic, unstratified deposits that conductivity is quite low. Tills are unstratified deposits, rich in clays and riddled with small pockets of sand and gravel as well as boulders throughout. Wells completed in tills are typically low producers, with yields of 1 to 10 gpm (Olcott, 1992). Lacustrine silts and clays and peat/muck areas are likely to be stratified deposits, but extremely small grain sizes results in minimal porosity and their confining character.

2a. Wells with screens or casings that are deeper than 100 ft in locations where tills are thin (<30 ft, THICK_GLAC = 1.) will be classed according to the underlying bedrock covered by a thin impermeable layer. Wells located in carbonate areas (formations BHD, BBF, BBG, ENG, MQG, MND, MAC, PAC, STF, TMP, TRN) are Class Id, because there is < 50 ft of impermeable material over them. If only well depth is available then all of the depth values are doubled, assuming that water is being sourced from the bottom half of the well.

2b. All other wells with screen or casings deeper than 100 ft in thin till areas are Class IIc. If only well depth is available then all of the depth values are doubled, assuming that water is being sourced from the bottom half of the well.

2c. Wells within the CONF region screen or casing depths greater than 100 ft are Class III. These wells are considered to be deriving water from a confined source (the well is screened beneath at least 50 ft of confining material), be it bedrock or unconsolidated sediment within the till. If only well depth is available then all of the depth values are doubled, assuming that water is being sourced from the bottom half of the well.

2d. Wells located within the CONF region are Class Id if screen or casing is 100 ft deep or shallower. The 100 ft depth cut-off is a conservative estimate of the depth at which groundwater can be confined. A thickness of 50 ft of till is likely to include small pockets of permeable material (and hence, does not constitute 50 ft if impermeable material). Therefore, the number is doubled, based on the assumption that 100 ft of till is comprised of at least 50 ft of clay. If only well depth is available then all of the depth values are doubled, assuming that water is being sourced from the bottom half of the well.

Rule 3. Carbonate bedrock aquifer (CARB)

The carbonate units that make up this aquifer range in age from Cambrian to Devonian and occur on the perimeter of the Michigan Basin, cropping out mainly in the southeastern Upper Peninsula. Michigan also has an extensive Mississippian-aged carbonate aquifer in the central Lower Peninsula, but it is totally covered by glacial sediments (both permeable and confining) and is therefore not shown in our aquifer coverage. In general, the units of the carbonate aquifer dip and thicken toward the center of the basin, which is roughly the center of the Lower Peninsula. Silurian and Devonian carbonates reach thicknesses of 500 ft at their downdip limit but are generally no thicker than 200 ft in outcrop (Olcott, 1992). Cambrian and Ordovician carbonates have a combined maximum thickness of about 250 ft in the USGS atlas, the carbonates make up portions of two separate aquifers: the Cambrian/Ordovician aquifer system, and the Silurian/Devonian aquifer. However, because relatively little of the rock is exposed at the land surface and for the sake of simplicity, all carbonates are grouped into one aquifer region. This is also more consistent with the aquifer coverages provided for the state of Wisconsin.

3. Wells located within the CARB region are Class Ib. Carbonate units are highly vulnerable to surface contaminants due to the potential for high porosity resulting from dissolution and karst features. After examining the total depth of the wells within the carbonate aquifers, it was determined that all wells were potentially screened in these units, making any depth cut-off changes in classification unnecessary.

Rule 4. Sandstone bedrock aquifer (SAND)

The terrigenous clastic units that make up this aquifer are of Cambrian to Pre-Cambrian age and are found only in the Upper Peninsula of the state. Michigan has an extensive Pennsylvanian age sandstone aquifer in the central Lower Peninsula, but it is totally covered by glacial sediments (both permeable and confining) and is therefore not shown in our aquifer coverage. As with the carbonate aquifer, all the clastic units cropping out in the Upper Peninsula have been grouped into a single aquifer for simplicity. In the USGS atlas, the units we've grouped are split into two to three aquifers: The Jacobsville Sandstone and portions of the Ironton-Galesville and Mount Simon aquifers. All units are highly consolidated, well cemented, and with low permeability. The thickness of the units of the Munising Formation may reach as much as 150 ft, whereas the Jacobsville Sandstone reaches thickness of 1000 ft along the shores of Lake Superior (Olcott, 1992).

4. Wells located within the SAND region are Class IIb, because they derive water from low-yield sandstone aquifers. After examining total well depth, it was determined that all wells were screened in the sandstone units, making any changes in classification at depth

unnecessary. It is possible that wells within the Jacobsville Sandstone derive water from confined aquifers at depth; however, given the cross sections available and the non-USA status of the wells, the issue was not pursued.

Rule 5. Crystalline bedrock aquifer (CRYS)

The crystalline bedrock aquifer consists of a range of intrusive igneous units, Pre-Cambrian volcanics, and metamorphic rocks throughout the Upper Peninsula. These units have extremely low yields and are a source of groundwater only where no other is available.

5. Wells located within the CRYS region are <u>Class IIb</u>, because they derive water from low-yield units, relatively impermeable crystalline bedrock.

Rule 6. Not A principle aquifer region (NAPA)

The "not a principle aquifer" (NAPA) region is comprised of any outcropping units consisting primarily of shale. These units range in age from Pre-Cambrian to Silurian and occur only in the Upper Peninsula. The Pre-Cambrian Nonesuch Formation is described by Catacosinos et al. (2000) as sandy shale and is presumably a low yield unit. The rest of the units included in the NAPA region make up portions of the Maquoketa confining unit. Included in this region are the Cabot Head, Collingwood, Queenston, and Utica Shales. While the Collingwood Shale is more or less pure shale, the Queenston, Cabot Head, and Utica Shales include significant amounts of interbedded dolomite and limestone. According to the USGS atlas, there is potential that carbonate may be exposed at the surface or thinly covered by shale (see description of Maquoketa Confining unit, Pg. 22). However, because the dolomite is still regarded as at least partially confining, these units were not grouped with the Carbonate aquifer. Still, the presence of thinly covered carbonates in the cases of the Queenston and Utica units is acknowledged, as reflected in the classifications below:

6a. Wells located within the Collingwood shale (CSM text code in the bedrock coverage) are <u>Class IIc</u> if it has screen or casing depths shallower than 100 ft depths greater than 100 ft are <u>Class III</u>. <u>Class IIc</u> is used because it is possible that a well may derive water from permeable lenses of sandstone within the shales. The rationale for the 100 ft cut-off is similar to that outlined previously in the discussion of the CONF region (Rule 2). If only well depth is available then all of the depth values are doubled, assuming the water is being sourced from the bottom half of the well.

6b. Wells located within the Cabot Head, Queenston, and Utica Shales (bedrock text codes CHS, QUS, USM, respectively) are conservatively labeled <u>Class Id</u> if screen or casing depth is 100 ft or shallower. It is possible that such wells could derive water from a carbonate aquifer covered by less than 50 ft of confining material. Wells deeper than 100 ft are <u>Class III</u>, confined. If only well depth is available then all of the depth values are doubled, assuming the water is being sourced from the bottom half of the well.

6c. Wells located within the Nonesuch Formation (NSF text code in the bedrock coverage) are <u>Class IIb</u>, because this sandy shale may be a low-yield aquifer.

Metadata Sources References

Catacosinos, P.A., W.B. Harrison, III, R.F. Reynolds, D.B. Westjohn, and M.S. Wollensack. 2000. Stratigraphic nomenclature for Michigan: Michigan Department of Environmental Quality, Geological Survey Division, 1 sheet.

Farrand, W.R. and D.L. Bell. 1982. Quaternary geology of Michigan. Department of Natural Resources.

Olcott, P.G. 1992. Ground water atlas of the United States: Segment 9, Iowa, Michigan, Minnesota, Wisconsin. Hydrologic Investigations Atlas 730-J, U.S. Geological Survey, Reston, VA, 33 pp.

Reed, R.C. and J. Daniels. 1987. Bedrock Geology of Northern Michigan, State of Michigan DNR Geological Survey Division, scale 1:500,000.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Minnesota

13 February 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-J (also called Ground Water Atlas of the United States, Segment 9; Olcott, 1992) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Casing depth
4. Screen depth
5. Source aquifer
6. Surficial geology
7. Aquifer boundaries

The aquifer coverage for Minnesota was produced from bedrock geology received from the state, and glacial sediment extents (Soller, 1992), using the Segment 9 Atlas (Olcott, 1992) as a guide. Glacial sediment permeability and thickness are recorded in THICK_SGEO according to the following coding scheme. THICK_SGEO codes are a two character alpha-numeric combination where the first letter indicates permeability (P – permeable, C – non-permeable), and the single digit number, which appears last, indicates the sedimentary thickness (0 – no sedimentary cover, 1 – 0-50 ft, 2 – 50-100 ft, 3 – 100-200 ft, 4 – 200-400 ft, 5 – 400-600 ft, 6 – 600-800 ft, 7 – 800-1000 ft, 8 – 1000-1200 ft, 9 – 1200-1400 ft)

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are five principal aquifers in Minnesota:

1. Glacial
2. Cretaceous
3. Silurian-Devonian
4. Cambrian-Ordovician
5. Crystalline rock

Rule 1. Glacial aquifer (GLAC)

The unconsolidated sediments of the glacial aquifer form a thick sedimentary section that overlies the consolidated bedrock surface over much of the state of Minnesota, except where they thin or are absent in the eastern part of the state. The aquifer consists primarily of material deposited during multiple advances and retreats of continental glaciers that produced stratified permeable units of sand and gravel, as well as unstratified impermeable deposits of clay, silt, sand, and gravel. The permeable units form an important source of water in Minnesota, while the impermeable units cover and confine underlying bedrock aquifers. The thickness of the glacial aquifer generally ranges from 50-800 ft, but can exceed 1200 ft. Yields to wells from the glacial aquifer can be as high as 500 gallons of water per minute where deposits are thickest.

1a. Wells located within the glacial aquifer (GLAC), sourcing permeable glacial deposits are Class Ia because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

1b. Wells located within the glacial aquifer (GLAC), sourcing non-permeable glacial deposits, with well depth less than 50 ft, are Class Id because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

1c. Wells located within the glacial aquifer (GLAC), sourcing non-permeable glacial deposits, with well depth greater than 50 ft, are Class III because the aquifer unit is confined.

1d. Wells located within the glacial aquifer (GLAC), with well depth greater than the thickness of unconsolidated sediments, are Class UNK because this depth exceeds the known thickness of the aquifer.

Rule 2. Cretaceous aquifer (CRET)

The consolidated siliciclastic sedimentary rocks of the Cretaceous aquifer outcrop in western Minnesota and extend to the south. These rocks are composed mostly of sandstone and are Lower Cretaceous in age. The thickness of the aquifer ranges from 90-170 ft, and contains water under unconfined conditions, except where the aquifer is directly overlain by glacial deposits. Yields of wells completed in the Cretaceous aquifer range from less than 100 gpm minute to over 1000 gpm and average 250 gpm.

2a. Wells sourcing the Cretaceous aquifer located within the aquifer outcrop (CRET_OUT), are Class IIa because the aquifer is consolidated and unconfined.

2b. Wells sourcing the Cretaceous aquifer outcrop (CRET_OUT) overlain by non-permeable glacial deposits are Class III because the aquifer is confined.

Rule 3. Silurian-Devonian aquifer (SILD)

The outcrop and subcrop boundary of the Silurian-Devonian aquifer, which includes the upper carbonate aquifer is confined to southern Minnesota. The aquifer is comprised of consolidated sedimentary rocks, and contains water under unconfined conditions, except along the western margin where the aquifer is overlain by the Cretaceous aquifer, and along the eastern margin where glacial sediments pinch out. The lithology of the aquifer is mostly limestone and dolomite, with minor shale beds. The aquifer thickness ranges from a featheredge along its periphery to 650 ft, and sustains high yields as a result of enhanced permeability due to dissolution of carbonate rocks.

3a. Wells sourcing the Silurian-Devonian aquifer located within the aquifer outcrop (SILD_OUT) in areas with permeable sedimentary cover are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

3b. Wells sourcing the Silurian-Devonian aquifer located within the aquifer outcrop (SILD_OUT) in areas with non-permeable sedimentary cover less than 50 ft thick are Class

Id because these carbonate aquifer units are overlain by unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

3c. Wells sourcing the Silurian-Devonian aquifer located within the aquifer outcrop (SILD_OUT) in areas with non-permeable sedimentary cover greater than 50 ft thick are Class III because the aquifer unit is confined.

3d. Wells sourcing the Silurian-Devonian aquifer subcrop (SILD_SUB) are Class III because the aquifer unit is confined.

Rule 4. Cambrian-Ordovician aquifer (CORD)

The consolidated sedimentary rocks of the Cambrian-Ordovician aquifer outcrop in southeastern Minnesota and subcrop to the west. Within the aquifer's outcrop water exists under unconfined conditions, whereas within the aquifer subcrop, the aquifer is confined. The lithology of the aquifer is dominantly sandstone, limestone, dolomite, and shale. The aquifer thickness ranges from 200 ft to over 700 ft.

4a. Wells sourcing the Cambrian-Ordovician aquifer located within the aquifer outcrop (CORD_OUT) are Class IIa because the aquifer is consolidated and unconfined.

4b. Wells sourcing the Cambrian-Ordovician aquifer outcrop (CORD_OUT) in areas with permeable sedimentary cover, with source codes CJDN, CJDW, CJMS, CJSL, CJTC, OPCJ, OPCM, OPCT, OPCW, OPDC, OPOD, OPSH, OSCM, OSPC, are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

4c. Wells sourcing the Cambrian-Ordovician aquifer outcrop (CORD_OUT) in areas with permeable sedimentary cover, not sourcing the units above, are Class IIa because the aquifer unit is consolidated and unconfined.

4d. Wells sourcing the Cambrian-Ordovician aquifer outcrop (CORD_OUT) in areas with non-permeable sedimentary cover less than 50 ft thick, with source codes CJDN, CJDW, CJMS, CJSL, CJTC, OPCJ, OPCM, OPCT, OPCW, OPDC, OPOD, OPSH, OSCM, OSPC, are Class Id because these carbonate aquifer units are overlain by unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

4e. Wells sourcing the Cambrian-Ordovician aquifer outcrop (CORD_OUT) in areas with non-permeable sedimentary cover less than 50 ft thick, not sourcing the units above, are Class IIc because these consolidated, siliciclastic aquifer units are overlain by unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

4f. Wells sourcing the Cambrian-Ordovician aquifer subcrop (CORD_SUB) are Class III because the aquifer unit is confined.

Rule 5. Crystalline rock aquifer (CRYS)

The consolidated rocks of the Archean-Middle Proterozoic crystalline rock aquifer outcrop in northern Minnesota, where the aquifer is unconfined, and subcrop to the south, where they are overlain by confining units. The lithology of the aquifer is a combination of igneous and metamorphic rocks, and tightly cemented mostly siliciclastic sedimentary rocks. Water generally moves through secondary openings, such as joints, fractures, and faults.

5a. Wells sourcing the crystalline rock aquifer located within the aquifer outcrop (CRYS_OUT) are Class IIa because the aquifer is consolidated and unconfined.

5b. Wells sourcing the crystalline rock aquifer outcrop (CRYS_OUT) in areas with permeable sedimentary cover, are Class IIa because the aquifer unit is consolidated and unconfined.

5c. Wells sourcing the crystalline rock aquifer outcrop (CRYS_OUT) in areas with non-permeable sedimentary cover less than 50 ft thick are Class IIc because these unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

5d. Wells sourcing the crystalline rock aquifer outcrop (CRYS_OUT) in areas with non-permeable sedimentary cover greater than 50 ft thick are Class III because the aquifer unit is confined.

5e. Wells sourcing the crystalline rock aquifer subcrop (CRYS_SUB) where the aquifer is overlain by the Cretaceous aquifer, in areas with permeable sedimentary cover, are Class IIa because the aquifer unit is consolidated and unconfined.

5f. Wells sourcing the crystalline rock aquifer subcrop (CRYS_SUB) where the aquifer is overlain by the Cretaceous aquifer, in areas with non-permeable sedimentary cover less than 50 ft thick, are Class IIc because these unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

5g. Wells sourcing the crystalline rock aquifer subcrop (CRYS_SUB) where the aquifer is overlain by the Cretaceous aquifer, in areas with non-permeable sedimentary cover greater than 50 ft thick are Class III because the aquifer unit is confined.

5h. Wells sourcing the crystalline rock aquifer subcrop (CRYS_SUB) where the crystalline rock aquifer is overlain by the Cambrian-Ordovician aquifer are Class III because the aquifer unit is confined.

Sole source Aquifers

Minnesota contains one EPA-designed sole source aquifer: the Mille Lacs Lake Confined Drift Aquifer.

Rule 6. Mille Lacs Lake Confined Drift aquifer (MLLA)

The Mille Lacs Lake Confined Drift aquifer is composed of heterogenous unstratified deposits of glacial drift, including gravel, sand, silt, and clay. The aquifer is overlain by impermeable units that confine the aquifer. The aquifer thickness ranges from 15-175 ft.

6a. Wells sourcing the Mille Lacs Lake Confined Drift aquifer (MLLA_SSA) are Class III because the aquifer unit is confined.

Metadata Sources References

Olcott, P.G. 1992. Ground water atlas of the United States: Segment 9, Iowa, Michigan, Minnesota, Wisconsin. Hydrologic Investigations Atlas 730-J, U.S. Geological Survey, Reston, VA, 33 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Soller, D.R. 1992. Text and references to accompany "Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains": U.S. Geological Survey Bulletin 1921, 54 p.

Rules for Applying the Pettyjohn Classification Scheme in Mississippi

21 August 2018

Introduction

The rules defined below were devised using the USGS Hydrologic Investigations Atlas 730-F (Renken, 1998) and the previously published DW USA reports (RSPA, 2002) as the primary source of information. The data available at the time these rules were written were:

1. Wells: location, top of screened interval, source, pump rate
2. Geology: surficial and bedrock
3. Aquifers based on geology

Note that well depth is not actual completion depth for each well. For the purpose of the model, screen tops have been used. Because wells are classified according to the shallowest interval that water is derived from, total well depth (data which were not available) is of less importance than the available screen position data.

The following aquifers of Mississippi were distinguished for this work:

1. Mississippi River Valley Alluvial

Coastal Lowlands aquifer system

2. Coastal deposits
3. Citronelle
4. Pascagoula and Hattiesburg
5. Catahoula

Mississippi Embayment aquifer system

6. Upper Claiborne
7. Sparta (Middle Claiborne)
8. Lower Claiborne/Wilcox
9. McNairy-Nacatosh

10. Black Warrior River
11. Paleozoic
12. Not a principal aquifer
13. Southern Hills Regional Aquifer System SSA

Rule 1. Mississippi River Valley Alluvial aquifer (ALLU)

The Mississippi River Valley Alluvial aquifer underlies the Mississippi River Valley, which is an extensive, low, flat plain. The sediments were deposited within a broad erosional stream valley formed by a preglacial drainage system. The erosional river valley served as a major drainage for glacial meltwater, and considerable amounts of coarse-grained detritus (sand and gravel) were deposited in the valley by a braided, ancestral Mississippi River system. As the glaciers waned, the braided ancestral Mississippi River gradually gave way to a meandering regime. This is reflected in the geologic character of sediments within the valley. The aquifer consists of a braided sequence of gravel and coarse sand that is overlain by a finer sequence of sand, silt and clay. The overlying finer sequence acts as a confining layer ranging from less than 20 to more than 60 ft in thickness (Figure 25, Renken, 1998). The thickness of the underlying Mississippi River Valley alluvial aquifer ranges from about 25 to more than 150 ft (Figure 26, Renken, 1998).

1a. Wells located within and deriving water from the Mississippi river valley alluvium (ALLU_OUT) are Class Id, because these wells are deriving water from highly permeable sands covered by a thin unit of floodplain silts and clays. These wells can be no deeper than 210 ft.

1b. Wells located within and deriving water from the Mississippi river valley alluvium (ALLU_OUT) with screen depths greater than 210 ft are Class UNK.

Coastal Lowlands aquifer system

The Coastal Lowlands aquifer system consists of a gulfward-thickening, heterogeneous, unconsolidated to poorly consolidated wedge of discontinuous beds of sand, silt and clay that range in age from Oligocene to Holocene. The sediments were deposited in a deltaic to marginal marine environment. The permeable zones of the aquifer system, therefore, contain a highly interbedded mix of sand and clay.

Wells within the Coastal Lowlands aquifer system may derive water from any one of five permeable zones composed of fluvial-deltaic sediments. It is difficult to distinguish one zone from another in the subsurface because all of the permeable zones produce at rates > 50 gpm, and are considered to be unconsolidated based on their lithofacies (p. F14, Renken, 1998). For the purposes of rule writing, this aquifer system is divided into four aquifers based on geological formations in the bedrock geology coverage (BGEO). These aquifers are the coastal deposits aquifer, Citronelle aquifer, Pascagoula and Hattiesburg aquifer, and Catahoula aquifer.

The 300-foot cut-off for the thickness of permeable sediments used in rule writing is supported by the following quote from page F15 of Renken (1998):

> “Although permeable zone A is not overlain by a regional confining unit, ground water is contained within the deeper parts of the zone under confining conditions. This is due to abundant, but discontinuous, fine-grained beds of local extent that act as confining units, but cannot be traced over an area larger than several counties. Because these local confining units combine to retard the vertical movement of ground water, water in the aquifer at depths of a few hundreds of feet is under confined conditions in most locations.”

This holds true for the other permeable zones as well, which is reasonable given that the thickest potential sand bodies within fluvial deltaic systems are delta mouth bars, a type of deposit known to average roughly 200 ft in thickness. To account for variation, 100 ft is added to this thickness to establish the depth cutoff of 300 ft.

Rule 2. Coastal deposits aquifer (COAS)

2a. Wells located within and deriving water from the Coastal deposits aquifer (COAS_OUT) with screen depths less than or equal to 300 ft are Class Ia.

2b. Wells located within and deriving water from the Coastal deposits aquifer (COAS_OUT) with screen depths greater than 300 ft are Class III.

Rule 3. Citronelle aquifer (CRNL)

3a. Wells located within and deriving water from the Citronelle aquifer (CRNL_OUT) with screen depths less than or equal to 300 ft are Class Ia.

3b. Wells located within and deriving water from the Citronelle aquifer (CRNL_OUT) with screen depths greater than 300 ft are Class III.

3c. Wells deriving water from the Citronelle aquifer subcrop (CRNL_SUB) with screen depths less than or equal to 300 ft are Class Ia.

3d. Wells deriving water from the Citronelle aquifer subcrop (CRNL_SUB) with screen depths greater than 300 ft are Class III.

Rule 4. Pascagoula and Hattiesburg aquifer (PCGL)

4a. Wells located within and deriving water from the Pascagoula and Hattiesburg aquifer (PCGL_OUT) with screen depths less than or equal to 300 ft are Class Ia.

4b. Wells located within and deriving water from the Pascagoula and Hattiesburg aquifer (PCGL_OUT) with screen depths greater than 300 ft are Class III.

4c. Wells deriving water from the Pascagoula and Hattiesburg aquifer subcrop (PCGL_SUB) with screen depths less than or equal to 300 ft are Class Ia.

4d. Wells deriving water from the Pascagoula and Hattiesburg aquifer subcrop (PCGL_SUB) with screen depths greater than 300 ft are Class III.

Rule 5. Catahoula aquifer (CTHL)

5a. Wells located within and deriving water from the Catahoula aquifer (CTHL_OUT) with screen depths less than or equal to 300 ft are Class Ia.

5b. Wells located within and deriving water from the Catahoula aquifer (CTHL_OUT) with screen depths greater than 300 ft are Class III.

5c. Wells deriving water from the Catahoula aquifer subcrop (CTHL_SUB) with screen depths less than or equal to 300 ft are Class Ia.

5d. Wells deriving water from the Catahoula aquifer subcrop (CTHL_SUB) with screen depths greater than 300 ft are Class III.

Mississippi Embayment aquifer system

Geologic units of the Mississippi Embayment aquifer system range in age from Late Cretaceous to middle Eocene. In southern Mississippi an extensive, thick clay confining unit, the Vicksburg-Jackson confining unit, separates the Mississippi Embayment aquifer system from the overlying Oligocene and younger water-yielding strata of the Coastal Lowlands aquifer system. This confining unit is designated as Not a Principal aquifer (NAPA). Over much of southwestern Mississippi, the Mississippi Embayment aquifer system is more than 5,000 ft thick. The main aquifers within the aquifer system are the Upper Claiborne, Sparta (Middle Claiborne), Lower Claiborne/Wilcox, and McNairy-Nacatoch aquifers. Based on their lithofacies, these aquifers are considered unconsolidated, which is supported by the following from page F17 of Renken (1998):

> "Aquifers of the Mississippi embayment aquifer system consist of an interbedded sequence of poorly consolidated fluvial, deltaic, and marine deposits in which diagenesis or post depositional geochemical processes have not greatly altered the original pattern of permeability. The hydraulic conductivity of the unconsolidated to poorly consolidated sediments that compose the aquifers of the Mississippi embayment aquifer system does not appear to have been greatly reduced by cementation or compaction."

The Cook Mountain unit, which confines the Middle Claiborne aquifer, and the Midway Group confining units that separate the McNairy-Nacatoch and Wilcox aquifers are not principal sources of groundwater and are designated NAPA.

Rule 6. Upper Claiborne aquifer (CLAI)

6a. Wells located in the outcrop belt of and deriving water from the Upper Claiborne aquifer (CLAI_OUT) are <u>Class Ia</u> because the aquifer consists of unconsolidated sand.

6b. Wells deriving water from the Upper Claiborne aquifer subcrop (CLAI_SUB) and located within the Mississippi River Valley alluvial aquifer (ALLU) are <u>Class Id</u>. The Claiborne is mostly unconfined in these areas, but is covered by up to 210 ft of unconsolidated alluvial deposits containing an upper confining unit generally 50 ft or less in thickness.

6c. Wells deriving water from the Upper Claiborne aquifer subcrop (CLAI_SUB) and located within the outcrop belts of the coastal lowlands aquifers (CRNL, CTHL) are <u>Class III</u>, because the Vicksburg-Jackson confining unit is overlying the Claiborne aquifer in these areas. This classification also applies to wells located within the outcrop belts of the Vicksburg-Jackson confining unit in NAPA.

Rule 7. Sparta (Middle Claiborne) aquifer (SPRT)

7a. Wells located in the outcrop belt of and deriving water from the Sparta aquifer (SPRT_OUT) are <u>Class Ia,</u> because the aquifer consists of unconsolidated sand.

7b. Wells deriving water from the Sparta aquifer (SPRT_SUB) and located within the Mississippi River Valley alluvial aquifer (ALLU) or the outcrop belts of the Coastal Lowlands aquifer system (CRNL, CTHL) or Upper Claiborne aquifer (CLAI) are <u>Class III,</u> because the Sparta aquifer is confined in these areas by at least one of the following units:

the Vicksburg-Jackson Group, the Cook Mountain formation. This classification also applies to wells located within the outcrop belts of the Vicksburg-Jackson confining unit in NAPA.

Rule 8. Lower Claiborne/Wilcox aquifer (WILC)

8a. Wells located in and deriving water from the outcrop belts of the Lower Claiborne/Wilcox aquifer (WILC_OUT) are <u>Class Ia,</u> because the aquifer consists of unconsolidated sand.

8b. Wells deriving water from the subcrop of the Lower Claiborne/Wilcox aquifer (WILC_SUB) are <u>Class III,</u> because the aquifer is confined by units such as the Cook Mountain Formation and the Zilpha Clay.

Rule 9. McNairy-Nacatosh aquifer (MCNA)

9a. Wells located in and deriving water from the outcrop belts of the McNairy-Nacatosh aquifer (MCNA_OUT) are <u>Class Ia,</u> because the aquifer consists of unconsolidated deposits.

9b. Wells deriving water from the subcrop of the McNairy-Nacatosh aquifer (MCNA_SUB) are <u>Class III,</u> because the aquifer is confined by units such as the Cook Mountain Formation and the Midway Group.

Rule 10. Black Warrior River aquifer (BLAC)

The Black Warrior River aquifer, located in northeastern Mississippi, consists of interbedded fluvial sand and gravel; deltaic sand, silt, and clay; marginal marine sand, silt, and clay. The aquifer includes unnamed water-yielding rocks of Early Cretaceous age, as well as the Tuscaloosa Group, the McShan and the Eutaw Formations, and the Coffee Sand of Late Cretaceous age. The Black Warrior River aquifer is confined by the Selma Group, a thick sequence of clay and marl that effectively separates the aquifer from the overlying Mississippi Embayment aquifer system.

Because the depositional setting for the Black Warrior River aquifer is fluvial-deltaic, a depth cutoff of 300 ft is used in the following rules (see the Coastal Lowlands aquifer for more information).

10a. Wells located within the Black Warrior River aquifer that derive water from that system (BLAC_OUT) at depths less than or equal to 300 ft are <u>Class Ia,</u> because the aquifer consists of unconsolidated sediments.

10b. Wells located within the Black Warrior River aquifer that derive water from that system (BLAC_OUT) at depths greater than 300 ft are <u>Class III</u>.

10c. Wells within the outcrop belts of the Demopolis, Mooreville, and Prairie Bluff chalks or the Clayton, Naheola, and Porters Creek confining units and deriving water from the Black Warrior River aquifer subcrop (BLAC_SUB) with a screen depth less than or equal to 50 ft are <u>Class Id</u>.

10d. Wells within the outcrop belts of the Demopolis, Mooreville, and Prairie Bluff chalks or the Clayton, Naheola, and Porters Creek confining units and deriving water from the Black

Warrior River aquifer subcrop (BLAC_SUB) with a screen depth greater than 50 ft are Class III due to the confining nature of the chalks and clays.

10e. Wells located within the Mississippi Embayment aquifer outcrop (CLAI, SPRT, WILC, MCNA) deriving water from the Black Warrior River aquifer (BLAC_SUB) are Class III, because the aquifer is confined.

Rule 11. Paleozoic aquifer (PALE)

Some water wells in northeastern Mississippi source Paleozoic formations. The subcrops of these rocks, which include carbonates, is covered by more than 300 ft of semi consolidated sands, silts, and clays, but potential karst zones are in hydraulic continuity with overlying saturated sediments. At depths greater than 300 ft, the aquifer is most likely confined by a layer of clay.

11a. Wells deriving water from Paleozoic outcrops (PALE_OUT) are Class Ib due to the potential presence of karst zones.

11b. Wells deriving water from Paleozoic subcrops (PALE_SUB) at depths less than or equal to 300 ft are Class Ib, because any karst zone would be in hydraulic continuity with the overlying saturated sediments.

11c. Wells deriving water from Paleozoic subcrops (PALE_SUB) at depths greater than 300 ft are Class III, because the aquifer is most likely confined by at least one layer of clay.

Rule 12. Not a principal aquifer (NAPA)

NAPA units act as confining layers for other aquifers and are not a principal source of groundwater. In Mississippi, these units include: Forest Hill formation and Red Bluff clay (Of), Vicksburg group and Chickasawhay limestone (Ov), Jackson group (Ej), Cook Mountain formation (Ecm), Naheola formation (Pan), Porters Creek formation (Pap), Clayton formation (Pac), Prairie Bluff chalk and Owl Creek formation (Kp), Demopolis chalk (Kd), and Mooreville chalk (Km). Only the Forest Hill formation (FRHL) has the potential to be a source of groundwater.

12. Wells sourcing NAPA in any location are Class III due to the presence of confining layers.

Rule 13. Southern Hills Regional aquifer system sole source aquifer (SOUT_SSA)

The Southern Hills regional aquifer SSA is comprised of a series of sandy gravel to clayey formations that generally dip south towards the Gulf of Mexico. This aquifer consists of the same formations as the Coastal Lowlands aquifer system: Catahoula, Pascagoula, Hattiesburg, Citronelle, and Terraces. A small portion of the Mississippi River Valley alluvial aquifer is also included in this SSA, but no wells are located within this area. The rules for this SSA will be the same as for the Coastal Lowlands aquifer, except that since no source information is provided, the most sensitive classification (Rule 2) will be assigned to wells falling within a particular formation.

13a. Wells with screen depths less than or equal to 300 ft are Class Ia, because they may derive water from the unconsolidated portion of the aquifer (see Rule 2a).

13b. Wells with screen depths greater than 300 ft are Class III (see Rule 2b).

Metadata Sources References

Renken, R.A. 1998. Ground water atlas of the United States: Segment 5, Arkansas, Louisiana, Mississippi. Hydrologic Investigations Atlas 730-F, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Missouri

8 May 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-D (Miller and Appel, 1997) and the previously published DW USA reports (RSPA, 2002). The data set available to us included:

1. Well location
2. Well depth
3. Source aquifer
4. Surficial geology
5. Aquifer boundaries

The aquifer boundaries were generated using surficial and bedrock geology and the Segment 3 atlas (Miller and Appel, 1997) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

The principal aquifers and confining units in Missouri are:

1. Alluvial stream valley including Mississippi River Valley
2. Glacial drift sediment
3. Mississippi Embayment
4. Western Interior Plains confining unit
5. Springfield Plateau
6. Mississippian
7. Ozark confining unit
8. Ozark/Cambrian Ordovician
9. St. Francois confining unit
10. St. Francois

Rule 1. Alluvial stream valley aquifer (ALLU)

The unconsolidated sediments in the stream valleys of the Mississippi and Missouri Rivers and their tributaries are the thickest, most widespread, and most productive in Missouri. The stream valley aquifer consists mostly of sand and gravel of the Holocene age. Average thickness of the aquifers are 90 to 100 ft, but locally can be as thick as 160 ft in some places and up to 250 ft near the Mississippi River. These are generally unconfined aquifers in hydraulic continuity with the underlying bedrock.

1a. Wells that derive water from and occur within the alluvial aquifer (ALLU_OUT) anywhere in Missouri and derive water from depths < 250 ft are Class Ia, because water in these unconsolidated, surficial sands and gravel deposits are in hydraulic continuity with the water table.

1b. Wells that derive water from and occur within the alluvial aquifer (ALLU_OUT) and are deeper than 250 ft are Class UNK, because the depth is greater than the maximum depth for the alluvial aquifer.

Rule 2. Glacial drift sediment aquifers (GLAC)

The southern extent of the glacial drift aquifer is the Missouri River. The deposits in Missouri are pre-Illinoian and some are as old as late Pliocene. Glacial deposits are on average 100 to 200 ft thick, but locally can be greater than 300 ft in eastern Missouri and 400 ft in western Missouri. The sediments are a complex interbedding of fine- and coarse-grained materials. In some areas, coarse-grained materials may fill the bottom of glacial stream channels, and upper layers are low permeable silt, clay, and till.

2a. Wells sourcing and located within glacial drift aquifer (GLAC_OUT) at depths of less than 50 ft are Class Id, because there are covered by less than 50 ft of till.

2b. Wells sourcing and located in the glacial aquifer (GLAC_OUT) deeper than 50 ft are Class III, because they would have over 50 ft of confining material above them.

2c. Wells sourcing the glacial aquifer (GLAC_SUB) and located in the alluvial aquifer (ALLU) are Class Id if shallower than 210 ft. This is because there is hydraulic continuity between the alluvial aquifer, which may be up to 160 ft thick, and the underlying glacial aquifer. And the well is classed based on the depth into the glacial aquifer.

2d. Wells sourcing the glacial aquifer (GLAC_SUB) and located in the alluvial aquifer (ALLU) deeper than 210 ft are Class III, because they would have over 50 ft of confining glacial material above them.

Rule 3. Mississippi Embayment aquifer (MESM)

Composed of Cretaceous and Tertiary rocks, the Mississippi Embayment aquifer is located within the coastal plain physiographic province of the southeastern (boot heel) part of the state. These aquifers are composed of semi-consolidated sediments. Most of the aquifer is overlain by the Mississippi River Valley alluvial aquifer, but it does outcrop in a few narrow bands.

3a. Wells sourcing the Mississippi Embayment aquifer (MSEM_OUT) and located within the aquifer are Class Ic because they are semi-consolidated sediments.

3b. Wells with a source of Wilcox in the Mississippi Embayment aquifer (MSEM_SUB) located in the Mississippi River valley alluvial aquifer (ALLU) are Class Ic. The alluvial aquifer is composed of very porous sediments and, in this area, there is no confining unit between the alluvial aquifer and the Mississippi Embayment aquifer.

3c. Wells with a source of Midway in the Mississippi Embayment aquifer (MSEM_SUB) locate in the alluvial aquifer (ALLU) are Class Id, because Midway is a low permeability layer of the Mississippi Embayment aquifer system.

3d. Wells with a source of Cretaceous in the Mississippi Embayment aquifer (MSEM_SUB) located in the alluvial aquifer (ALLU) are Class III because the Cretaceous McNairy is overlain by the Midway confining unit.

3e. When the model determines the aquifer to be the Mississippi Embayment subcrop (MSEM_SUB) for wells with unknown source located in the alluvial aquifer (ALLU), the most conservative classification of Class Ic is used.

3f. Wells identified as deriving water from the Mississippi Embayment subcrop (MSEM_SUB) and located in the outcrop of the Ozark aquifer are Class UNK since this is not possible.

Rule 4. Western Interior Plains confining unit (WEST)

The Western Interior Plains confining unit is composed of Pennsylvanian rocks of low permeability. This is a confining unit for the Western Interior Plains aquifer and the western portion of the Mississippian aquifer; however, the Western Interior Plains and Mississippian aquifers contain no freshwater in the subcrop under the Western Interior Plains confining unit.

4a. Wells that derive water from and are located in the outcrop of the Western Interior Plains confining unit (WEST_OUT) are Class IIb, at depths < 50 ft, since this is a low yield bedrock aquifer.

4b. Wells sourcing and located in the outcrop the Western Interior Plains confining unit (WEST_OUT) at depths > 50 ft are Class III, since there would be more than 50 ft of confining unit over the well.

4c. Wells that derive water from the Western Interior Plains confining unit (WEST_SUB) and located in alluvial aquifers (ALLU) are Class IIb at depths < 210 ft, since the alluvial aquifer is very porous and there is hydraulic continuity between the two layers.

4d. Wells that derive water from the Western Interior Plains confining unit (WEST_SUB) and located in the alluvial aquifer (ALLU) at depths > 210 ft are Class III, since the alluvial aquifer is at most 160 ft thick and the Western Interior Plains confining unit is a confining unit the total depth would mean there are at least 50 ft of confining layer at the well location.

4e. Wells that derive water from the Western Interior Plains confining unit (WEST_SUB) and located in glacial drift aquifers (GLAC) are Class IIc at depths < 50 ft, since the glacial drift aquifer has a high probability of confining units.

4f. Wells that derive water from the Western Interior Plains confining unit (WEST_SUB) and located in glacial drift aquifers (GLAC) at depths > 50 ft are Class III, since both glacial drift and the aquifer are confining units and would be thicker than 50 ft at the well location.

Rule 5. Springfield Plateau aquifer (SPRI)

The Springfield Plateau aquifer is the uppermost aquifer in the Ozark aquifer system. It is composed almost entirely of limestone of the Mississippian age. The thickness of the aquifer ranges from 200 to 400 ft. Water occurs in and moves through secondary openings such as fractures and bedding planes. The slightly acidic groundwater that moves through has dissolved parts of the limestone creating a network of solution channels. The subcrop for this aquifer is not a significant source of groundwater."

5a. Wells that derive water from and located in the Springfield Plateau aquifer outcrop (SPRI_OUT) (e.g. Burlington and Koekuk Limestones) in the southwestern and central portions of the state are Class Ib, because these limestones contain solution cavities. These wells should be <400 ft deep to derive water from the Mississippian rocks.

5b. Wells >400 ft deep with the source ascribed to the Springfield aquifer (SPRI_OUT) are Class UNK.

5c. Wells that derive water from the Springfield Plateau aquifer (SPRI_SUB) located in the alluvial stream valley aquifers (ALLU) are Class Ib, because the alluvial aquifer has hydraulic continuity with the underlying Springfield aquifer.

5d Wells that derive water from the Springfield Plateau aquifer (SPRI_SUB) located in the Western Interior Plains confining unit (WEST) are Class III, because the aquifer is overlain by a confining unit.

Rule 6. Mississippian aquifer (MSAQ)

The Mississippian aquifer is composed of the same formations as the Springfield Plateau aquifer. The Mississippian aquifer is north of the Missouri River. There is no connectivity between the 2 aquifer systems. Both systems discharge into the Missouri River. The characteristics of the Mississippian aquifer are the same as the Springfield aquifer. Water quality varies with location. The eastern third of the aquifer has freshwater. The remainder has slightly saline to very saline water. The salinity is greatest where it is overlain by thick confining unit.

6a. Wells that derive water from the Mississippian aquifer (MSAQ_OUT) located in the Mississippian aquifer (MSAQ) (e.g. Burlington and Koekuk Limestones) in the northeast portions of the state are Class Ib, because these limestones contain solution cavities. These wells should be <400 ft deep to derive water from the Mississippian rocks.

6b. Wells in the outcrop deeper than 400 ft are Class UNK, since the maximum thickness of the aquifer is 400 ft.

6c. Wells that derive water from the Mississippian aquifer (MSAQ_SUB) located in the alluvial stream valley aquifers (ALLU) are Class Ib, because the alluvial aquifer has hydraulic continuity with the underlying Mississippian aquifer.

6d. Wells that derive water from the Mississippian aquifer (MSAQ_SUB) located in glacial drift (GLAC) are Class Id. Wells overlain by less than 50 ft of glacial till should be 1b, and those overlain by more than 50 ft of glacial till should be III. However digital till isopachs are not available, making an automated distinction between these Pettyjohn classes impossible so the more sensitive of the classifications is used.

Rule 7. Ozark confining unit (OZCN)

The Ozark confining unit underlies the Springfield aquifer and hydraulically separates the Springfield and Ozark aquifers. The confining unit consists mostly of shale but also has some minimally permeable limestone. The thickness is generally less than 100 ft. North of the Missouri River, similar rock formations separate the Mississippian and Cambrian-Ordivician aquifers.

7a. Wells sourcing the Ozark confining unit (OZCN_OUT) and located in the outcrop belt are Class IIb, since this is a low permeable bedrock aquifer.

7b. Wells sourcing the Ozark confining unit (OZCN_SUB) and located in the outcrops of the Springfield Plateau (SPRI), Mississippian aquifer (MSAQ), or alluvial aquifer (ALLU) and are Class IIb, since this is a low permeable bedrock aquifer overlain by permeable aquifers in hydraulic continuity with the Ozark confining unit.

7c. Wells deriving water from the Ozark confining unit subcrop (OZCN_SUB) and located in the outcrop of Western Interior Plains confining unit (WEST) or glacial drift (GLAC) are Class III because all well depths are greater than 50 ft indicating it is overlain by at least 50 ft of confining material.

Rule 8. Ozark/Cambrian Ordovician aquifer (OZAR)

The Ozark aquifer is the primary aquifer in the Ozark Plateau. It is composed of numerous geologic formations from Devonian to Cambrian in age. Most of these formations are limestone and dolomite, but there are also some beds of sandstone. North of the Missouri River, rocks that are the equivalent of the Ozark aquifer are called the Cambrian-Ordovician aquifer. There is some hydraulic continuity between these two aquifers. Because of the equivalence and hydraulic continuity, these two aquifers are managed together.

8a. Wells that derive water from the St. Peter Sandstone in the Ozark/Cambrian-Ordovician outcrop belt (OZAR_OUT) are Class IIa because the source rocks are consolidated, high-yield sandstones.

8b. Wells deriving water from the Ozark/Cambrian-Ordovician outcrop (OZAR_OUT) limestones and dolomites located in the southeastern and central parts of the state are Class Ib, because they are fractured, porous limestones. Source formations include Cincinnatian, Cotter, Decorah/Plattin, Devonian/Silurian, Eminence, Everton, Gasconade, Jefferson City, Joachim/Dutchtown, Kimmswick, Plattin Limestone, Potosi, Powell, Roubidoux, Smithville/Powell.

8c. Wells identified as deriving water from the Ozark outcrop (OZAR_OUT) and not located in the outcrop are Class UNK since this is not possible.

8d. Wells deriving water from the St. Peter Sandstone in the Ozark/Cambrian-Ordovician aquifer (OZAR_SUB) sandstones and located within alluvium (ALLU) overlaying the alluvium (Qal), Eminence and Potosi dolomites (Cep), or any Ordovician (O) formations are classed as though they derive water from the outcrop (Class IIa,)

8e. Wells deriving water from the Ozark/Cambrian-Ordovician aquifer (OZAR_SUB) and located within alluvium (ALLU) overlaying the alluvium (Qal), Eminence and Potosi dolomites (Cep), or any Ordovician (O) formations are classed as though they derive water from the outcrop (Class Ib,).

8f. Wells deriving water from the St. Peter Sandstone in the Ozark/Cambrian-Ordovician aquifer (OZAR_SUB) sandstones and located within Glacial drift aquifer (GLAC) overlaying the Eminence and Potosi dolomites (Cep) or any Ordovician (O) formations are classed as though they derive water from the outcrop (Class IIc,) 8g. Wells deriving water from the Ozark/Cambrian-Ordovician aquifer (OZAR_SUB) and located within Glacial drift aquifer (GLAC) overlaying the Eminence and Potosi dolomites (Cep) or any Ordovician (O) formations are classed as though they derive water from the outcrop (Class Id,).

8h. Wells identified as deriving water from the Ozark/Cambrian-Ordovician aquifer subcrop (OZAR_SUB) and located in the outcrop of the Ozark/Cambrian-Ordovician aquifer are Class UNK since this is not possible.

8i. Wells that derive water from the Ozark/Cambrian-Ordovician aquifer subcrop (OZAR_SUB) located anyplace else in the state are Class III, because the source aquifer is covered by the Ozark confining unit.

Rule 9. St. Francois confining unit and aquifer (STFR)

The St. Francois confining unit underlies the Ozark aquifer and separates it from the St. Francois aquifer. The confining unit contains primarily dolomite but also includes shale, siltstone, and limestone. It is composed of the Davis formation and Derby and Doe Run Dolomites, which all together form the Elvins group. It is considered to be a confining unit but the Derby and Doe Run Dolomites yield a small amount of water. In creating the aquifer coverage information was not available to differentiate between the St. Francois confining unit and St. Francois aquifer, so they were both combined into the St. Francois aquifer.

The St. Francois aquifer is the lowermost level of the Ozark Plateau aquifer system and is exposed only around the St. Francois Mountains in the southeastern portion of the state. The aquifer slopes down into the subsurface in all directions away from the mountains. The aquifer consists of the Bonneterre dolomite and Lamotte sandstone, all of Cambrian age. The Lamotte sandstone has yields as high as 500 gallons per minute. The Bonneterre dolomite is not as productive with only 10 to 50 gallons per minute yields.

9a. Wells deriving water from the Elvins unit of the St. Francois aquifer outcrop (STFR_OUT) are Class IIb, because these are low yield consolidated aquifers.

9b. Wells deriving water from the Bonneterre unit of the St. Francois aquifer outcrop (STFR_OUT) are Class Ib, because these are dolomite formation that may have solution cavities or fractures.

9c. Wells deriving water from the Lamotte sandstone unit of the St. Francois aquifer outcrop (STFR_OUT) are Class IIa, because these are high yield consolidated sandstone formations.

9d. Wells deriving water from the Elvins unit of the St. Francois aquifer subcrop (STFR_SUB) and located in the alluvial aquifer (ALLU) are Class IIb, because the alluvial aquifer is very porous and they are classed as though they derive water from the outcrop.

9e. Wells deriving water from the Bonneterre unit of the St. Francois aquifer subcrop (STFR_SUB) and located in the alluvial aquifer (ALLU) are Class Ib, because the alluvial aquifer is very porous and they are classed as though they derive water from the outcrop.

9f. Wells deriving water from the Lamotte sandstone unit of the St. Francois aquifer subcrop (STFR_SUB) and located in the alluvial aquifer (ALLU) are Class IIa, because the alluvial aquifer is very porous and they are classed as though they derive water from the outcrop.

9g Wells identified as deriving water from the St. Francis aquifer subcrop (STFR_SUB) and located in the outcrop of the St. Francis aquifer are Class UNK since this is not possible.

9h. Wells deriving water from the St. Francois aquifer subcrop (STFR_SUB) everywhere else are Class III because the aquifer subcrop is overlain by a confining unit throughout the state.

Rule 10. Basement Confining Unit (BASE)

The basement confining unit consists of Precambrian volcanic and intrusive rocks that underlie the Ozark Plateau aquifer system. These rocks outcrop in the St. Francois Mountains in the southeastern part of the state. They are low yield aquifers.

10a. Wells that derive water from the Precambrian rocks of the basement confining unit outcrop (BASE_OUT) are Class IIb (lower yield bedrock aquifers).

10b. Wells that derive water from the Precambrian rocks of the basement confining unit subcrop (BASE_SUB) and are located in alluvial or basement confining unit are Class IIb because the alluvial aquifer is very porous and they are classed as though they derive water from the outcrop.

10c. All other wells deriving water from the basement confining unit subcrop (BASE_SUB) are Class III because of intervening confining units.

Metadata Sources References

Miller, J.A. and C.L. Appel. 1997. Ground water atlas of the United States: Segment 3, Kansas, Missouri, and Nebraska. Hydrologic Investigations Atlas 730-D, U.S. Geological Survey, Reston, VA, 26 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Montana

9 June 2018

Introduction

The following rules were devised primarily on the basis of information provided in the USGS Hydrologic Investigations Atlas 730-I (Miller, 2000) and the previously published DW USA reports (RSPA, 2002). The dataset available at the time these rules were written consisted of:

1. Well location, source, and depth, and casing depth
2. Bedrock geology

Spatial extent of aquifers is generally derived from detailed bedrock geology data (Vuke et al., 2007) together with maps of extent and thickness of quaternary glacial sediments in the United States (Soller, 1992), using Miller (2000) as a guide. Wells are classified primarily on basis of their described source, depth, and the lithology of the bedrock or sedimentology of the unconsolidated material in the area. The following aquifers of Montana were distinguished for this work:

1. Surficial unconsolidated
2. Glacial
3. Quaternary volcanic and sedimentary rock
4. Lower Tertiary
5. Upper Cretaceous
6. Lower Cretaceous
7. Paleozoic
8. Confining unit
9. Geologic units that are not a principle aquifer
10. The Missoula Valley Sole Source Aquifer

Rule 1. Surficial unconsolidated aquifers (SURF)

Surficial aquifers in Montana consist of alluvial sediments which fill stream valleys or broad tectonic basins of mountainous areas, formed by faulting or erosion or both. The alluvium in the basins was deposited primarily as coalescing alluvial fans by streams that flowed into the valleys from the surrounding mountains. Alluvial sediments of Quaternary age are unconsolidated, permeable materials. Also included as part of surficial unconsolidated aquifers are the unconsolidated to semi-consolidated sand and gravel deposits of upper Tertiary (Miocene/Pliocene) age commonly located along the margins of the intermontane basins of western Montana, or underlying Quaternary sediments in these basins. While occasionally confined when underlying more modern sediments, these deposits can be extremely permeable and are often hydrologically connected to overlying Quaternary sediments. Yields of wells sourcing these upper Tertiary sediments range from 5 to 800 gallons per minute.

1a. Wells sourcing from surficial Quaternary and upper Tertiary unconsolidated-deposit aquifers are Class Ia, because these aquifers can have high hydraulic conductivity and contain water primarily under unconfined or water-table conditions.

Rule 2. Glacial aquifer (GLAC)

During the Pleistocene, continental glaciers covered portions of northeastern Montana. Glacial deposits that were redistributed by glacial meltwater during ice retreats (called glacial outwash) consist of stratified sand and gravel and form productive aquifers. In contrast, clay and silt that were deposited in glacial lakes, and poorly sorted, unstratified deposits of clay, silt, sand, gravel, and boulders (called till) have minimal permeability and form confining units. Permeable lenses of sand and gravel within till can form locally productive aquifers. Outwash deposits are found along stream valleys and in outwash plains. Although some of these sand and gravel aquifers are exposed at the land surface, most are buried, ancient channel deposits that formed either in valleys of meltwater streams or valleys incised into the bedrock. These buried valley deposits are commonly covered with confining units consisting of till or fine-grained glacial lake deposits. Most of the continental glacial deposits consist of till, which is a mixture of unsorted clay, silt, sand, gravel and boulders that was deposited beneath or at the margins of the ice. In some cases, glacial deposits in isolated mountain basins in the western portion of Montana may serve as small, localized aquifers. These are not well mapped by existing geology data, but are included in this aquifer when indicated well source. In general, most glacial deposits in Montana are less than 100 ft thick.

2a. Wells sourcing glacial aquifers with a casing or overall depth shallower than 50 ft, or with unknown depth, are <u>Class Id,</u> because these wells are commonly covered with confining units consisting of till or fine-grained glacial lake deposits.

2b. Wells sourcing glacial aquifers with a casing or overall depth deeper than 50 ft are of <u>Class III</u>.

Rule 3. Quaternary volcanic and sedimentary rock aquifers (VOLC)

Volcanic and sedimentary rock aquifers are generally present in small area of southwestern Montana and consist of complexly interbedded Quaternary basalt and rhyolite, beds of tuff and volcanic ash, and beds of sedimentary rocks. The permeability in these aquifers is extremely variable, because they are complexly interbedded and consist of numerous rock types.

3a. Wells that derive water from this aquifer and are located within the outcrop of this aquifer are <u>Class IIb</u>, because these are highly consolidated, low yield rocks.

3b. Wells that derive water from this aquifer but are covered by unconsolidated material, with a casing or overall depth shallower than 50 ft, or with unknown depth, are <u>Class IIc</u>.

3c. Wells that derive water from these units, and located outside of the outcrop of these aquifers, or covered by unconsolidated material and with a casing or overall depth deeper than 50 ft, are generally confined, and are <u>Class III</u>.

Rule 4. Lower Tertiary aquifers (LTRT)

The Lower Tertiary aquifers are located in eastern Montana. These are chiefly consolidated sandstone beds of Oligocene to Paleocene age within the Fort Union Formation or Group. The water-yielding sandstones are interbedded with shale, mudstone, siltstone, lignite and coal and locally with beds of limestone. Most of the Tertiary rocks were deposited in continental environments, but some of the shale and limestone beds were deposited in a marine environment and form confining units.

4a. Wells sourcing lower Tertiary aquifers and located within the outcrop of these aquifers are Class IIa.

4b. Wells sourcing lower Tertiary aquifers, but covered by unconsolidated material, with a casing or overall depth shallower than 50 ft, or with unknown depth, are Class IIc.

4c. Wells sourcing lower Tertiary aquifers and located outside of the outcrop of these aquifers, or covered by unconsolidated material and with a casing or overall depth deeper than 50 ft, are generally confined, and are Class III.

Rule 5. Upper Cretaceous aquifers (UCRT)

The Upper Cretaceous aquifers are consolidated sandstones interbedded with shale, siltstone and sparse thin, lenticular beds of coal. The upper Cretaceous aquifers consist of sandstone beds in the Hell Creek and Lance Formations and the Fox Hills Sandstones. The Hell Creek and Lance Formations consist of interbedded sandstone, siltstone, claystone, and local thin beds of coal or lignite, all of which were deposited in a continental environment. The underlying Fox Hills sandstones consist primarily of sandstone that was deposited in mostly a deltaic to marine environment and contains local beds of siltstone and shale. Water in the upper Cretaceous aquifers is under unconfined conditions in most places. The permeability of the upper Cretaceous aquifers is somewhat variable, but generally not as great as that of the aquifers in younger rocks. Wells completed in these units are generally are less than 800 ft deep and have yields that range from 5 to 50 gallons per minute (Miller, 2000).

5a. Wells sourcing upper Cretaceous aquifers and located within the outcrop of these aquifers are Class IIb.

5b. Wells sourcing upper Cretaceous aquifers, but covered by unconsolidated material, with a casing or overall depth shallower than 50 ft, or with unknown depth, are Class IIc.

5c. Wells sourcing upper Cretaceous aquifers and located outside of the outcrop of these aquifers, or covered by unconsolidated material and with a casing or overall depth deeper than 50 ft, are generally confined, and are Class III.

Rule 6. Lower Cretaceous aquifers (LCRT)

The Lower Cretaceous aquifers form principal water supplies primarily in the Judith River basin in central Montana. The Lower Cretaceous aquifers are also composed of consolidated sandstones; the best known of these formations are the Kootenai Formation. Sandstones of late Jurassic age may form minor aquifers in some areas and are included as part of the Lower Cretaceous aquifer.

6a. Wells sourcing lower Cretaceous aquifers and located within the outcrop of these aquifers are Class IIa.

6b. Wells sourcing lower Cretaceous aquifers, but covered by unconsolidated material, with a casing or overall depth shallower than 50 ft, or with unknown depth, are Class IIc.

6c. Wells sourcing lower Cretaceous aquifers, and located outside of the outcrop of these aquifers, or covered by unconsolidated material and with a casing or overall depth deeper than 50 ft, are generally confined and are Class III.

Rule 7. Paleozoic aquifers (PALE)

Paleozoic aquifers extend over most of Montana in the subsurface but are exposed at the land surface only in small areas in the central and southern regions. They consist mostly of limestone and dolomite (primarily, the Madison formation), but some Paleozoic sandstones also yield water. Confining units that overlie and separate the aquifers consist of shale and siltstone with some beds of anhydrite and halite (rock salt).

7a. Wells sourcing Paleozoic aquifers and located within the outcrop of these aquifers are Class Ib.

7b. Wells sourcing Paleozoic aquifers, but covered by unconsolidated material, with a casing or overall depth shallower than 50 ft, or with unknown depth, are Class Id.

7c. Wells sourcing Paleozoic aquifers, and located outside of the outcrop of these aquifers, or covered by unconsolidated material and with a casing or overall depth deeper than 50 ft, and are Class III.

Rule 8. Confining units (CONF)

A variety of Cretaceous shales form effective confining units that separate the lower Cretaceous aquifers from overlying aquifers in Montana. These include the Colorado, Claggett and Bearpaw Shales, as well as the Judith River, Eagle, Virgelle, Livingston, Two Medicine, Telegraph Creek, Pierre, Niobrara, and Marias River Formations. Locally, these units may yield small volumes of water from thin interbedded sandstones or from highly weathered or fractured zones in the uppermost shale beds (Miller, 2000). However, these are not considered principal aquifers. The Jurassic Morrison and Swift Formations form confining units that separate the Paleozoic aquifers from the overlying lower Cretaceous aquifers.

8a. Wells sourcing confining units and located within the outcrop of those confining units are Class IIb.

8b. Wells sourcing confining units, but covered by unconsolidated material, with a casing or overall depth shallower than 50 ft, or with unknown depth, are Class IIc.

8c. Wells sourcing confining units and located outside of the outcrop of these confining units, or covered by unconsolidated material and with a casing or overall depth deeper than 50 ft, are Class III.

Rule 9. Not a principle aquifer (NAPA)

NAPA has been constructed from various formations that usually do not represent principal aquifers. Generally, Cretaceous and Paleozoic formations not discussed above have been made parts of NAPA. Igneous rocks of all ages and the Precambrian rocks are low-yield, consolidated formations, thus they have been grouped under NAPA. These formations occur in large areas in western Montana and some areas in the central and southeastern regions.

9a. Wells sourcing these units and located within the outcrop of those units are Class IIb.

9b. Wells sourcing these units, but covered by unconsolidated material, with a casing or overall depth shallower than 50 ft, or with unknown depth, are Class IIc.

9c. Wells sourcing these units and located outside of the outcrop of these units, or covered by unconsolidated material and with a casing or overall depth deeper than 50 ft, are Class III.

Sole Source Aquifers

Montana contains a single EPA-designated sole source aquifer (SSA), the Missoula Valley aquifer (MSVA_SSA), located in the Missoula Valley in the western portion of the state. The extent of this SSA overlaps both the basin-fill valley aquifer extent included in the surficial aquifers as defined above, and the Precambrian rocks that form the mountainous margins of these basin-fill valley aquifers. These rocks do not form principle aquifers, as defined above. The Missoula Valley aquifer is a nearly continuous formation of Quaternary sand and gravel approximately 150 to 250 ft thick between 0 and 200 ft below the surface that was deposited during the catastrophic drainage of Glacial Lake Missoula. The aquifer is largely unconfined and wells commonly yield in excess of 50 gallons per minute. Any wells deriving water from the MSVA_SSA and located in the extent of the surficial aquifer (SURF) as defined above will be assigned a classification of Ia based on rule 1a. Any wells deriving water from the MSVA_SSA aquifer and located in the extent of no principle aquifer (NAPA), as defined above, will be assigned a classification of IIb based on rule 9a.

Metadata Sources References

Miller, J.A. 2000. Ground water atlas of the United States. U.S. Geological Survey Hydrologic Atlas 730, 13 chapters.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Soller, D.R. 1992. Text and references to accompany "Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains": U.S. Geological Survey Bulletin 1921, 54 p.

Vuke, S.M., K.W. Porter, J.D. Lonn and D.A. Lopez. 2007. Geologic Map of Montana. Montana Bureau of Mines and Geology. Geologic Map 62A. 73 pp. 1:500,000

Rules for Applying the Pettyjohn Classification Scheme in Nebraska

21 August 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-D (also called Ground Water Atlas of the United States, Segment 3; Miller and Appel, 1997), An Overview of Secondary Aquifers in Nebraska (Devine and Sibray, 2017) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Pump rate
4. Bedrock geology
5. Surficial geology
6. Glacial sediment thickness
7. Aquifer boundaries

The aquifer boundaries were generated using the Segment 3 Atlas (Miller and Appel, 1997) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are five principal aquifers in the state of Nebraska:

1. Alluvial
2. Glacial Drift
3. High Plains
4. Great Plains
5. Not a principal aquifer

The aquifer features were constructed from the bedrock geology features (BGEO), the surface geology features (SGEO) and glacial till thickness (SEDTHICK).

Rule 1. Alluvial aquifer (ALLU)

The unconsolidated sediments of the Alluvial aquifer outcrop in bands that fill the valleys of rivers that have down cut into glacial deposits, older alluvium and bedrock across the state of Nebraska. The Alluvial aquifer consists of predominantly Quaternary age unconfined surficial sand and gravel in hydraulic continuity with the water table. Important alluvial water sources in Nebraska occur in the alluvium of the Missouri, Niobrara, Loup, Platte, Republican and Blue Rivers. The average thickness of the alluvial aquifer is approximately 90 to 100 ft, but locally obtains a thickness of 160 ft. A buffer of 40 ft was added to the aquifer thickness to allow for uncertainty in the measurement of well depth, resulting in an estimated maximum thickness of 200 ft. All usage of “subcrop” is in reference to the spatial distribution of the aquifers, not official subcrops.

1a. Wells located within the Alluvial aquifer outcrop (ALLU_OUT), with well depths less than or equal to 200 ft are Class Ia because the aquifer is surficial, unconsolidated and permeable.

1b. Wells located within the Alluvial aquifer outcrop (ALLU_OUT) within the Glacial Drift aquifer subcrop (THICK_SGEO codes: 1 and 2), with well depths between 200 and 300 ft are Class Id because the aquifer is overlain by less than 50 ft of low permeability glacial till deposits.

1c. Wells located within the Alluvial aquifer outcrop (ALLU_OUT) within the Glacial Drift aquifer subcrop (THICK_SGEO codes: 1 and 2), with well depths greater than 300 ft are Class III because the aquifer is overlain by more than 50 ft of low permeability glacial till material.

1d. Wells located within the Alluvial aquifer outcrop (ALLU_OUT) within the High Plains aquifer subcrop, within the Ogallala (To) Formation or White River Group (Tw), with well depths greater than 200 ft are Class Ia because the aquifer is hydraulically connected to and considered to be part of the underlying High Plains aquifer.

1e. Wells located within the Alluvial aquifer outcrop (ALLU_OUT) within the Great Plains aquifer subcrop, within the Dakota Group (Kd) with well depths greater than 200 ft with pump rates less than or equal to 50 gpm are Class IIb because they are unconfined, consolidated and lower yield.

1f. Wells located within the Alluvial aquifer outcrop (ALLU_OUT) within the Great Plains aquifer subcrop, within the Dakota Group (Kd) with well depths greater than 200 ft with pump rates greater than 50 gpm are Class IIa because they are unconfined, consolidated and higher yield.

1g. Wells located within the Alluvial aquifer outcrop (ALLU_OUT) within the Not a Principal aquifer subcrop, with well depths between 200 and 250 ft are Class IIc because they are covered by less than 50 ft of confining material.

1h. Wells located within the Alluvial aquifer outcrop (ALLU_OUT) within the Not a Principal aquifer subcrop, with well depths greater than 250 ft are Class III because the aquifer is overlain by more than 50 ft of low permeability material.

Rule 2. Glacial Drift aquifer (GLDA)

The unconsolidated sediments of the Glacial Drift aquifer outcrop across the eastern one fourth of Nebraska. The aquifer consists of Plio-Pleistocene age complex interbedded clay, silt, sand and gravel. The thickness of the Glacial Drift aquifer is on average between 100 and 200 ft, but locally in Nebraska thicknesses have exceeded more than 350 ft. Water is for the most part obtained from sand beds ranging in thickness from 20 to 40 ft. Because of the complexity of the glacial sediment, water is under unconfined conditions in some locations and confined conditions in other locations.

2a. Wells located within the Glacial Drift aquifer outcrop (GLDA_OUT), with well depths 100 ft or less, are Class Id because it is likely that the aquifer is covered by less than 50 ft of low permeability material.

2b. Wells located within the Glacial Drift aquifer outcrop (GLDA_OUT), with well depths exceeding 100 ft are Class III because it is likely that the aquifer is covered by at least 50 ft of low permeability material.

Rule 3. High Plains aquifer (HPLA)

The unconsolidated to semi-consolidated sediments of the High Plains aquifer outcrop across central and western Nebraska. The aquifer consists undifferentiated loess, gravel, sand, silt and clay of Quaternary age, as well as gravel, sand, silt and clay of the Miocene Ogallala Formation. In western Nebraska, the High Plains aquifer also includes the fine-grained sandstone of the Miocene Arikaree Group, as well as the fractured siltstone and sandstone of the Oligocene White River Group. In Nebraska, the average saturated thickness of the High Plains aquifer is approximately 340 ft, but in some locations can be as thin as 50 ft in central Nebraska, the High Plains aquifer can reach a saturated thickness of 1,200 ft. The aquifer is generally considered to be unconfined or under water table conditions, although local confining clay and loess deposits do exist.

3a. Wells located within the High Plains aquifer outcrop (HPLA_OUT), located within the loess surficial deposits with depths less than or equal to 100 ft are Class Id because the thickness of the low permeability loess is likely less than 50 ft.

3b. Wells located within the High Plains aquifer outcrop (HPLA_OUT), located within the loess surficial deposits with depths greater than 100 ft are Class III because the low permeability loess likely obtains a thickness of more than 50 ft.

3c. Wells located within the High Plains aquifer outcrop (HPLA_OUT), with the exception of wells located within the surficial loess deposits, are Class Ia because the aquifer is predominantly surficial and unconsolidated.

Rule 4. Great Plains aquifer (GPLA)

The consolidated sedimentary rocks of the Great Plains Aquifer are exposed at the surface in a band running north-south across eastern Nebraska. The aquifer consists of Cretaceous age loosely cemented sandstone. The Great Plains aquifer only contains fresh water along its eastern margin, and in a small area in Northwest Nebraska (Groundwater Atlas of the United States, Segment 3, Pg. D18). The Great Plains confining system, consisting of Upper Cretaceous shale, overlies the Great Plains aquifer west of the outcrop. The aquifer is confined below by shale, limestone and sandstone, and is known as the Western Interior Plains confining system. The Great Plains aquifer has an average thickness of 200 to 300 ft, but in some locations in central Nebraska it can exceed 800 ft in thickness. However, the freshwater section of Great Plains aquifer is known to be no deeper than 600 ft below land surface (Groundwater Atlas of the United States, Segment 3, Pg. D16, F. 78 and 79).

4a. Wells located within the Great Plains aquifer outcrop (GPLA_OUT), with a pump rate less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

4b. Wells located within the Great Plains aquifer outcrop (GPLA_OUT), with a pump rate greater than 50 gpm are Class IIa because they are consolidated and higher yield.

Rule 5. Not A principal aquifer (NAPA)

The Cretaceous and Pennsylvanian age consolidated sedimentary rocks that receive the not a principal aquifer designation outcrop in a band west of the Great Plains aquifer, and east of the High Plains aquifer. This aquifer consists of the Pierre Shale and Niobrara Formation which is predominantly shale with beds of limestone. Portions of northeastern Nebraska also received the not a principal aquifer designation because the Pennsylvanian age mudstone and shale outcrops here do not yield enough water to be considered a principal aquifer.

5a. Wells located within the not a principal aquifer outcrop (NAPA_OUT) with depths less than or equal to 50 ft are Class IIc because they are consolidated and covered by less than 50 ft of confining material.

5b. Wells located within the not a principal aquifer outcrop (NAPA_OUT), with depths greater than 50 ft are Class III because the aquifers are overlain by more than 50 ft of low permeability shale and/or mudstone.

Metadata Sources References

Divine, D. and S.S. Sibray. 2017. An Overview of Secondary Aquifers in Nebraska. Conservation and Survey Division. University of Nebraska – Lincoln, NE, pp 44.

Miller, J.A. and C.L. Appel. 1997. Ground water atlas of the United States: Segment 3, Kansas, Missouri, and Nebraska. Hydrologic Investigations Atlas 730-D, U.S. Geological Survey, Reston, VA, 26 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Nevada

8 April 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-L (also called Ground Water Atlas of the United States, Segment 1; Planert and Williams, 1995) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Surficial geology
3. Aquifer boundaries

The aquifer extents for Nevada were acquired from the state and were checked for accuracy using the USGS Ground Water Atlas (Planert and Williams, 1995).

There are three principal aquifers and one non-principal aquifer in Nevada:

6. Basin fill
7. Carbonate rock
8. Volcanic rock
9. Not a principal aquifer

Rule 1. Basin Fill aquifer (FILL)

The unconsolidated sediments of the Basin fill aquifer are exposed at the land surface in the Basin and Range province across much of the state of Nevada. The aquifer comprised of unconsolidated gravel, sand, silt, and clay of Pliocene to Holocene age deposited as alluvial fans, alluvial slopes, and playas. Holocene-age sediments were deposited in modern or ancestral stream beds. The basin fill aquifer contains water predominately under unconfined conditions.

1a. Wells that are located within the basin fill aquifer outcrop (FILL), with FM codes QToa, Qa, Qls are <u>Class Ia</u> because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

1b. Wells that are located within the basin fill aquifer outcrop (FILL), with FM codes Qp, QTs are <u>Class Id</u> because these fine grain silt and clay deposits are impermeable.

1c. Wells that are located within the basin fill aquifer outcrop (FILL), with FM codes KJim, MZgr, QTb, Ta3, Tbr, Ts1, Ts3, Tt3 are <u>Class IIa</u> because these deposits are consolidated.

1d. Wells that are located within the basin fill aquifer outcrop (FILL), with FM codes PPc, TRc are <u>Class Ib</u> because these deposits are soluble carbonates.

Rule 2. Carbonate Rock aquifer (CARB)

The consolidated rocks of the Carbonate rock aquifer underlie the alluvial basins of the Basin and Range and outcrop in eastern Nevada. The aquifer is Paleozoic to Mesozoic in age, and is comprised of an upper sequence of limestone and minor dolomite interbedded with shale and sandstone, and a lower sequence of limestone and dolomite that contains little clastic material. The aquifer may be greater than 15,000 ft in thickness and is highly fractured and locally brecciated. The aquifer contains water under unconfined conditions.

2a. Wells located within the Carbonate rock aquifer outcrop (CARB), are Class Ib because the aquifer is comprised of soluble carbonate rocks.

Rule 3. Volcanic Rock aquifer (VOLC)

The volcanoclastic rocks of the Volcanic rock aquifer outcrops along the northern border and in southern Nevada. The aquifer is Cenozoic in age and is comprise of a mixture of welded ash flows, bedded ash flows, and lava flows. The aquifer contains water under unconfined conditions, which is hosted in fractures and locally in intergranular spaces in porous tuffs.

3a. Wells located within the Volcanic rock aquifer outcrop (VOLC) are Class IIa because the aquifer unit is consolidated and unconfined.

Rule 4. Not a principal aquifer (NAPA)

The areas of Nevada designated "not a principal aquifer" lack sufficient basin-fill sediments or permeable consolidated rocks to yield significant amounts of water to wells. The aquifer is comprised of consolidated igneous, metamorphic, and sedimentary rocks, and contains both clastic and carbonate lithologies.

4a. Wells located within the Not a principal aquifer outcrop (NAPA) are Class IIa because the aquifer is consolidated and unconfined.

Metadata Sources References

Planert, M. and J.S. Williams. 1995. Ground water atlas of the United States: Segment 1, California and Nevada. Hydrologic Investigations Atlas 730-B, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in New Hampshire

25 May 2018

Introduction

The rule set below is based primarily on information published in the USGS Ground Water Atlas of the United States, Segment 12, Hydrologic Investigations Atlas 730-M (Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The data available for New Hampshire included:

1. Well location
2. Well depth
3. Pump rate
4. Source-aquifer type
5. Bedrock geology
6. Surficial aquifers

Classification of wells is based on source-aquifer-type information provided in the PWS data set and the intersection of the PWS coverage with the Surficial aquifers coverage.

Source-aquifer type is described as "bedrock aquifer," "surficial aquifer" or "unknown." Bedrock aquifers in New Hampshire are overlain by Quaternary sediments of primarily glacial and alluvial origin. Where these sediments consist of stratified sand and gravel, they can form productive aquifers. The Surficial aquifers coverage consists of two regions delineated on the basis of the grain size and sorting of the surficial materials. Bedrock aquifers consist of crystalline rocks.

Surficial Aquifers

The Surficial aquifers of New Hampshire consist primarily of Quaternary glacial deposits of sand and gravel that were laid down during several advances and retreats of continental glaciers that encroached from the north or northwest. The glacial stage between the culmination of the most recent advance, ~21,000 years ago, and the final retreat, ~12,000 years ago, is referred to as the Wisconsinian. During this stage, glacial ice covered all of New Hampshire. The glacial ice and meltwater derived from the ice laid down several characteristic deposits. Till, which consists of unsorted and unstratified material ranging in size from clay to boulders, was deposited directly from the ice. Meltwater laid down outwash, which consists chiefly of stratified deposits of sand and gravel; ice-contact deposits, which consist primarily of poorly stratified sand and gravel; and glacial-lake deposits, which consist mostly of clay, silt, and fine sand. Coarse-grained outwash and ice-contact deposits and modern stream alluvium form productive aquifers. Where surficial aquifers consist primarily of ice-contact deposits, well yields commonly range from 10 to 1,000 gallons per minute and might be as much as 3,000 gallons per minute. Where these aquifers consist primarily of outwash deposits, well yields commonly range from 10 to 400 gallons per minute and might be as much as 2,000 gallons per minute (Table 2 in Olcott, 1995). In contrast, fine-grained glacial-lake deposits and till have minimal permeability and form confining units. Permeable lenses of sand and gravel within till can form locally productive aquifers.

Rule 1. Stratified sand and gravel deposits (STRA)

Stratified sand and gravel deposits include both coarse-grained glacial meltwater deposits and postglacial modern stream alluvium. Glacial meltwater deposits include glacial outwash, outwash plains, and valley trains deposited by meltwater streams in front of the receding late Wisconsinan ice margin and ice-contact deposits, such as kames, kame terraces, eskers, and crevasse fillings deposited by meltwater streams directly adjacent to and within glacial ice. Glacial meltwater deposits are concentrated in valley and lowland areas. Postglacial stream alluvium was deposited on flood plains and streambeds by postglacial streams. The alluvium is largely reworked from glacial materials and has similar physical characteristics. Outwash and alluvium often cover varved or marine clay.

1. Because unconsolidated sand and gravel aquifers contain water under unconfined or water-table conditions and are, therefore, susceptible to contamination, all wells that derive water from stratified sand and gravel deposits (STRA) located in the stratified sand and gravel outcrop are Class Ia.

Rule 2. Till (TILL)

Till consists of low-permeability deposits including ground moraines and drumlins. Till, the most widespread of the unconsolidated surficial materials of New Hampshire, was laid down directly by glacier ice and is characterized by an unsorted matrix of sand, silt, and clay with variable amounts of stones and large boulders. Because of its poorly sorted matrix, till generally yields little water. However, some tills contain lenses of sorted sand and gravel that can locally yield water. Till forms a ground moraine that blankets the bedrock surface of New Hampshire and generally conforms to the underlying bedrock topography. It is typically thicker in the valleys and thinner on the uplands. Till also forms drumlins and other glacially streamlined hills. Other fine-grained deposits including varved-clay localities are also included in the till coverage.

2. Wells that derive their water from Till (TILL), are deriving water from buried, unconsolidated sand and gravel aquifers that are covered by an undetermined thickness of low-permeability, unconsolidated material and, thus, are Class Id.

Bedrock Aquifers

Rule 3. Crystalline rock aquifers (CRYS)

The bedrock surface of New Hampshire consists of Precambrian to Cretaceous crystalline rocks of igneous or metamorphic origin. In uplands and other areas where thin or low-permeability deposits of till blanket the bedrock, surficial aquifers are not readily available and the crystalline bedrock itself is an important source of water (Olcott, 1995). In New Hampshire, crystalline-rock aquifers consist of igneous and associated volcanic rocks, and metavolcanic and metasedimentary rocks. These aquifers contain water generally under confined conditions. Movement of water through the crystalline rocks is totally dependent on secondary openings, such as fractures and joints. Generally, secondary openings in the rocks are most prevalent near the land surface and decrease in number and size with depth. Thus, wells completed in crystalline rocks are commonly less than 600 ft deep, though some may exceed 800 ft. Well yields typically range from 1 to 10 gallons per minute. Some may exceed 100 gallons per minute (Table 16 in Olcott, 1995).

3a. All wells that derive water from the crystalline-rock aquifer (CRYS) located within the stratified sand and gravel aquifer (STRA) or outside any surficial aquifer boundary, and have a pump rate greater than 50 gpm are Class IIa.

3b. Because wells completed in crystalline-rock aquifers in New Hampshire typically yield less than 50 gallons per minute, the crystalline-rock aquifers are considered lower-yield bedrock aquifers. Therefore, all wells that derive water from the crystalline-rock aquifer (CRYS) located within the stratified sand and gravel aquifer (STRA) or outside any surficial aquifer boundary and have a pump rate of 50 gpm or less or have no listed pump rate (i.e., pump rate = 0) are Class IIb.

3c. Wells that derive water from a crystalline-rock aquifer (CRYS_SUB) located within the till aquifer are Class IIc because the aquifer is covered by an undetermined thickness of low-permeability, unconsolidated material.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in New Jersey

21 February 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-L (Ground Water Atlas of the United States, Segment 11; Trapp and Horn, 1997) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules included:

1. Well location
2. Screen depth
3. Well depth
4. Source aquifer
5. Pump rate
6. Bedrock geology
7. Surficial geology
8. Aquifer boundaries

The aquifer boundaries were generated using a combination of the state provided bedrock and surficial aquifer coverages, as well as referencing the bedrock geology coverage. The SEDTHICK layer provided by the state divides the permeable surficial sediments into the following eight sediment thickness ranges from least to greatest (discontinuous and less than 10 ft, 0-50 ft, 50-100 ft, 100-150 ft, 150-200 ft, 200-250 ft, 250-300., 300-350 ft). The Surficial aquifer was created from this layer, using the sediment thicknesses greater than 50 ft. Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are two major aquifer systems in New Jersey that are subdivided into nine principal aquifers:

North Atlantic Coastal Plain aquifer system

1. Surficial
2. Kirkwood-Cohansey
3. Castle Hayne Aquia
4. Severn-Magothy
5. Potomac

Piedmont and Blue Ridge aquifer systems

6. Aquifers in Early Mesozoic basins
7. Crystalline
8. Carbonate-rock
9. Valley and Ridge

Rule 1. Surficial aquifer (SURF)

The unconsolidated sediments of the Surficial aquifer outcrop throughout the northern third of the state where glacial sediments were deposited as well as along the east and southeast coast where predominantly dune sediments were deposited. The Surficial aquifer consists of Pleistocene to Holocene age sand and gravel alluvium as well as sand, silt and gravel till in northern New Jersey and sand dune and beach deposits in the coastal regions of the state. In some valleys in the northern third of the state, alluvium and till deposits obtain thicknesses of 350 ft along the eastern and southeastern coast of New Jersey, beach and dune deposits obtain thicknesses of 250 ft.

1a. Wells sourcing the Surficial aquifer (SURF_OUT), with screen depths less than the SEDTHICK in that location are conservatively Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.

1b. Wells sourcing the Surficial aquifer (SURF_OUT), with screen depths greater than the SEDTHICK in that location are Classified as UNK because the well is sourcing water greater than the known depth of the Surficial aquifer in that location.

Rule 2. Kirkwood-Cohansey aquifer (KIRK)

The unconsolidated sediments of the Kirkwood-Cohansey aquifer are exposed at the surface across much of southern New Jersey. The aquifer consists of Miocene to Pliocene age fine to coarse sand with clay beds present in the deeper portions of the aquifer near the coastline. The maximum thickness of the aquifer in New Jersey is 960 ft but the upper unconfined 510 ft is predominantly used as a water resource (State of New Jersey, Pinelands Commission. 2015).

2a. Wells sourcing the Kirkwood-Cohansey aquifer outcrop (KIRK_OUT) with a screen depth of less than or equal to 510 ft are Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.

2b. Wells sourcing the Kirkwood-Cohansey aquifer outcrop (KIRK_OUT) with a screen depth of greater than 510 ft are Class UNK because these wells are sourcing water at a depth greater than the predominantly used portion of the aquifer.

2c Wells sourcing the Kirkwood-Cohansey aquifer subcrop (KIRK_SUB) with screen depths less than or equal to 760 ft (this number was used because it is the maximum thickness of the Kirkwood-Cohansey aquifer combined with the maximum thickness of the coastal surficial sediments) are Class Ia because the Kirkwood-Cohansey aquifer is hydraulically connected to the Surfical aquifer and therefore the aquifer is predominantly unconsidered unconfined.

2d. Wells sourcing the Kirkwood-Cohansey aquifer subcrop (KIRK_SUB) with screen depths greater than 760 ft (this number was used because it is the maximum thickness of the Kirkwood-Cohansey aquifer combined with the maximum thickness of the coastal surficial sediments) are Class UNK because these wells are sourcing water at a depth greater than the predominantly used portion of the aquifer.

Rule 3. Castle Hayne-Aquia aquifer (CAST)

The Castle Hayne-Aquia aquifer is comprised of two local aquifers in the state of New Jersey. The Vincentown aquifer (lower portion of the Castle Hayne-Aquia aquifer) outcrops in a northeast trending band across the center of the state and subcrops to the southeast. Further to the east, the local Piney Point aquifer (upper portion of the Castle Hayne-Aquia aquifer) only exists in the subsurface and is completely confined. The two local aquifers are laterally separated from each other by less permeable sediments. The Castle Hayne-Aquia aquifer consists of Paleocene to Oligocene age glauconitic, fossiliferous, calcareous quartz sand. The Castle Hayne-Aquia aquifer obtains a maximum thickness of 220 ft but on average is approximately 90 ft thick in the state of New Jersey.

3a. Wells sourcing the Castle Hayne-Aquia aquifer outcrop (CAST_OUT) are Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.

3b. Wells stating that they are sourcing the Castle Hayne-Aquia aquifer subcrop (CAST_SUB), located in the Castle Hayne-Aquia aquifer outcrop are Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.

3c. Wells sourcing the Castle Hayne-Aquia aquifer subcrop (CAST_SUB) are conservatively Class Id because these wells are most likely sourcing aquifers covered by less than 50 ft of low permeability silt and clay.

Rule 4. Severn-Magothy aquifer (SEVE)

The Severn-Magothy aquifer is comprised of two local aquifers in the state of New Jersey. Both the Mount-Laurel Wenonah aquifer (upper portion of the Servern-Magothy aquifer) and the Englishtown aquifer (lower portion of the Severn-Magothy aquifer) outcrop in northeast trending bands across the center of the state and subcrop to the southeast. The two aquifers are separated by a silt and clay confining unit that is generally 25 to 70 ft thick. The Mount-Laurel Wenonah aquifer consists of glauconitic sand and the Englishtown aquifer consists of cross-bedded sands both of Cretaceous age. In the state of New Jersey, the Severn-Magothy aquifer can exceed 720 ft in thickness with an average of 340 ft.

4a. Wells sourcing the Severn-Magothy aquifer outcrop (SEVE_OUT) are Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.

4b. Wells stating that they are sourcing the Severn-Magothy subcrop (SEVE_SUB) located in the Severn-Magothy outcrop (SEVE_OUT) are Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.

4c. Wells sourcing the Severn-Magothy aquifer subcrop (SEVE_SUB) are Class III because these wells are most likely sourcing aquifers covered by multiple confining units exceeding 50 ft in thickness.

4d. Wells stating that they are sourcing the Severn-Magothy subcrop (SEVE_SUB) located in formations that are geologically older than the Severn-Magothy are Class UNKNOWN because a well cannot source a subcrop which stratigraphically cannot exist in the area.

Rule 5. Potomac aquifer (POTO)

The unconsolidated sediments of the Potomac aquifer outcrop in northeast trending bands across the center of the state and subcrop to the southeast. The aquifer consists of fine to course sand of Cretaceous age that can be further divided into an upper, middle and lower section separated by clay confining units generally between 50 and 150 ft thick. In New Jersey, the Potomac aquifer can reach a thickness of 3,400 ft with an average thickness of 630 ft.

5a. Wells sourcing the Potomac aquifer outcrop (POTO_OUT) are Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.

5b. Wells sourcing the Potomac aquifer subcrop (POTO_SUB), located in the Surficial outcrop, with screen depths less than or equal 50 ft are Class Ia because the wells are hydrologically connected with the surficial aquifer which is unconsolidated and unconfined.

5c. Wells sourcing the Potomac aquifer subcrop (POTO_SUB) with screen depths greater than 50 ft are Class III because these wells are most likely sourcing aquifers covered by multiple confining units exceeding 50 ft in thickness.

Rule 6. Aquifers in Early Mesozoic Basins (MESO)

The consolidated sedimentary rocks of the Aquifers in Early Mesozoic Basins outcrop in the low areas of the northern half of the state of New Jersey. The aquifer consists of predominantly sandstone, siltstone, and conglomerate of Triassic to Jurassic age. Local beds of dolomite and coal are also present in these basins but are not considered major lithologic constituents. The rocks in these basins have been calculated to be more than 20,000 ft thick.

6a. Wells sourcing the Aquifers in Early Mesozoic Basins outcrop (MESO_OUT), with pump rates less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

6b. Wells sourcing the Aquifers in Early Mesozoic Basins outcrop (MESO_OUT), with pump rates greater than 50 pgm are Class IIa because they are consolidated and higher yield.

6c. Wells sourcing the Aquifers in Early Mesozoic Basins subcrop (MESO_SUB), within the Surficial aquifer outcrop, with pump rates less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

6d. Wells sourcing the Aquifers in Early Mesozoic Basins subcrop (MESO_SUB), within the Surficial aquifer outcrop, with pump rates greater than 50 gpm are Class IIa because they are consolidated and higher yield.

6e. Wells sourcing the Aquifers in Early Mesozoic Basins subcrop (MESO_SUB), within the Crystalline aquifer outcrop are Class III because these wells are most likely sourcing aquifers covered by at least50 ft of consolidated rock.

Rule 7. Crystalline aquifers (CRYS)

The consolidated igneous and metamorphic rocks of the Crystalline aquifer outcrop throughout northern New Jersey. The aquifer consists of predominantly basalt, diabase, granite and gneiss of Proterozoic to Jurassic age. In crystalline rock areas, the fractures in bedrock serve as the principal places for the transmission of water. Generally, these aquifers produce much less than the surficial and carbonate aquifers in the surrounding basins.

7a. Wells sourcing the Crystalline aquifers outcrop (CRYS_OUT), with pump rates less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

7b. Wells sourcing the Crystalline aquifers outcrop (CRYS_OUT), with pump rates greater than 50 pgm are Class IIa because they are consolidated and higher yield.

7c. Wells sourcing the Crystalline aquifer subcrop (CRYS_SUB), within the Surficial outcrop, with pump rates less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

7d. Wells sourcing the Crystalline aquifer subcrop (CRYS_SUB), within the Surficial aquifer outcrop, with pump rates greater than 50 gpm are Class IIa because they are consolidated and higher yield.

7e. Wells sourcing the Crystalline subcrop (CRYS_SUB), within the Aquifers in Early Mesozoic Basins aquifer outcrop with screen depths less than or equal to 50 ft are Class IIc because these wells are sourcing aquifers bedrock covered by less than 50 ft of low permeability material.

7f. Wells sourcing the Crystalline subcrop (CRYS_SUB), within the Aquifers in Early Mesozoic Basins aquifer outcrop with screen depths greater than 50 ft are Class III because these wells are sourcing aquifers covered by more than 50 ft of low permeability material.

7g. Wells sourcing the Crystalline subcrop (CRY_SUB), within the Carbonate-rock aquifer outcrop, with pump rates less than or equal to 50 gpm are Class IIb because these wells are consolidated and lower yield.

7h. Wells sourcing the Crystalline subcrop (CRY_SUB), within the Carbonate-rock aquifer outcrop with pump rates greater than 50 gpm are Class IIa because these wells are consolidated and higher yield.

Rule 8. Carbonate rock aquifers (CARB)

The consolidated carbonate rocks of the Carbonate-Rock aquifers outcrop in northeast trending bands across the northwest portion of the state. The aquifer consists of predominantly limestone and dolomite of Precambrian to Ordovician age. These carbonate rocks are exposed due to faulting and although they cover a small portion of the state, they are significant local sources of water.

8a. Wells sourcing the Carbonate-rock aquifers outcrop (CARB_OUT) are Class Ib because these wells derive water from rocks that are soluble and potentially karstic.

8b. Wells sourcing the Carbonate-rock aquifers subcrop (CARB_SUB), within the Surficial aquifer outcrop, are Class Ib because these wells derive water from rocks that are soluble and potentially karstic.

8c. Wells sourcing the Carbonate-rock aquifers subcrop (CARB_SUB), within the Crystalline or Valley and Ridge aquifer outcrop with screen depths less than or equal to 50 ft are Class Id because these wells are sourcing carbonate rock covered by less than 50 ft of low permeability material.

8d. Wells sourcing the Carbonate-rock aquifers subcrop (CARB_SUB), within the Crystalline or Valley and Ridge aquifer outcrop with screen depths greater than 50 ft are Class III because these wells are sourcing carbonate rock covered by more than 50 ft of low permeability material.

Rule 9. Valley and Ridge aquifers (VALL)

The consolidated sedimentary rocks of the Valley and Ridge aquifers outcrop in the north and northwest section of the state. The aquifer consists of sandstone, siltstone, shale, conglomerate and limestone of Ordovician to Devonian age. Well yields vary from as much as 850 gallons per minute in the carbonate units to 15 gallons per minute in the siliciclastic units.

9a. Wells sourcing the Valley and Ridge aquifers outcrop (VALL_OUT), located in the follow bedrock geology (BGEO) formation codes (FM): Db, Dkc, Dmn, DSrd, Sbv, Sp are Class Ib because these wells derive water from rocks that are soluble and potentially karstic.

9b. Wells sourcing the Valley and Ridge aquifers outcrop (VALL_OUT), excluding those located in the formations mentioned in rule 9a., with pump rates less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

9c. Wells sourcing the Valley and Ridge aquifers outcrop (VALL_OUT), excluding those located in the formations mentioned in rule 9a., with pump rates greater than 50 gpm are Class IIa because they are consolidated and higher yield.

9d. Wells stating that they are sourcing the Valley and Ridge aquifer subcrop (VALL_SUB), located in the Valley and Ridge aquifers outcrop, excluding those located in the formations mentioned in rule 9a., with pump rates less than 50 gpm are Class IIb because they are consolidated and lower yield.

9e. Wells sourcing the Valley and Ridge aquifers subcrop (VALL_SUB), located in the Surficial aquifer outcrop, located in the following bedrock geology (BGEO) formation codes (FM): Db, Dmn, Dkc DSrd, Sbv, SP are Class Ib because these wells derive water from rocks that are soluble and potentially karstic.

9f. Wells sourcing the Valley and Ridge aquifers subcrop (VALL_SUB), located in the Surfical aquifer outcrop, excluding those located in the formations mentioned in rule 9a., with pump rates less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

9g. Wells sourcing the Valley and Ridge aquifers subcrop (VALL_SUB), located in the Surfical aquifer outcrop, excluding those located in the formations mentioned in rule 9a., with pump rates greater than 50gpm are Class IIa because they are consolidated and higher yield.

Sole Source Aquifers

New Jersey contains seven EPA-designed sole- ource aquifers:

- Buried Valley Aquifers, Central Basin, Essex and Morris Counties
- Highlands Aquifer System Passaic, Morris & Essex Counties, NJ
- New Jersey Coastal Plain Aquifer System
- New Jersey Fifteen Basin Aquifers
- Ramapo River Basin Aquifer Systems
- Ridgewood Area Aquifers
- Upper Rockaway River Basin

Some of the sole source aquifers mentioned above are located within multiple aquifers according to the boundaries provided by the state; therefore, these sole source aquifers are classified based on the aquifer they are most likely sourcing.

10. The Buried Valley Aquifers, Central Basin, Essex and Morris Counties SSA (BDVA_SSA) is primarily composed of surficial permeable silt, sand and gravel underlain by sandstone and siltstone in the basins and composed on crystalline rock in the uplands. The unconsolidated sediments are of glacial or alluvial origin and can obtain thicknesses of up to 350 ft. The rocks are of near-shore, volcanic and plutonic origin.
    a. Wells sourcing the Buried Valley Aquifers, Central Basin, Essex and Morris Counties SSA (BDVA_SSA) located in the Surficial aquifer outcrop with well depths less than the maximum thickness of the surficial sediment (SEDTHICK) in that location are classified the same as wells sourcing the Surficial aquifer, and are Class Ia.
    b. Wells sourcing the Buried Valley Aquifers, Central Basin, Essex and Morris Counties SSA (BDVA_SSA), with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location with pump rates less than or equal to 50 gpm are Class IIb because they are sourcing consolidated non-carbonate rock aquifers that are lower yield.
    c. Wells sourcing the Buried Valley Aquifers, Central Basin, Essex and Morris Counties SSA (BDVA_SSA), with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location with pump rates greater than 50 gpm are Class IIa because they are sourcing consolidated non-carbonate rock aquifers that are higher yield.

11. New Jersey Coastal Plains Aquifer SSA (COAS_SSA) is primarily composed of permeable silt, sand and gravel. The unconsolidated sediments are of alluvial, deltaic, shallow marine and marine origin and can obtain thicknesses of 3,400 ft in the state of New Jersey.
    a. Wells sourcing New Jersey Coastal Plains Aquifer SSA (COAS_SSA) located in any of the following aquifer outcrops: Surficial aquifer (SURF_OUT), Kirkwood-Cohansey Aquifer (KIRK_OUT), Castle Hayne-Aquia aquifer (CAST_OUT), Severn-Magothy aquifer (SEVE_OUT), Potomac Aquifer (POTO_OUT), are conservatively Class Ia because these wells are sourcing predominantly surficial, unconsolidated, permeable sediments.
    b. Wells sourcing the New Jersey Coastal Plains Aquifer SSA (COAS_SSA) located in the Not a Principal aquifer outcrop are conservatively Class Id because these wells are most likely sourcing aquifers covered by low permeability silts and clays.

12. Highlands Aquifer System Passaic, Morris & Essex Counties, NJ SSA (HIGH_SSA) is composed of surficial permeable silt, sand and gravel underlain by sedimentary, igneous and metamorphic rocks. The consolidated rocks are of plutonic, volcanic and marine origin.
    a. Wells sourcing the Highlands Aquifer System Passaic, Morris & Essex Counties, NJ SSA (HIGH_SSA) located in the Surficial aquifer with well depths less than the

maximum thickness of the surficial sediment (SEDTHICK) in that location are classified the same as wells sourcing the Surficial aquifer, and are Class Ia.

b. Wells sourcing the Highlands Aquifer System Passaic, Morris & Essex Counties, NJ SSA (HIGH_SSA) with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location, with pump rates less than or equal to 50 gpm are Class IIb because they are sourcing consolidated non-carbonate rock aquifers that are lower yield.

c. Wells sourcing the Highlands Aquifer System Passaic, Morris & Essex Counties, NJ SSA (HIGH_SSA) with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location, with pump rates greater than 50 gpm are Class IIa because they are sourcing consolidated non-carbonate rock aquifers that are higher yield.

13. New Jersey Fifteen Basin Aquifers SSA (FTBA_SSA) is composed of sedimentary, igneous and metamorphic rocks. The consolidated rocks are of plutonic, volcanic and marine origin.

    a. Wells sourcing the New Jersey Fifteen Basin Aquifers SSA (FTBA_SSA) located in the Surficial aquifer with well depths less than the maximum thickness of the surficial sediment (SEDTHICK) in that location are classified the same as wells sourcing the Surficial aquifer, and are Class Ia.

    b. Wells sourcing the New Jersey Fifteen Basin Aquifers SSA (FTBA_SSA) located in the Surficial aquifer with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location, located in a non-carbonate bedrock outcrop or subcrop with pump rates less than or equal to 50 gpm are Class IIb because they are sourcing consolidated non-carbonate rocks and are lower yield.

    c. Wells sourcing the New Jersey Fifteen Basin Aquifers SSA (FTBA_SSA) located in the Surficial aquifer with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location, located in a non-carbonate bedrock outcrop or subcrop with pump rates greater than 50 gpm are Class IIa because they are sourcing consolidated non-carbonate rocks and are higher yield.

d. Wells sourcing the New Jersey Fifteen Basin Aquifers SSA (FTBA_SSA) located in the Surficial aquifer with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location, located in the Carbonate-rocks outcrop or subcrop (CARB) are conservatively classified the same as wells sourcing the Carbonate-rock aquifer, and are Class Ib.

14. Ramapo River Basin Aquifer Systems SSA (RAMA_SSA) is composed of predominantly permeable silt, sand and gravel. The unconsolidated sediments are of glacial or alluvial origin.

    a. Wells sourcing the Ramapo River Basin Aquifer Systems SSA (RAMA_SSA) are classified the same as wells sourcing the Surficial aquifer; therefore, they are Class Ia.

15. Ridgewood Area Aquifers SSA (RIDG_SSA) is composed of sandstone, siltstone and conglomerate. The consolidated rocks are predominantly of fluvial, shallow marine and marine origin.

    a. Wells sourcing the Ridgewood Area Aquifers SSA (RIDG_SSA) located in the Aquifers in Early Mesozoic Basins (MESO) outcrop with pump rates less than or equal to 50 gpm are Class IIb because they are sourcing consolidated non-carbonate rocks and are lower yield.

    b. Wells sourcing the Ridgewood Area Aquifers SSA (RIDG_SSA) located in the Aquifers in Early Mesozoic Basins (MESO) outcrop with pump rates greater than 50 gpm are Class IIa because they are sourcing consolidated non-carbonate rocks and are higher yield.

16. Upper Rockaway River Basin SSA (ROCK_SSA) is composed of predominantly permeable silt, sand and gravel. The unconsolidated sediments are of glacial or alluvial origin.

    a. Wells sourcing the Upper Rockaway River Basin SSA (ROCK_SSA) located in the Surficial aquifer with well depths less than the maximum thickness of the surficial sediment (SEDTHICK) in that location are classified the same as wells sourcing the Surficial aquifer, and are Class Ia.

    b. Wells sourcing the Upper Rockaway River Basin SSA (ROCK_SSA) located in the Surficial aquifer with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location, located in a non-carbonate bedrock outcrop or subcrop with pump rates less than or equal to 50 gpm are Class IIb because they are sourcing consolidated non-carbonate rocks and are lower yield.

    c. Wells sourcing the Upper Rockaway River Basin SSA (ROCK_SSA) located in the Surficial aquifer with well depths greater than the maximum thickness of the surficial sediment (SEDTHICK) in that location, located in a non-carbonate bedrock outcrop or subcrop with pump rates greater than 50 gpm are Class IIa because they are sourcing consolidated non-carbonate rocks and are higher yield.

Metadata Sources References

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

State of New Jersey, Pinelands Commission. 2015.Kirkwood-Cohansey Project. Retrieved from: https://www.nj.gov/pinelands/science/complete/kc/

Trapp, Jr., H. and M.A. Horn, 1997. Ground water atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. Hydrologic Investigations Atlas 730-L, U.S. Geological Survey, Reston, VA, 32 pp.

Rules for Applying the Pettyjohn Classification Scheme in New Mexico

12 April 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-C (referred to as Segment 2 atlas, Robson and Banta, 1995 below) and the previously published DW USA reports (RSPA, 2002). The available data set included:

1. Wells: location, depth, casing depth, pump rate
2. Aquifers
3. Bedrock geology (with Quaternary Alluvium)

Feature classes were provided for some aquifer boundaries by the New Mexico Bureau of Geology and Mineral Resources. All other aquifer coverages were interpreted from the bedrock geology coverage provided by the USGS.

The following aquifers of New Mexico were distinguished for this work:

1. Alluvial
2. Basin and Range
3. Rio Grande
4. High Plains
5. Colorado Plateau: Uintah-Animas
6. Colorado Plateau: Mesaverde
7. Colorado Plateau: Dakota-Glen Canyon
8. Colorado Plateau: Coconino-De Chelly
9. Roswell Basin
10. Capitan
11. Not a principal aquifer

Rule 1. Alluvial aquifers (ALLU)

Unconsolidated Tertiary and Quaternary deposits of sand and gravel form four principal aquifers in New Mexico, the alluvial aquifers, Basin and Range aquifers, Rio Grande aquifer system, and High Plains aquifer. Unconsolidated Quaternary deposits of alluvial gravel, sand, silt, and clay or Quaternary deposits of eolian sand and silt are present on the eastern plains of New Mexico and in valleys of the mountainous area of western New Mexico. These deposits generally form the shallowest aquifers in the state and, collectively, are referred to as alluvial aquifers. In general, the alluvial aquifers of New Mexico are thin and little utilized. Aquifers also occur in the alluvial deposits of the Basin and Range Physiographic Province, the Rio Grande Basin, and the Roswell Basin. However, these shallow aquifers are part of deeper and more extensive aquifers that are discussed below. All alluvial aquifers contain water primarily under unconfined or water-table conditions. The hydraulic conductivity of these aquifers is variable, depending on the sorting of the materials and the amount of silt and clay present, but generally it is high. Accordingly, alluvial aquifers are considered to be susceptible to contamination.

1a. Wells throughout the state, located within the Alluvial aquifer, that derive water from the surficial (Holocene) sediments (alluvial valley and floodplain deposits, eolian sands, landslide deposits, alluvial fans etc.) are Class Ia, because these Holocene sands and gravels are unconsolidated deposits that connect directly with the surficial water table. Wells deriving water from these units should be no deeper than 250 ft.

1b. Wells deriving water from the surficial sediments at depths greater than 250 ft are Unknown.

Rule 2. Basin and Range aquifers (BASI)

The Basin and Range Physiographic Province is a vast arid region in the western U.S. that extends from northern Mexico to southern Idaho and Oregon, including a portion of southwestern New Mexico. It consists of broad alluvial basins in downfaulted blocks of the Earth's crust bordered by mountain ranges formed by uplifted blocks. Aquifers present in the downfaulted, alluvium-filled basins constitute the Basin and Range aquifers.

Basin-fill material consists primarily of Quaternary and Tertiary unconsolidated to moderately consolidated, poorly to well-sorted beds of gravel, sand, silt, and clay that were deposited on alluvial fans, pediments, floodplains, and playas. Stream alluvium is also present within most of the larger stream valleys. More cemented or compact sediments in the older basin fill and finer-grained sediments near the center of basins are less permeable than coarser-grained sediments near the margins of basins. Evaporites are present in the deeper fine-grained sediments in the centers of some basins. Extrusive volcanic rocks are interspersed with basin fill in some basins and overlie basin fill in a few areas. The thickness of basin fill typically ranges from 1000 to 5000 ft and may exceed 10,000 ft in a few deep basins (Robson and Banta, 1995). The Basin and Range basin-fill aquifers contain water primarily under unconfined or water-table conditions. Fine-grained deposits of silt and clay may form local confining units.

2a. The Basin and Range aquifers, located in the southwestern part of the state are, for the most part, unconsolidated sand and gravel sediments of Pliocene to Holocene age. These sediments are deposited in isolated basins created by horst and graben fault systems. All wells in the Basin and Range aquifers within course alluvium (unit abbreviations Qa, QTg,) are Class Ia, because these aquifers are most likely in hydraulic continuity with the water table. Wells may be as deep as 5,000 ft and conceivably derive water from basin fill sediments.

2b. Wells located in playa deposits (unit abbreviation Qp) within the basin and range aquifers are Class III, because any aquifers present would be confined by fine-grained sediments. Wells may be as deep as 5,000 ft and conceivably derive water from basin fill sediments.

2c. Wells located in deposits other than those listed in rules 2a or 2b and deriving water from the Basin and Range aquifer system are most likely Class IIb lower yield, igneous bedrock aquifers. Wells may be as deep as 5,000 ft and conceivably derive water from basin fill sediments.

2d. Wells deriving water from Basin and Range aquifers at depths greater than 5,000 ft are classified as Unknown.

Rule 3. Rio Grande aquifer system (RIOG)

The Rio Grande aquifer system is the principal aquifer in a 70,000-square-mile area of southern Colorado, central New Mexico, and western Texas. The aquifer system consists of hydraulically interconnected aquifers in Tertiary and Quaternary basin-fill deposits along the Rio Grande Valley and surrounding valleys. The Rio Grande rift is the principal geologic feature of the area. The rift is a north-south trending series of interconnected, downfaulted and rotated blocks located between uplifted blocks to the east and west.

The basin-fill deposits consist of unconsolidated gravel, sand, silt, and clay, or partly consolidated sedimentary or volcanic materials. The thickness of the basin fill is unknown in most areas, but is estimated to be as much as 20,000 ft near Albuquerque, NM (Robson and Banta, 1995). Most basins are bounded on the west by Quaternary and Tertiary volcanic rocks and on the east by Precambrian to Mesozoic igneous, metamorphic, and sedimentary rocks. Although some volcanic rocks, solution-altered carbonate rocks, or extensively fractured units can locally yield water, the bedrock as a whole has minimal permeability and is considered to form an impermeable base to the Rio Grande aquifer system. Older and younger basin fill are the principal water-yielding materials in the Rio Grande aquifer system. Older basin fill consists of the Santa Fe Group in most of the area and its lateral equivalent, the Gila Conglomerate, in the southwestern part of the aquifer system. The Santa Fe Group is a Tertiary and Quaternary rock-stratigraphic unit that consists of unconsolidated to moderately consolidated lenticular deposits of gravel, sand, and clay interbedded in some areas with andesitic and rhyolitic lava flows, tuffs and breccias. Younger basin fill consists of unconsolidated, poorly to well-sorted, interbedded Quaternary gravel, sand, silt, and clay. Alluvial fans and pediment-cover deposits near the mountains generally grade into, and intertongue with, either fine-grained fluvial deposits in valleys or coarser-grained fluvial deposits. Terrace deposits consisting of gravel, sand, and silt extend up to 175 ft above the floodplain. Sediments consisting of alluvial deposits of the Santa Fe Group and floodplain deposits of the Rio Grande and its tributaries form the most permeable part of the Rio Grande aquifer system. Water in the Rio Grande aquifer system is present under both unconfined and confined conditions. Beds of relatively impermeable clay, silt, or unfractured volcanic rocks form confining units.

3a. Wells in the Rio Grande aquifer system (central and southwest New Mexico) derive water primarily from Cenozoic unconsolidated to semi-consolidated alluvium. Limited amounts of water are derived from igneous units of the same age. Wells that are located in Quaternary and Tertiary alluvium are Class Ia, if they derive water from depths shallower than 200 ft.

3b. Wells deeper than 200 ft or that are located in the Mancos shale units (Km, Kml) generally are Class III because of the high probability of confining units. The segment 2 atlas (Robson and Banta, 1995) states that, in general, the contact between Quaternary alluvium and moderately consolidated, older basin fill is at 100 ft depth and is characterized by changes in lithology and consolidation. This, coupled with Figure 61, which shows the interfingering of clay units with alluvial sands, supports the 200 ft rule. It should be noted that the rule incorporates a 100 ft buffer, which was used to accommodate the potential for changes in unit thickness.

3c. Wells located in igneous rocks of any age (unit abbreviations Qb, Qbo, Qbt, QTb, Qv, Thb, TKav, Tla, Tlrf, Tlrp, Tlv, Tmb, Tnb, Tnr, Tnv, Tpb, Tual, Tuau, Turf, Turp, Tuv, Tv) and deriving water from the Rio Grande aquifer system are most likely Class IIb, lower yield bedrock aquifers.

Rule 4. High Plains aquifer (HIGH)

Near-surface Tertiary and Quaternary deposits of unconsolidated or partly consolidated gravel, sand, silt, or clay underlie the Great Plains of eastern New Mexico and compose the High Plains aquifer.

The High Plains aquifer extends across an area of about 174,000 square miles in parts of eight western states, including eastern New Mexico. The boundary of the aquifer approximates the boundary of the Great Plains Physiographic Province. Tertiary geologic units include the Bidahochi Formation, Picuris Formation, Las Feveras Formation, and Ogallala Formation.

Quaternary deposits include alluvial deposits, loess, dune sand, and valley-fill deposits. In eastern New Mexico, saturated Quaternary sediments are generally thin and discontinuous. Loess deposits are generally impermeable and do not form aquifers. The Ogallala Formation is the principle water-bearing geologic unit in the High Plains aquifer in eastern New Mexico. It consists of an unconsolidated sequence of gravel, sand, silt, and clay. Moderately- to well-cemented zones within the Ogallala are resistant to weathering and form ledges in outcrop areas. The most distinctive of these ledges, the Ogallala caprock, is near the top of the Ogallala in large areas of New Mexico, where it can be as thick as 60 ft. The Ogallala was deposited by ancient streams that flowed eastward from the Rocky Mountains. The aggrading streams deposited fluvial sediments in stream valleys that were eventually filled and buried and thick deposits of Ogallala sediments extended over a vast area. Present stream valleys of eastern New Mexico do not necessarily correspond to the location of the ancient stream valleys. The thickness of the Ogallala Formation is highly irregular and ranges from 0 to approximately 500 ft (Robson and Banta, 1995). The bedrock formations underlying the High Plains aquifer consist primarily of impermeable shale. The average hydraulic conductivity of the High Plains aquifer in Colorado is 60 ft per day. It has an average saturated thickness of about 75 ft and an average transmissivity of about 4,500 ft squared per day (Robson and Banta, 1995).

- 4a. Wells within the boundary of the High Plains aquifer that derive water from surficial Quaternary sediments (Qa, Qe, Qoa, Qp) at depths less than 150 ft are Class Ia.
- 4b. Wells with depths between 150 ft and 600 ft (see rule 4d) and located within the surficial deposits (including basaltic lava flows) are most likely deriving water from the underlying Ogallala sandstones and are therefore Class Ic. The wells are classed as such because the alluvium, which is described in the segment 2 atlas (Robson and Banta, 1995) as “thin and discontinuous” is very permeable.
- 4c. Wells located in and deriving water from the semi-consolidated sandstones of the Tertiary Ogallala Formation (Unit abbreviation To) at depths of 600 ft or less (see rule 4d) are Class Ic.
- 4d. Wells anywhere within the High Plains aquifer that are deeper than 600 ft derive water from older units underlying the aquifer. These wells are Class III, because the aquifer overlies confining Mesozoic units (Robson and Banta, 1995, Segment 2 atlas, pg C18).

Colorado Plateaus Aquifers

In the Colorado Plateaus region of northwestern New Mexico, a thick Permian to Eocene sequence of poorly to well-consolidated conglomerate, sandstone, and shale form the Colorado Plateaus aquifers. Volcanic rocks, carbonate rocks, and evaporite deposits also form locally productive aquifers.

The Colorado Plateaus aquifers underlie an area of ~110,000 square miles in western Colorado, northwestern New Mexico, Northeastern Arizona, and eastern Utah. This area is roughly coincident with the Colorado Plateaus Physiographic Province. Structural deformation and faulting, associated with uplift of the Rocky Mountains, and lateral changes in the lithology of the rocks have produced a complex sequence of water-yielding layers. Uplift of the Colorado Plateaus steepened stream gradients and accelerated the downcutting of the Colorado River. Broad structural basins were developed between some of the uplifted areas. The thickness and hydraulic characteristics of the geologic units that compose the aquifers vary greatly. Thickness of aquifers generally increases toward the central parts of basins. The principal aquifers of the Colorado Plateaus aquifers are the Uinta-Animas aquifer, Mesaverde aquifer, Dakota-Glen Canyon aquifer system, and Coconino-De Chelly aquifer. Relatively impermeable confining units separate each of the four principal aquifers. The two thickest of these confining units are the Mancos Shale, which underlies the Mesaverde aquifer, and the Chinle-Moenkopi confining unit, which underlies the Dakota-Glen Canyon aquifer system.

Rule 5. Colorado Plateau: Uintah-Animas aquifer (UINT)

The Uinta-Animas aquifer in the San Juan Basin of northwestern New Mexico consists of water-yielding units in the Eocene San Jose Formation and the underlying Upper Cretaceous to Paleocene Animas Formation and its lateral equivalents, the Nacimiento Formation and Ojo Alamo Sandstone. The San Jose Formation is the uppermost significant bedrock formation in the San Juan Basin and primarily consists of permeable, coarse, arkosic sandstone interlayered with mudstone. The Animas and Nacimiento Formations and the Ojo Alamo Sandstone primarily consist of permeable conglomerate and medium to vary coarse sandstone interlayered with relatively impermeable shale and mudstone. In the northwestern part of the San Juan Basin, the maximum thickness of the Uinta-Animas aquifer is about 3,500 ft (Robson and Banta, 1995).

5a. Wells located in the northwestern counties of Rio Arriba, San Juan, Sandoval, and McKinley that derive water from the Tertiary (Eocene/Paleocene) Uinta-Animas aquifer [Consisting of San Jose, Nacimiento, Animas Formations and the Ojo Alamo Sandstone] are <u>Class IIa</u>. These aquifers, composed of consolidated bedrock (sandstones, conglomerates, etc.), may be as much as 3500 ft thick.

5b. Wells located within the outcrops of the aquifer that are deeper than 3500 ft are <u>Class III</u>, because these wells derive water from older, confined units.

Rule 6. Colorado Plateau: Mesaverde aquifer (MESA)

The Mesaverde aquifer occurs in the San Juan Basin of northwestern New Mexico and consists of sandstone, coal, siltstone, and shale of the Upper Cretaceous Mesaverde Group. The principal geologic units that form the Mesaverde aquifer in this region are the Cliff House Sandstone, Menefee Formation, Point Lookout Sandstone, Crevasse Canyon Formation, and Gallup Sandstone. The Point Lookout Sandstone is the most areally extensive of the Mesaverde Group formations in the San Juan Basin. The formations of the Mesaverde Group intertongue extensively with the Mancos Shale and, to a lesser extent, with the Lewis Shale, which act as confining units.

6a. Wells that derive water from Cretaceous sandstones of the Mesa Verde aquifer (e.g., Mesaverde group (Kmv); Cliff House Sandstone (Kch, Klv); Menefee Formation (Kmf); Point Lookout Sandstone (Kph, Kpl); Crevasse Canyon Formation (Kcc); Gallup Sandstone (Kg); and are located within the outcrop belt of those sandstones are Class IIa. Wells may be as deep as 4500 ft and still derive water from the Mesaverde aquifer (Robson and Banta, 1995, Segment 2 atlas, C28).

6b. Wells deeper than 4500 ft anywhere in the aquifer are Class III due to underlying confining units.

6c. Wells located within the Lewis shale or Kirtland and Fruitland formations (Kls, Kkf) or the interbedded sandstone and Mancos Shale formations (Kmu, Kpg, Kth) are Class III, because these formations contain confining units overlying or inter-tongued with the permeable units of the Mesaverde aquifer.

Rule 7. Colorado Plateau: Dakota-Glen Canyon aquifer (DAKO)

A sequence of Upper Triassic to Cretaceous rocks underlie most of the Colorado Plateaus and contain a series of aquifers and confining units referred to as the Dakota-Glen Canyon aquifer system. In the San Juan Basin and surrounding areas of northwestern New Mexico, the geologic units that form the bulk of these aquifers are the Upper Cretaceous Dakota Sandstone, the lower part of the Upper Jurassic Morrison Formation, and the Middle Jurassic San Rafael Group, including the Entrada Sandstone. Rocks that compose the Dakota-Glen Canyon aquifer system are older than the Mancos shale, which forms the overlying Mancos confining unit, and younger than the Chinle and Moenkopi Formations, which form the underlying Chinle-Moenkopi confining unit. Sandstone, conglomerate, and conglomeratic sandstone are the principal water-yielding rocks. Low-permeability layers of mudstone, claystone, siltstone, shale, and limestone form confining units that separate individual aquifers in the Dakota-Glen Canyon aquifer system. Lithology of the Dakota Sandstone varies widely and includes conglomerate, sandstone, siltstone, mudstone, carbonaceous shale, and coal. The middle and lower parts of the Morrison Formation consist of interbedded fine to medium sandstone, siltstone, and mudstone. The principal water-yielding unit in the San Rafael Group is the Entrada Sandstone, which is generally a very fine to fine sandstone commonly of eolian origin.

7a. Wells that derive water from Jurassic sandstones of the Dakota-Glen Canyon Aquifer system [e.g., Entrada Sandstone or sandstones within the Morrison Formation (unit abbreviations J, Jm, Jmsu, Je, Jze, Jz, Jsr)] or the Lower Cretaceous Dakota Sandstone (unit abbreviations Kdr, Kmd, Kd, Kdg) are Class IIa. Wells within the Jurassic unit outcrops may be as deep as 300 ft. Wells within Cretaceous unit outcrops may be as deep as 200 ft.

7b. Wells deeper than the limits specified in rule 7a are Class III due to underlying confining units (Robson and Banta, 1995, Segment 2 atlas, C29).

7c. Wells within the Mancos Shale confining units (unit abbreviations Km, Kml, Kmm, Kmr, and Kms) and deriving water from the Dakota-Glen Canyon aquifer system are Class III.

Rule 8. Colorado Plateaus: Coconino-De Chelly aquifer (COCO)

The Coconino-De Chelly aquifer consists of water-yielding Permian rocks that underlie the southern part of the Colorado Plateaus, including much of northwestern New Mexico. The formations that compose the Coconino-De Chelly aquifer in this region are the Glorieta Sandstone, Yeso Formation, and San Andres Limestone. The Glorieta Sandstone is a well-sorted, well-cemented, fine- to medium-grained quartz sandstone. The Yeso Formation consists of interbedded sandstone, siltstone, limestone, anhydrite, and gypsum and forms a low-permeability zone within the aquifer. The San Andres Limestone consists of dolostone, limestone, and fine-grained clastic rocks. The carbonate rocks of the San Andres Limestone contain abundant solution openings that substantially increase the permeability of the formation.

8a. Wells located within and deriving water from Pennsylvanian and Permian sandstones of the Coconino-De Chelly Aquifer [Hermosa Formation, Glorieta Sandstone, Yeso Formation, De Chelly Sandstone, and Cutler Formation (unit abbreviations Pg, Py, Pct, and Psy)] are Class IIa if they yield > 50 gpm (because they are consolidated sandstones).

8b. Wells that yield < 50 gpm are Class IIb. If the yield is unknown, these wells should be categorized as Class IIa, subject to further verification.

8c. Wells within the overlying San Andres Limestone (Psa, Psg) are Class Ib because while this unit overlies and to some degree confines the aquifer, it potentially has dissolution porosity.

8d. Wells deriving water from the Coconino-De Chelly aquifer units located in the following outcrops are Class III because of a likely presence of confining units: Chinle Group (^c) and Rock Point Formation (^rp).

Rule 9. Roswell Basin aquifer (ROSW)

In the Roswell Basin of southeastern New Mexico, an alluvial aquifer and an underlying carbonate-rock aquifer form the Roswell Basin aquifer system. This aquifer system underlies part of the Pecos River and extends through an area of ~2,200 square miles from north of Roswell to northwest of Carlsbad, NM. Although Quaternary and Tertiary alluvium covers an area of ~1,200 square miles, it is an important aquifer only in about 740 square miles, primarily along the western side of the Pecos River. Groundwater in underlying Permian carbonate rocks is present in openings formed by dissolution of portions of the limestone, dolomite, and gypsum that are prevalent in the rock. Carbonate rocks underlie an area of ~12,000 square miles between Vaughn, NM and the New Mexico-Texas border. The most permeable and extensively utilized aquifer in the carbonate rocks is in the Roswell Basin.

Groundwater in the carbonate-rock aquifer in the Roswell basin primarily is present in solution-altered zones in the San Andres Limestone and the overlying Queen and Grayburg Formations. Limestone and dolomite are the principal rocks in the San Andres, though a 100- to 200-foot-thick sandstone (Glorieta Sandstone) is located near the base of the formation. The Grayburg Formation predominantly consists of dolomite and gypsum with interbedded sandstone and shale. The Queen Formation consists of fine-grained sandstone and siltstone with interbedded gypsum. The carbonate-rock aquifer is 200 to 500 ft thick in the eastern half of the basin and thins northward and westward (Robson and Banta, 1995). The lower boundary of the aquifer is formed by the lower part of the San Andres Limestone or the Glorieta Sandstone, or the underlying Yeso Formation, all of which are much less permeable than the aquifer. The upper parts of the Queen and Grayburg Formations generally have been little altered by dissolution and have low permeability. The Seven Rivers, Yates, and Tansil Formations overlie the Queen Formation. These three formations consist of dolomite, limestone, and gypsum, with interbedded sandstone and siltstone. There is an uneven distribution of solution openings in the carbonate-rock aquifer of the Roswell Basin.

Quaternary alluvium consisting of unconsolidated gravel, sand, silt, and clay unconformably overlies the Permian rocks in the Roswell Basin. The alluvium is generally 150 to 300 ft thick near the Pecos River and thins to the west (Robson and Banta, 1995). The alluvial aquifer is hydraulically connected to the underlying carbonate-rock aquifer by leakage through the upper confining unit of the carbonate-rock aquifer.

9a. Wells that derive water from the alluvial sediments (unit abbreviations Qa, Qp, Qep, Qoa) in the Roswell Basin are Class Ia, because these sand and gravel deposits connect directly with the water table. Wells deriving water from the alluvium in the Roswell Basin should be no deeper than 300 ft.

9b. Wells deeper than 300 ft most likely derive water from underlying Permian or older units and are Class III, because a confining unit under lies the alluvium (Figures 94 and 96, Robson and Banta, 1995, Segment 2 atlas).

9c. Wells deriving water from the San Andres, Tansil and Yates, Queen and Grayburg, and Seven Rivers Formations (Unit abbreviations Psa, Pat, Pty, Pqg, Psr) in the east and southeast portions of the aquifers are Class Ib, because the limestones and dolomites have undergone dissolution.

Rule 10. Capitan aquifer (CAPI)

The Capitan aquifer occurs in the Capitan Reef Complex, an ancient reef that formed around the margins of the Delaware Basin, an embayment covered by a shallow sea that persisted throughout most of the Permian. Most of the reef complex was buried by tectonism and subsequent sedimentation; however, relatively undeformed remains of the reef are exposed in New Mexico. The Capitan Reef Complex (Permian) is composed of “cavernous dolomite” and a highly porous limestone. Common rock names: Capitan Limestone, Goat Seep Dolomite, and most of the Carlsbad facies of the Artesia Group, including the Grayburg, Queen, Seven Rivers, Yates, and Tansil formations. A 1200 ft depth cut-off for wells deriving water from this aquifer is based on a statement in the Segment 4 Atlas, USGS (1996) that the aquifer has been “penetrated by wells to depths >1000 ft”, and reports of water levels that “range between 280 to 1000 ft below the surface” in the same publication. The addition of 200 ft is to allow for uncertainty in the measurement of well depth.

10a. Wells in the outcrop belt of the Capitan Reef Complex aquifer that derive water from that aquifer at depths up to 1200 ft are Class Ib.

10b. Wells deeper than 1200 ft are classified as Unknown.

Not a principal aquifer (LIME, SAND, VOLC, GRAN)

The outcrop belts of some rock units in New Mexico are designated as 'not a principal aquifer' (Fig. 1; modified from Fig. 11, Robson and Banta, 1995). This designation covers areas where aquifers either do not exist, yield too little water to be significant, or yield sufficient water to supply only local requirements, but are not extensive enough to be considered major aquifers. These outcrop belts consist of Precambrian to Quaternary igneous, metamorphic, and sedimentary rocks.

Rule 11. Limestone aquifers (LIME)

11a. Wells located in the outcrop belt of Permian carbonate rocks/gypsum in the southeastern part of the state (outside outcrops of other aquifers; Figure 92; Robson and Banta, 1995, Segment 2) that derive water from the San Andres Limestone, Queen, Grayburg and Seven Rivers Formations at depths of 1500 ft or shallower are Class Ib, because these rocks contain solution cavities.

11b. Wells located in the outcrop of the carbonate aquifers and deriving water at depths greater than 1500 ft are classified as Unknown.

Rule 12. Sandstone and shale aquifers (SAND)

12a. Wells located within the and deriving water from the Greenhorn Formation and Carlisle Shale (Kgc) or the San Andres Limestone and Glorieta Sandstone (Psg) are Class Ib, because these rocks may contain solution cavities.

12b. Wells located within and deriving water from sandstones in the NAPA regions are Class IIa unless otherwise specified, because they are consolidated sandstones.

12c. Wells that derive water from Cretaceous or Jurassic sandstones and are located within the outcrop belt of those sandstones are Class IIa. Wells that derive water from Cretaceous sandstones (Kmv, Kch, Klv, Kmf, Kph, Kpl, Kcc, Kg) may be as deep as 4500 ft (see rule 6a). Wells that derive water from Jurassic sandstones (J, Jm, Jmsu, Je, Jze, Jz, Jsr) may be as deep as 300 ft. Wells that derive water from the Lower Cretaceous Dakota Sandstone (Kdr, Kmd, Kd, Kdg) may be as deep as 200 ft (see rule 7a).

12d. Wells that derive water from Cretaceous or Jurassic sandstones at depths greater than those specified in rule 12b are Class III due to underlying confining units.

12e. Wells that derive water from the low-yield Cretaceous Pierre Shale, Mancos Shale, and Niobrara Formation (Kpn, Kmb, Kml, Km) or the low-yield sedimentary rocks of the Santa Fe Group (QTs, QTsf, Tlp, Tsf), Chinle Group (^c), Santa Rosa Formation (^s), and Trujillo Formation (^t) are Class IIb.

12f. Wells within the boundary of the sandstone and shale aquifers that derive water from the low-yield Tertiary intrusive rocks (Ti) are Class IIb.

Rule 13. Volcanic and igneous rock aquifers (VOLC)

13. Wells located in areas designated as "not a primary aquifer" in the state within and deriving water from Cenozoic-aged geologic units designated as volcanic, pyroclastic, basalt andesites, and intrusives are Class IIb because these units are low yield bedrock aquifers.

Rule 14. Granite and similar crystalline rock aquifers (GRAN)

14. Wells anywhere in the state within and deriving water from igneous or metamorphic crystalline rocks are Class IIb, because these units are low yield bedrock aquifers.

Metadata Sources References

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Robson, S.G. and E.R. Banta. 1995. Ground water atlas of the United States: Segment 2, Arizona, Colorado, New Mexico, Utah. Hydrologic Investigations Atlas 730-C, U.S. Geological Survey, Reston, VA, 34 pp.

Rules for Applying the Pettyjohn Classification Scheme in New York

28 February 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-M (also called Ground Water Atlas of the United States, Segment 12; Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Case depth
3. Well depth
4. Pump rate
5. Surficial Geology

The aquifer boundaries were generated using surface geology and the Segment 12 Atlas as a guide (Olcott, 1995).

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are six principal aquifers and one non-principal aquifer in New York:

1. Surficial
2. Long Island Surficial
3. Atlantic Coastal Plain
4. Sandstone
5. Carbonate
6. Crystalline
7. Not a principal aquifer

Rule 1. Surficial aquifer (SURF)

The unconsolidated sediments of the surficial aquifer are exposed at the land surface across the state of New York. The aquifer is comprised primarily of a combination of Quaternary age stratified and unstratified glacial deposits. Coarse-grained glacial outwash and ice-contact deposits partially fill deeply incised bedrock valleys throughout the state. The lithology of the aquifer is a combination of sand, gravel, and clay. The thickness of the surficial aquifer in New York is commonly less than 150 ft, and the aquifer contains water under unconfined conditions. Yields from wells sourcing the surficial aquifer commonly range from 10 gpm to 1,000 gpm, but may exceed 2,000 gpm.

1a. Wells located within the outcrop boundary of the surficial aquifer (SURF) with depth less than 150 ft are <u>Class Ia</u> because water in these unconsolidated sand and gravel deposits is under unconfined conditions.

1b. Wells located within the outcrop boundary of the sandstone aquifer (SAND), crystalline aquifer (CRYS), or not a principal aquifer (NAPA), overlain by permeable sediments of the surficial aquifer, with well depth greater than 150 ft and yield greater than 50 gpm are Class IIa because the aquifer is consolidated and the wells are higher yield.

1c. Wells located within the outcrop boundary of the sandstone aquifer (SAND), crystalline aquifer (CRYS), or not a principal aquifer (NAPA), overlain by permeable sediments of the surficial aquifer, with well depth greater than 150 ft and yield less than 50 gpm are Class IIb because the aquifer is consolidated and the wells are lower yield.

1d. Wells located within the outcrop boundary of the carbonate aquifer (CARB), overlain by permeable sediments, with well depth greater than 150 ft are Class Ib because these wells derive water from rocks that are soluble and fractured.

Rule 2. Long Island surficial aquifer (LISA)

The unconsolidated sediments of the Long Island surficial aquifer are exposed at the land surface over nearly the entirety of Long Island and Staten Island. Like the surficial aquifer elsewhere in New York, the Long Island surficial aquifer is comprised of Quaternary age stratified and unstratified glacial deposits, but unlike elsewhere, these outwash deposits are sheet-type, as opposed to valley-fill. The lithology of the aquifer is a combination of sand, gravel, and clay. The Long Island surficial aquifer is significantly thicker than surficial deposits elsewhere in New York, with the island's upper glacial aquifer reaching thicknesses of 600 ft, and the aquifer contains water under unconfined conditions. Yields from wells sourcing the Long Island surficial aquifer commonly range from 50 gallons per minute to 1,000 gpm, but may exceed 1,500 gpm.

2a. Wells located within the outcrop boundary of the Long Island surficial aquifer (LISA) with depth less than 1500 ft are Class Ia because water in these unconsolidated sand and gravel deposits is under unconfined conditions.

2b. Wells located within the outcrop boundary of the Long Island surficial aquifer (LISA) with depth greater than 1500 ft are Class Id because these wells are most likely sourcing water from the portion of the underlying Atlantic Coastal Plain aquifer where a leaky confining unit impedes the vertical flow of water.

Rule 3. Atlantic Coastal Plain aquifer (ACPA)

The Atlantic Coastal Plain aquifer underlies Long Island and parts of Staten Island, and overlies crystalline rocks that slope southeastward, and the unconsolidated sediments that form the aquifer thicken in the same direction. The lithology of the aquifer is a combination of sand and gravel with some clay. Together, the productive Magothy and Lloyd aquifer units contain water under unconfined conditions, and range in thickness from 200 to over 1500 ft. The Lloyd aquifer unit is separated from the overlying Magothy aquifer unit by a leaky confining unit. Yields from wells sourcing the Atlantic Coastal Plain aquifer range from 50 gpm to over 2000 gpm, and the aquifer is a major source of water for New York City and Long Island.

3a. Wells located within the outcrop boundary of the Atlantic Coastal Plain aquifer (ACPA), with well depth less than 1500 ft are <u>Class Ia</u> because water in these unconsolidated sand and gravel deposits is under unconfined conditions.

3b. Wells located within the outcrop boundary of the Atlantic Coastal Plain aquifer (ACPA), with well depth greater than 1500 ft are <u>Class Id</u> because these wells are most likely sourcing water from the portion of the aquifer where a leaky confining unit impedes the vertical flow of water.

Rule 4. Sandstone aquifer (SAND)

The consolidated siliciclastic sedimentary rocks of the sandstone aquifer outcrop in northern and western New York, as in the Newark and Connecticut basins. These rocks are composed mostly of sandstone, with subordinate siltstone, shale, and dolomite, and are lower Paleozoic to Mesozoic in age. Lower Paleozoic aquifers, from Precambrian to Pennsylvanian age, attain thicknesses of up to 270 ft, while the thicknesses of Mesozoic age aquifers reach 4,800 ft. While both aquifers lack a confining unit, the interbedding of sandstone and shale or carbonate reduces the vertical movement of water through the aquifers, and overlying glacial deposits further impede the vertical flow of water. Yields of wells completed in Paleozoic sandstones range from 3 to 30 gallons per minute, while wells deriving water from Mesozoic sandstones range from 13 to 34 gallons per minute.

4a. Wells located within the outcrop boundary of the sandstone aquifer (SAND), with well depth less than 50 ft are <u>Class IIc</u> because the aquifer is consolidated and is overlain by less than 50 ft of low permeability deposits.

4b. Wells located within the outcrop boundary of the sandstone aquifer (SAND), with well depth greater than 50 ft are <u>Class III</u> because the aquifer is confined.

Rule 5. Carbonate aquifer (CARB)

The consolidated carbonate rocks of the carbonate aquifer in northwestern New York and along belts that across central New York and along the state’s eastern border. These rocks are composed mostly of limestone, dolomite, and marble, and are Cambrian to Ordovician in age. Yields of wells completed in the carbonate aquifer range from 10 to 30 gpm, but can reach 1,000 gpm or more.

5a. Wells located within the outcrop boundary of the carbonate aquifer (CARB), with well depth less than 50 ft are <u>Class Id</u> because the aquifer is overlain by less than 50 ft of low permeability deposits.

5b. Wells located within the outcrop boundary of the carbonate aquifer (CARB), with well depth less than 50 ft are <u>Class III</u> because the aquifer is confined.

Rule 6. Crystalline aquifer (CRYS)

The consolidated igneous and metamorphic rocks of the crystalline rock aquifer cover outcrop in northern New York and are Paleozoic in age. These rocks contain water under unconfined conditions, mostly in secondary openings, such as joints, fractures, and faults. Yields from wells completed in the crystalline aquifer generally range from 2-10 gpm, but may exceed 500 gpm.

6a. Wells located within the outcrop boundary of the crystalline aquifer (CRYS), with well depth less than 50 ft are Class IIc because the aquifer is consolidated and is overlain by less than 50 ft of low permeability deposits.
6b. Wells located within the outcrop boundary of the crystalline aquifer (CRYS), with well depth greater than 50 ft are Class III because the aquifer is confined.

Rule 7. Not a principal aquifer (NAPA)

Some outcrop belts of Paleozoic igneous, metamorphic, and sedimentary rocks in New York are designated as 'not a principal aquifer' (NAPA). This designation covers areas where aquifers either do not exist, yield too little water to be significant, or yield sufficient water to supply only local requirements, but are not extensive enough to be considered major aquifers. The rocks are chiefly shale, but also include outcrops of metamorphic quartzite, phyllite, and greenstone.

7a. Wells located within the outcrop boundary of not a principal aquifer (NAPA), with well depth less than 50 ft are Class IIc because the aquifer is consolidated and is overlain by less than 50 ft of low permeability deposits.

7b. Wells located within the outcrop boundary of not a principal aquifer (NAPA), with well depth greater than 50 ft are Class III because the aquifer is confined.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in North Carolina

22 June 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-L (also called Ground Water Atlas of the United States, Segment 11; Trapp and Horn, 1997), the USGS Professional Paper 1773 entitled Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina (Campbell and Coes, 2010) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Source aquifer
4. Pump rate
5. Surficial geology
6. Aquifer boundaries

The aquifer boundaries were generated using surface geology and the Segment 11 Atlas (Trapp and Horn, 1997) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are eight principal aquifers in North Carolina:

1. Surficial*
2. Chesapeake*
3. Castle Hayne-Aquia*
4. Peedee-upper Cape Fear*
5. Potomac*
6. Crystalline rock and undifferentiated sedimentary rock+
7. Early Mesozoic basin+
8. Carbonate rock+
9. Not a principal aquifer

*The Surficial, Chesapeake, Castle Hayne-Aquia, and Peedee-upper Cape Fear aquifers comprise the Northern Atlantic Coastal Plain Aquifer System.

+The crystalline rock and undifferentiated sedimentary rock aquifers, the early Mesozoic basin aquifers, and the carbonate rock aquifers comprise the Piedmont and Blue Ridge Aquifer System.

Rule 1. Surficial aquifer (SURF)

The unconsolidated sediments of the surficial aquifer are exposed at the land surface in the eastern coastal plain of North Carolina, and consist of locally gravelly sand, mostly of Quaternary age.

The average thickness of the surficial aquifer in North Carolina is generally 50 ft or less, and contains water predominately under unconfined conditions. A buffer of 50 ft is added to this average thickness in order to establish a conservative rule for the classification of wells. The aquifer is defined as a principal aquifer where it is capable of yielding at least 50 gallons of water per minute. Throughout much of its extent in North Carolina, the surficial aquifer is recognized as a principal aquifer, not because of its potential to yield large volumes of water, but because the underlying aquifers commonly contain saline water and their use is restricted.

1a. Wells that derive water from the surficial aquifer, occur within the surficial aquifer outcrop (SURF_OUT), and derive water from less than 100 ft depth are Class Ia because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

1b. Wells that derive water from the surficial aquifer, occur within the surficial aquifer outcrop (SURF_OUT), and are deeper than 100 ft with the Source Code S, Kpd are Class III because the wells likely source the Peedee-upper Cape Fear aquifer subcrop, which is overlain by a confining unit.

1c. All other wells that derive water from the surficial aquifer, occur within the surficial aquifer outcrop (SURF_OUT), and are deeper than 100 ft are Class UNK because the depth is greater than the maximum depth for the surficial aquifer.

Rule 2. Chesapeake aquifer (CHPK)

The unconsolidated sediments of the Chesapeake aquifer outcrop in the northeastern part of the North Carolina coastal plain, and subcrops to the east, lying stratigraphically below the surficial aquifer. The Chesapeake aquifer consists of shelly sand, silty sand, and shell beds, and fine to medium phosphatic sand of Miocene age. The maximum thickness of the aquifer is about 1,000 ft, and the average thickness is about 330 ft. The aquifer underlies the surficial aquifer, and is partially confined by a clay-rich unit. Because areas under confinement cannot be distinguished from the aquifer's unconfined extent, for the purpose of applying the Pettyjohn classification the aquifer is treated as unconfined.

2a. Wells sourcing the Chesapeake aquifer and located within the aquifer outcrop (CHPK_OUT) are Class Ia because the aquifer is unconfined and consists of unconsolidated sediments.

2b. All other wells sourcing the Chesapeake aquifer subcrop (CHPK_SUB) are Class Ia because the aquifer is unconfined and consists of unconsolidated sediments.

Rule 3. Castle Hayne-Aquia aquifer (CHAQ)

The unconsolidated to semi-consolidated sediments of the Castle Hayne-Aquia aquifer outcrop in the southeastern coastal plain of North Carolina, and subcrops to the east, lying stratigraphically below the Chesapeake aquifers. The Castle Hayne-Aquia aquifer is confined, except where it outcrops, and consists of a highly productive upper unit of limestone, sandy marl, and fine to coarse limey sand and a less productive lower unit of fine to medium glauconitic sand with thin beds of shell and limestone. The total average thickness of the aquifer is about 185 ft.

3a. Wells sourcing the Castle Hayne-Aquia aquifer and located within the Beaufort unit (Tpa) of the aquifer outcrop (CHAQ_OUT) are Class Ia because the aquifer unit is unconsolidated and unconfined.

3b. Wells sourcing the Castle Hayne-Aquia aquifer and located elsewhere in the aquifer outcrop (CHAQ_OUT) are Class Ib because the aquifer unit is semi-consolidated carbonate and unconfined.

3c. All other wells sourcing the Castle Hayne-Aquia aquifer subcrop (CHAQ_SUB) are Class III because the Castle Hayne-Aquia aquifer is overlain by a confining unit.

Rule 4. Peedee-Upper Cape Fear aquifer (PDCF)

The semi-consolidated sediments of the Peedee-upper Cape Fear aquifer outcrop in the southern coastal plain of North Carolina, along the South Carolina border, and subcrop to the east, lying stratigraphically below the Castle Hayne-Aquia aquifer. The Peedee-upper Cape Fear aquifer is separated from the Castle Hayne-Aquia aquifer by a confining unit, and is comprised of fine to medium glauconitic sand with minor shell material and calcareous sandstone beds in the upper unit, and fine to medium sand with lenses of coarse sand and clay in the lower unit, all of Late Cretaceous age. The maximum thickness of the aquifer is about 1,200 ft; the average is about 570 ft.

4a. Wells sourcing the Peedee-upper Cape Fear aquifer and located within the aquifer outcrop (PDCF_OUT) are Class Ic because the aquifer is semi-consolidated and unconfined.

4b. All other wells sourcing the Peedee-upper Cape Fear aquifer subcrop (PDCF_SUB) are Class III because the Peedee-upper Cape Fear aquifer is overlain by confining units.

Rule 5. Potomac aquifer (PTMC)

The semi-consolidated sediments of the Potomac aquifer do not outcrop in North Carolina, and only form an aquifer subcrop in the eastern coastal plain of the state, lying stratigraphically below the Peedee-upper Cape Fear aquifer. The Potomac aquifer is separated from the Peedee-upper Cape Fear aquifer by a confining unit of clay and sandy clay, and is composed of fine to medium sand interbedded with clay in the upper unit, and fine to medium sand with a few beds of coarse sand and limestone in the lower unit, all of Lower Cretaceous age. The maximum thickness of the aquifer is about 4,900 ft, and the average thickness is about 500 ft.

6a. Wells sourcing the Potomac aquifer subcrop (PTMC_SUB) are Class III because the Potomac aquifer is confined.

Rule 6. Crystalline rock and undifferentiated sedimentary rock aquifer (CRYS)

The crystalline and consolidated sedimentary rocks of the crystalline rock and undifferentiated sedimentary rock aquifer outcrop in central and western North Carolina, in the Piedmont and Blue Ridge physiographic provinces of the state. The aquifer consists of pre-Cretaceous age crystalline igneous and metamorphic rocks and tightly cemented, predominantly clastic sedimentary rocks. Water is obtained from the regolith and/or fractures in these rocks.

6a. Wells sourcing the crystalline rock and undifferentiated sedimentary rock aquifer and located within the outcrop of the aquifer (CRYS_OUT), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

6b. Wells sourcing the crystalline rock and undifferentiated sedimentary rock aquifer and located within the outcrop of the aquifer (CRYS_OUT), with a pump rate less than or equal to 50 gpm are Class IIb because they are unconfined and lower yield.

6c. Wells sourcing the crystalline rock and undifferentiated sedimentary rock aquifer and located outside of the aquifer boundary (CRYS_SUB), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

6d. Wells sourcing the crystalline rock and undifferentiated sedimentary rock aquifer and located outside of the aquifer boundary (CRYS_SUB), with a pump rate less than or equal to 50 gpm are Class IIb because they are unconfined and lower yield.

Rule 7. Early Mesozoic Basin aquifer (MESO)

The Triassic- and Jurassic-age consolidated sedimentary rocks and minor crystalline rocks of the Early Mesozoic basin aquifers outcrop in elongate rift basins developed within crystalline rocks of the Piedmont physiographic province and located in northern North Carolina, along the Virginia border. The aquifer is comprised predominately of interbedded shale, sandstone, and siltstone, and commonly has been intruded by diabase dikes and sills.

7a. Wells sourcing the Early Mesozoic basin aquifers and located within the aquifer (MESO_OUT), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

7b. Wells sourcing the Early Mesozoic basin aquifers and located within the aquifer (MESO_OUT), with a pump rate less than or equal to 50 gpm are Class IIb because they are unconfined and lower yield.

Rule 8. Carbonate rock aquifer (CARB)

The Paleozoic and Precambrian age carbonate rock aquifer outcrop locally in western North Carolina and are contained within two windows eroded through major thrust sheets, which expose the underlying rocks. The aquifer is composed of either dolomite or marble.

8a. Wells sourcing the carbonate rock aquifer and located within the aquifer (CARB_OUT) are Class Ib because they are unconfined and higher yield.

Rule 9. Not a principal aquifer (NAPA)

The Triassic- and Jurassic-age consolidated sedimentary rocks and minor crystalline rocks that receive the not a principal aquifer designation outcrop in central and southern North Carolina, and are similar in comparison to the Early Mesozoic basin aquifer that outcrops in northern North Carolina. These rocks are more compacted and highly cemented than the rocks of the Early

Mesozoic basin aquifer, however, and do not yield sufficient quantities of water to be considered a principal aquifer.

9a. Wells sourcing the non-principal aquifer and located within the aquifer (NAPA_OUT), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

9b. Wells sourcing the non-principal aquifer and located within the aquifer (NAPA_OUT), with a pump rate less than or equal to 50 gpm are Class IIb because they are unconfined and lower yield.

Metadata Sources References

Campbell, B.G. and A.L. Coes (eds.). 2010. Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina. USGS Professional Paper 1773, U.S. Geological Survey, Reston, VA, 272 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Trapp, H. and M.A. Horn. 1997. Ground water atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. Hydrologic Investigations Atlas 730-L, U.S. Geological Survey, Reston, VA, 26 pp.

Rules for Applying the Pettyjohn Classification Scheme in North Dakota

12 February 2018

Introduction

The following rules were devised primarily on the basis of information provided in the USGS Hydrologic Investigations Atlas 730-I (Whitehead, 1996) and the previously published DW USA reports (RSPA, 2002). The dataset available at the time these rules were written consisted of:

1. Digital geology (including both quaternary and bedrock geology)
2. Location of shallow aquifers within glacial cover
3. Well locations

Note that well depth and source information were not available in the well database. The addition of this information would in most cases significantly alter the guidelines listed below. Wells are classified solely on the basis of their location and the lithology of the bedrock or sedimentology of the unconsolidated material in the area.

1. Surficial
2. Glacial
3. Tertiary
4. Cretaceous

Rule 1. Surficial aquifers (SURF)

These aquifers consist of alluvial valley fill, pro-glacial lake shoreline deposits, and eolian sands. The alluvial sediments fill stream valleys or broad tectonic basins of mountainous areas. The tectonic basins were formed by faulting or erosion or both. The alluvium in the basin was deposited primarily as coalescing alluvial fans by streams that flowed into the valleys from the surrounding mountains. All the surficial sediments are unconsolidated, permeable materials.

1. Wells located within the mapped area of and deriving water from the Surficial aquifer are Class Ia, because these Quaternary sands and gravels are unconsolidated, highly permeable deposits in direct contact with the water table. These aquifers consist of alluvial valley fill, pro-glacial lake shoreline deposits, and eolian sands.

Rule 2. Glacial aquifers (GLAC)

During the Pleistocene time, massive ice sheets covered most of North Dakota except for the southwestern corner of the state. Most of the continental glacial deposits consist of till, which is a mixture of unsorted clay, silt, sand, gravel and boulders that was deposited beneath or at the margins of the ice. Glacial meltwater deposited well-sorted sand and gravel along stream valleys and in outwash plains. These coarse-grained sediments are important aquifers.

2. Wells located in the glacial aquifer region have a Pettyjohn classification of Class Id, because the shallowest aquifer in the area consists of sandy lenses within the relatively impermeable and unstratified tills. The deposits of the region are primarily of glacial origin (tills, Glacio-lacustrine sediments, and loess), though impermeable fluvial sediments were

included in this region of the aquifer coverage due to their similar aquifer classification. It should be noted that due to the lack of information regarding the thickness of the impermeable cover associated with this aquifer, it is deemed most conservative to treat these aquifers as though they are covered with <50 ft of impermeable material. Depth information and better digital thickness information would most likely result in a lower number of preliminary USAs than estimated here.

Rule 3. Tertiary aquifer (TERT)

The Tertiary aquifer is composed of lower Tertiary sediments and is located in southwestern North Dakota. These are chiefly consolidated sandstone beds of Oligocene to Paleocene age. These water-yielding sandstones are interbedded with shale, mudstone, siltstone, lignite and coal and locally with beds of limestone. Most of the Tertiary rocks were deposited in continental environments, but some of the shale and limestone beds, which form confining units, were deposited in a marine environment.

3. Wells within the Tertiary aquifer of southwestern North Dakota [Williston Basin (Fig. 31; in Whitehead, 1996 USGS segment 8 atlas)] derive water from some portion of the Fort Union Group (predominately Lower Tertiary/Upper Cretaceous units). Depositional environments in the Fort Union Group range from marine to fluvial, swamp and lacustrine settings. According to the USGS segment 8 atlas, water production from the Fort Union Group ranges from 1 to 100 gpm. Therefore, wells within this aquifer could be classified IIa or IIb. Because no data exists to help differentiate between these two classes, the most conservative approach is taken, and wells are Class IIa.

Rule 4. Cretaceous aquifer (CRET)

The Cretaceous aquifer is located in southern and southwestern North Dakota. The Upper Cretaceous formations are consolidated sandstones interbedded with shale, siltstone and rare thin, lenticular beds of coal. The permeability of these aquifers is variable and generally not as great as that of the aquifers in younger rocks. The best-known Lower Cretaceous formations are the Dakota and Newcastle Sandstones, consolidated sandstone units. The Upper Cretaceous rocks are underlain by a major confining unit.

4a. Wells located within the Cretaceous units on the edge of the Williston Basin of western North Dakota may have a range of Pettyjohn classes depending on the lithology of the bedrock they are located within. Wells located in the outcrops of the two highest yield consolidated sandstones (the Foxhills (Kf) and Hell Creek (Kh) Formations) may produce water at rates up to 300 gpm. Therefore, these wells are Class IIa.

4b. Wells located within the outcrops of the Pierre Shale, Carlisle Formation (Kp) and other shale Cretaceous units are Class IIc, because, whereas this unit is a widespread and thick (up to 3000 ft thick) confining unit, it does contain sandy lenses throughout and is a local water producer in many areas. The sandy lenses of the Pierre shale are covered with an unknown thickness of impermeable material and are therefore given a more conservative classification.

4c. Wells sourcing the Dakota and Newcastle Sandstones (Inyan Kara, Mowry, Newcastle, and Skull Creek formations), consolidated sandstone units are typically overlain by thick confining units and are assigned a classification of Class III.

4d. Any well sourcing units of Cretaceous age that underlie Tertiary aquifer outcrops, or glacial or surficial aquifers are given a classification of Class III.

TABLE 1. Aquifers of North Dakota and their Pettyjohn classification.

Aquifer Name	Aquifer Description	Pettyjohn Classification
Surficial aquifers	Quaternary deposits of alluvial gravel, sand, silt, and clay.	Class Ia (Rule 1).
Glacial aquifers	Unconsolidated sands and semi consolidated terrace deposits in glacial till	Class Id (Rule 2)
Tertiary aquifer	Consolidated sandstone	Class IIa (Rule3)
Cretaceous aquifer	Consolidated sandstone	Class IIa, IIc, or III (Rule 4)

Metadata Sources References

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Whitehead, R.L. 1996. Ground water atlas of the United States: Segment 8, Montana, North Dakota, South Dakota, Wyoming. Hydrologic Investigations Atlas 730-I, U.S. Geological Survey, Reston, VA, 24 pp.

Rules for Applying the Pettyjohn Classification Scheme in Ohio

17 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-K (also called Ground Water Atlas of the United States, Segment 10; Lloyd and Lyke, 1995) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Source aquifer
3. Surficial geology
4. Aquifer boundaries

The aquifer boundaries were generated using surface geology and the Segment 10 Atlas (Lloyd and Lyke, 1995) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

The following aquifers of Ohio were distinguished for this work:

1. Surficial
2. Paleozoic sandstone
3. Paleozoic carbonate
4. Not a principal aquifer

Rule 1. Surficial aquifer (SURF)

The unconsolidated sediments of the surficial aquifer are exposed at the land surface within the Central Lowlands physiographic province of Ohio, and within river and stream valleys across the state. The aquifer is comprised primarily of a combination of Quaternary age stratified and unstratified glacial deposits and alluvial sediments, also of Quaternary age. The lithology of the aquifer is a combination of alluvial sand, gravel, and clay; and glacial sand, gravel, and clay. The thickness of the surficial aquifer in Ohio is commonly less than 100 ft, but may reach thicknesses of 600 ft in buried bedrock valleys, and contains water predominately under unconfined conditions. Yields from wells sourcing the surficial aquifer range from less than 100 gallons per minute to 500 gpm, but can exceed 4000 gpm near major rivers.

1a. Wells that derive water from the surficial aquifer, occur within the surficial aquifer outcrop (SURF_OUT) are <u>Class Ia</u> because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

Rule 2. Paleozoic Sandstone aquifer (PZSA)

The consolidated siliciclastic sedimentary rocks of the Paleozoic sandstone aquifer outcrop in the Appalachian Plateau physiographic province of Ohio. These rocks are composed mostly of sandstone, siltstone, and shale, with subordinate limestone, and coal, and are Devonian to Permian in age. Pennsylvanian age aquifers range in thickness from 30 to 300 ft, while the thicknesses of Mississippian age aquifers are between 100 and 600 ft. While both aquifers lack a confining unit, the interbedding of sandstone and shale reduces the vertical movement of water through the aquifers. Yields of wells completed in Pennsylvanian sandstones range from 1 to 25 gpm, but may exceed 100 gallons per minute, while wells deriving water from Mississippian sandstones range from 5 to 25 gpm, but may exceed 250 gpm.

2a. Wells sourcing the Paleozoic sandstone aquifer and located within the aquifer outcrop (PZSA_OUT) are <u>Class IIa</u> because these wells derive water from rocks that are consolidated and unconfined.

2b. Wells sourcing the Paleozoic sandstone aquifer subcrop (PZSA_SUB) are <u>Class IIc</u> because these wells derive water from rocks that are consolidated and covered by less than 50 ft of low permeability material.

Rule 3. Paleozoic Carbonate aquifer (PZCA)

The consolidated carbonate rocks of the Paleozoic carbonate aquifer outcrop in the Appalachian Plateau physiographic province of Ohio, and subcrop to the west. These rocks are composed mostly of limestone and dolomite and are Silurian to Mississippian in age. Permeable units are tilted in the Appalachian Plateau province, but are relatively flat-lying in the Interior Central Lowlands province. Although both the Mississippian age carbonate aquifer of the Appalachian Plateau province and the Silurian-Devonian age aquifer of the Central Lowlands province lack confining units, the interbedding of carbonate and shale in the case of the Mississippian aquifer, or the presence of an overlying lower permeability shale aquifer in the case of the Silurian-Devonian aquifer impede the vertical movement of water through the aquifers.

3a. Wells sourcing the Paleozoic carbonate aquifer and located within the aquifer outcrop (PZCA_OUT) are <u>Class Ib</u> because the aquifer unit is comprised of soluble carbonate rocks.

3b. Wells sourcing the Paleozoic carbonate aquifer subcrop (PZCA_SUB) are <u>Class Id</u> because here the Paleozoic carbonate aquifer is covered by less than 50 ft of low permeability material.

Rule 4. Not a principal aquifer (NAPA)

Some outcrop belts of Paleozoic sedimentary rocks in Ohio, mostly outcropping in the Central Lowlands, are designated as ‘not a principal aquifer’ (NAPA). This designation covers areas where aquifers either do not exist, yield too little water to be significant, or yield sufficient water to supply only local requirements, but are not extensive enough to be considered major aquifers. The rocks are chiefly shale, but their compositions vary between carbonate and siliciclastic.

4a. Wells located within the outcrop boundary of not a principal aquifer (NAPA_OUT), with the FM codes Oc, Oda, Odl, Ogf, Ogm, Op, Ou, Owa, Dpl, are Class Ib because these wells derive water from rocks that are soluble carbonates.

4b. All other wells located within the outcrop boundary of not a principal aquifer (NAPA_OUT) are Class IIa because these wells derive water from rocks that are consolidated and unconfined.

4c. Wells sourcing the not a principal aquifer subcrop (NAPA_SUB), with the FM codes Oc, Oda, Odl, Ogf, Ogm, Op, Ou, Owa, Dpl, are Class Id because these wells derive water from rocks that are covered by less than 50 ft of low permeability material.

4d. All other wells sourcing the not a principal aquifer subcrop (NAPA_SUB) are Class IIc because these wells derive water from rocks that are covered by less than 50 ft of low permeability material.

Sole source Aquifers

Ohio contains four EPA-designated sole source aquifers: Pleasant City aquifer system in eastern Ohio; Bass Island aquifer system on Catawba Island; Allen County Combined aquifer system in west-central Ohio; and Greater Miami buried valley aquifer in west-central and southwestern Ohio. All of these sole source aquifers are contained within the coverage of one of the larger principal aquifers described above.

5. The shallow and unconfined Pleasant City aquifer is composed of permeable sands and gravels interbedded with less permeable silt and clay. The unconsolidated sediments of glacial or alluvial origin reach a total thickness of up to 60 ft. Wells sourcing the Pleasant City aquifer are classed the same as well sourcing the Surficial aquifer: see Rule 1a.
6. The Bass Island aquifer is an unconfined to semi-confined bedrock aquifer consisting of jointed and brecciated dolomite that contains dissolution cavities. This karst aquifer transmits water to wells via conduits formed by the joints and cavities. The dolomite formation ranges in thickness from 100-120 ft. Wells sourcing the Bass Island aquifer SSA are classed the same as well sourcing the Paleozoic Carbonate aquifer: see Rule 3a.
7. The Allen County Combined aquifer consists of a combination of carbonate bedrock and up to 50 ft or more overlying unconsolidated glacial deposits. The carbonate bedrock aquifer contains dissolution cavities, making it karst. Wells sourcing the Allen County Combined aquifer SSA are classed the same as well sourcing the Paleozoic Carbonate aquifer: see Rule 3a.
8. The Greater Miami Buried Valley aquifer formed as a result of successive episodes of glacial discharge, which deposited sediment in pre-existing bedrock valleys. These deposits are composed of heterogeneous gravel, sand, silt, and clay. The sand and gravel form the principal water-yielding units, and range in thickness from 20-400 ft. Wells sourcing the Greater Miami Buried Valley SSA are classed the same as wells sourcing the Surficial aquifer: see Rule 1a.

Metadata Sources References

Lloyd Jr., O.B. and W.K. Lyke. 1995. Ground water atlas of the United States: Segment 10, Illinois, Indiana, Kentucky, Ohio, Tennessee. Hydrologic Investigations Atlas 730-K, U.S. Geological Survey, Reston, VA, 32 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Oklahoma

14 November 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-E (also called Ground Water Atlas of the United States, Segment 4; Ryder, 1996) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Bedrock geology
2. Aquifer boundaries
3. Well location

The aquifer boundaries were generated using bedrock geology, aquifer extents from the state and the Segment 4 Atlas (Ryder, 1996) as a guide.

Due to the lack of source or depth data, classification of all wells is based solely on the location of the well within the aquifer coverage.

There are ten principal aquifers in the state of Oklahoma in addition to a region that is considered not a principal aquifer (NAPA). The aquifers of Oklahoma distinguished for this work were:

1. Alluvial
2. High Plains
3. Trinity
4. Rush Springs
5. Elk City
6. Blaine
7. Central Oklahoma
8. Ada-Vamoosa
9. Arbuckle-Simpson
10. Springfield Plateau
11. Not a principal aquifer

The aquifer features were constructed from the bedrock geology features (BGEO) and the incomplete “aquifer_state” coverage as a guide.

Rule 1. Alluvial aquifer (ALLU)

The unconsolidated sediments of the Alluvial aquifer are present within the major river valleys of Oklahoma such as the Salt Fork, Arkansas, Cimarron, Canadian, Washita and Red rivers as well as on the flanks of these river valleys in the form of high terrace deposits. The aquifer predominantly consists of sand and gravel from modern fluvial deposition as well as sand, silt and clay from older fluvial deposition. The aquifer is predominantly unconfined throughout the state of Oklahoma.

1a. Wells located within the Alluvial aquifer outcrop (ALLU) are Class Ia because these unconsolidated sand and gravel deposits are predominantly under unconfined conditions.

Rule 2. High Plains aquifer (HPLA)

The unconsolidated to semi-consolidated sediments of the High Plains aquifer predominantly outcrop across the panhandle of Oklahoma. The aquifer consists undifferentiated gravel, sand, silt and clay of Quaternary and Pleistocene age, as well as gravel, sand, silt and clay of the Miocene Ogallala Formation. In Oklahoma, the saturated thickness of the High Plains aquifer can vary from 0 to 600 ft with an average of 200 ft. The aquifer is at its thickest in the north central portion of the panhandle and thins out in every direction. The aquifer is generally considered to be unconfined or under water table conditions, although local confining clay and loess deposits do exist.

2a. Wells located within the High Plains aquifer outcrop (HPLA), are conservatively Class Ia because the aquifer is predominantly composed of surficial, unconsolidated sediments.

Rule 3. Trinity aquifer (TRIN)

The consolidated clastic and carbonate rocks and unconsolidated sediments of the Trinity aquifer outcrop in south-central and southeastern Oklahoma. In Oklahoma, the Trinity aquifer consists of sandstone, limestone, shale, dolomite and conglomerate as well as interbedded sand, silt, clay and marl. The aquifers saturated thickness varies considerably from only a few feet where it outcrops to more than 1,000 ft at the Oklahoma/Texas border. The Trinity aquifer is underlain by low-permeability rocks of Precambrian to Jurassic age.

3a. Wells located within the Trinity aquifer outcrop (TRIN) within the following FM: Kbr, Kcf, Kdc, Kdq, Kgw, Kgb, and Ko are Class Ib because these formations contain a major carbonate component according to the USGS and therefore may contain karstic solution cavities.

3b. Wells located within the Trinity aquifer outcrop (TRIN) excluding those located in the formations mentioned in Rule 3a. are Class IIa because these bedrock formations contain predominantly non-carbonate lithologies according to the USGS and are conservatively classified as higher yield.

Rule 4. Rush Springs aquifer (RUSP)

The predominantly consolidated sedimentary rocks of the Rush Springs aquifer outcrop across western Oklahoma. The Rush Springs aquifer consists of fine-grained sandstone, dolomite, shale and gypsum beds of Permian age. The Rush Springs Sandstone is the predominant water-yielding unit and in some locations in southern Caddo County can obtain a thickness of more than 300 ft. Water in the Rush Springs aquifer is considered to be predominantly unconfined and wells yields are commonly 200 to 600 gallons per minute.

4a. Wells located within the Rush Springs aquifer outcrop (RUSP) are Class IIa because the bedrock is predominantly non-carbonate and the wells are conservatively classed as higher yield.

Rule 5. Elk City aquifer (ELKC)

The consolidated sedimentary rock of the Elk City aquifer outcrop in west-central Oklahoma. The Elk City aquifer consists of sandstone with thin clay lenses of Permian age. The aquifer has a maximum saturated thickness of 260 ft and is underlain by the Doxey Shale confining unit (Oklahoma Water Resource Board: https://www.owrb.ok.gov/studies/groundwater/elkcity.php).

5a. Wells located within the Elk City aquifer outcrop (ELKC) are Class IIa because these wells are sourcing non-carbonate rock conservatively classed as higher yield.

Rule 6. Blaine aquifer (BLAN)

The consolidated sedimentary rocks of the Blaine aquifer outcrop in southwest Oklahoma and in a northwest trending band in western Oklahoma. The Blaine aquifer consists of shale, gypsum, dolomite and sandstone of Permian age. The aquifer has a maximum thickness of 400 ft and the water is predominantly located in the porous dolomite and solution cavities in the gypsum beds. The Blaine aquifer is considered to be under unconfined conditions and well yields within the aquifer are commonly yield 100 to 500 gpm.

6a. Wells located within the Blaine aquifer outcrop (BLAN) are Class Ib because the aquifer is composed of potentially cavernous and highly fractured rocks.

Rule 7. Central Oklahoma aquifer (CENT)

The consolidated sedimentary rocks of the Central Oklahoma aquifer outcrop in a north-south trending band across the center of the state and in an east-west trending band across south-central Oklahoma. The Central Oklahoma aquifer consists of predominantly sandstone and shale of Permian age. The maximum saturated thickness of the Central Oklahoma aquifer ranges from 150 to 600 ft. The water in the aquifer is generally unconfined and well yields are commonly between 100 and 300 gallons per minute.

7a. Wells located within the Central Oklahoma aquifer outcrop (CENT) are Class IIa because these wells are sourcing non-carbonate rock conservatively classed as higher yield.

Rule 8. Ada-Vamoosa aquifer (ADAV)

The consolidated sedimentary rocks of the Ada- Vamoosa aquifer outcrop in a north-south trending band across east-central Oklahoma. The Ada-Vamoosa aquifer consists of sandstone, shale, siltstone and limestone of Pennsylvanian age. The maximum thickness of the aquifer is 900 ft and wells within the aquifer commonly yield between 25 and 150 gallons per minute.

8a. Wells located within the Ada-Vamoosa aquifer outcrop (ADAV), within the "IPa" FM attribute are Class Ib because limestone is considered a major lithology according to the USGS and therefore karstic environments are possible.

8b. Wells located within the Ada-Vamoosa aquifer outcrop (ADAV), excluding the "IPa" FM attribute are Class IIa because wells found in these predominantly non-carbonate units are conservatively classed as higher yield.

Rule 9. Arbuckle-Simpson aquifer (ARBU)

The consolidated sedimentary rocks of the Arbuckle-Simpson aquifer outcrop in south-central Oklahoma. The Arbuckle-Simpson aquifer consists of primarily limestone, dolomite, sandstone and shales of Cambrian to Ordovician age. The aquifer is as much as 9,000 ft thick and its high permeability is due to solution cavities in the limestone as well as enlargement of joints and fractures. Wells sourcing the Arbuckle-Simpson aquifer commonly yield between 100 to 500 gallons per minute.

9a. Wells located within the Arbuckle-Simpson aquifer outcrop (ARBU) are Class Ib because the aquifer is composed of carbonate, potentially cavernous rocks.

Rule 10. Springfield Plateaus aquifer (SPRI)

The consolidated sedimentary rocks of the Springfield Plateaus aquifer outcrop in the high plateau region of northeast Oklahoma. The Springfield Plateaus aquifer consists of limestone, marlstone and shale of Mississippian age. The aquifer has a maximum thickness of 500 ft in the state of Oklahoma and wells within the aquifer commonly yield between 2 and 80 gallons per minute. The Chattanooga Shales provides a confining unit between the Springfield Plateau aquifer and deeper aquifers.

10a. Wells located within the Springfield Plateaus aquifer outcrop (SPRI) are Class Ib because the aquifer is composed of carbonate, potentially cavernous rocks.

Rule 11. Not a principal aquifer (NAPA)

The consolidated igneous and sedimentary rocks of the Not a Principal aquifer outcrop across the entire state of Oklahoma. The Not a Principal aquifer consists granite, gabbro, sandstone, shale, limestone and coal of Cambrian to Triassic age. Local aquifers do exist in these formations but none were considered to be principal aquifers according to the state of Oklahoma aquifer coverage.

11a. Wells located within the Not a Principal aquifer outcrop (NAPA), located in predominantly carbonate rocks are Class Ib because these units have dissolution potential.

11b. Wells located within the Not a Principal aquifer outcrop (NAPA) located in predominantly non-carbonate rocks are Class IIa because these wells are sourcing bedrock wells that are conservatively class as higher yield.

Metadata Sources References

Oklahoma Water Resource Board. n.d. Groundwater Studies. Retrieved from https://www.owrb.ok.gov/studies/groundwater/elkcity.php.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Ryder, P.D. 1996. Ground water atlas of the United States: Segment 4, Oklahoma, Texas. Hydrologic Investigations Atlas 730-E, U.S. Geological Survey, Reston, VA, 32 pp.

Rules for Applying the Pettyjohn Classification Scheme in Oregon

19 December 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-G (also called Ground Water Atlas of the United States, Segment 7; Whitehead, 1994) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Well location
2. Bedrock geology
3. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology and the Segment 7 Atlas (Whitehead, 1994) as a guide.

Due to the lack of source or depth data, classification of all wells is based solely on the location of the well within the aquifer coverage.

There are five principal aquifers in the state of Oregon:

1. Unconsolidated deposit
2. Volcanic and sedimentary rock
3. Pliocene and younger basaltic rock
4. Miocene basaltic rock
5. Pre-Miocene rock

The aquifer features were constructed from the bedrock geology features (BGEO).

Rule 1. Unconsolidated deposit aquifers (UNCO)

The unconsolidated sediments of the Unconsolidated deposit aquifers are found in a north-south trending basin from Portland to Eugene, in former glacial valleys throughout the state, and in large plains in the center and eastern portion of the state. This aquifer is associated with erosional or structural basins that were filled with glacial and/or alluvial sediments predominantly within in the last three million years. The Unconsolidated deposit aquifers consist of predominantly unconfined surficial sediments ranging in size from sand to cobble. The sediments of the Unconsolidated deposit aquifers reach a maximum thickness of 800 ft near Portland and gradually thin to the south.

1a. Wells located in the Unconsolidated deposit aquifers outcrop (UNCO), excluding those located in the loess deposits (Ql), are Class Ia because these wells are most likely sourcing unconsolidated sand and gravel deposits predominantly under unconfined conditions.

1b. Wells located in the loess deposits (Ql) of the Unconsolidated deposit aquifers outcrop (UNCO) are conservatively Class Id because these wells are sourcing aquifers overlain by low permeability material presumably less than 50 ft thick.

Rule 2. Volcanic and sedimentary rock aquifers (VOLC)

The consolidated volcanic and sedimentary rocks of the volcanic and sedimentary rock aquifers outcrop in the Cascades Range of west-central Oregon, as well as in valleys in central and eastern Oregon. The aquifers predominantly consist of Pliocene-age and younger volcanic rocks, such as basalt, andesite, pumice, rhyolite, dacite and ash-flow tuff, as well as sedimentary rocks, such as sandstone and siltstone. In some locations the aquifer may be composed of several interbedded rock types. The thickness of the Volcanic and sedimentary-rock aquifers is largely unknown because they are located in very remote areas of the state, however, some wells access the geothermal waters within the aquifer, which can be as deep as 2,000 ft below land surface.

2a. Wells located within the Volcanic and sedimentary-rock aquifers outcrop (VOLC) are conservatively Class IIa because these wells are sourcing non-carbonate bedrock assumed to be higher yield.

Rule 3. Pliocene and younger basaltic-rock aquifers (PLIO)

The consolidated volcanic rocks of the Pliocene and younger basaltic-rock aquifers outcrop east of the Cascade Range in central and eastern Oregon. The aquifers predominantly consist of basaltic flows of Pliocene and younger age. The permeability of these flows is dependent on the cooling rate of the lava flows and the thickness of the flows. The thickness of the flows is variable, but the Holocene and Pleistocene flows average thickness is approximately 25 ft, while the Pliocene flows average 40 ft in thickness.

3a. Wells located within the Pliocene and younger basaltic-rock aquifers outcrop (PLIO) are conservatively Class IIa because these wells are sourcing non-carbonate bedrock assumed to be higher yield.

Rule 4. Miocene basaltic-rock aquifers (MIOC)

The consolidated volcanic rocks of the Miocene basaltic-rocks aquifer outcrop throughout central and eastern Oregon. The aquifer consists of predominantly basalt and andesite flows extruded from major fissures of Miocene age. Many of the open spaces initially formed during cooling have filled with clay minerals reducing the permeability of the Miocene basaltic-rock aquifers. The thickness of the Miocene basaltic-rock aquifers can be as much as 15,000 ft in the southern portion of the Columbia Plateau. This is also where the aquifers are most productive (wells yields of greater than 100 gpm) due to wells often sourcing multiple semi-consolidated zones between flow events.

4a. Wells located within the Miocene basaltic-rock aquifer outcrop (MIOC) are conservatively Class IIa because these wells are sourcing non-carbonate bedrock assumed to be higher yield.

Rule 5. Pre-Miocene rock aquifers (PREM)

The consolidated volcanic, sedimentary, igneous and metamorphic rocks of the Pre-Miocene rock aquifers outcrop throughout the state of Oregon. The aquifers consist of predominantly pre-

Miocene age volcanic rocks such as basalt and rhyolite, sedimentary rocks such as sandstone and siltstone, intrusive igneous rocks such as granite and gabbro and metamorphic rocks such as schist and marble. The Pre-Miocene Rock aquifers, like the Volcanic-rock aquifers, are located in remote areas of the state, therefore, the thickness of the aquifer is largely unknown, but it is reasonable to assume that with increased depth, fracture void space decreases, and, therefore, the volume of water pumped in most cases, decreases with depth.

5a. Wells located within the Pre-Miocene rock aquifers outcrop (PREM) are conservatively Class IIa because these wells are sourcing non-carbonate bedrock assumed to be higher yield.

Metadata Sources References

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Whitehead, R.L. 1994. Ground water atlas of the United States: Segment 7, Idaho, Oregon, Washington. Hydrologic Investigations Atlas 730-H, U.S. Geological Survey, Reston, VA, 33 pp.

Rules for Applying the Pettyjohn Classification Scheme in Pennsylvania

26 March 2019

Introduction

The rules below are based primarily on information published in the USGS Ground Water Atlas of the United States, Segment 11, Hydrologic Investigations Atlas 730-L (Trapp and Horn, 1997), the lithological descriptions included with the geological map compiled by Pennsylvania's Department of Environmental Resources (Berg et al., 1980) and the previously published DW USA reports (RSPA, 2002). The available digital data set included:

1. Wells: location, well depth, casing depth, yield
2. Bedrock geology

All aquifer delineations were interpreted from the hydrogeology as provided by the Pennsylvania Department of Conservation and Natural Resources. The following aquifers of Pennsylvania were distinguished for this work:

1. Surficial
2. Carbonate rock
3. Sandstone
4. Crystalline rock
5. Not a principal aquifer (shales and confining rock units)

In the rule set outlined below, wells are largely classified on the basis of location. Classification of all wells is based on the shallowest interval in the well from which water is derived. In most cases, the well depth information available is of little use in conclusively deducing the well's source because of the structural complexity in most of the state. Approximately 25% of the wells have a record of the lithology of the primary source aquifer.

Rule 1. Surficial aquifers (SURF)

The Surficial aquifers consist of the Quaternary and late Tertiary unconsolidated sediments of the Coastal Plain physiographic province. The western limit of the aquifer system is the landward edge of water-yielding strata where they pinch out against crystalline rocks of the Piedmont physiographic province at the fall line. The Bridgeton Formation is predominantly gravel but contains both sand and loam and some clay. The Pensauken Formation is predominantly a braided river deposit. These formations unconformably overlie the Cretaceous Potomac or Peedee groups. In Pennsylvania, rocks of Cretaceous and Tertiary age are generally semi-consolidated. Deposits of Quaternary age are unconsolidated. The combined thickness of coarse- and fine-grained surficial material is as much as 350 ft in some valleys.

1a. Wells located within the Surficial aquifer (SURF) with a lithology description of bedrock (BEDR) and pump rates less than or equal to 50 gpm are <u>Class IIb</u>, because they are likely sourcing low-yield consolidated bedrock units.

1b. Wells located within the Surficial aquifer (SURF) with a lithology description of bedrock (BEDR) and pump rates greater than 50 gpm or with no pump rate information are Class IIa, because they are likely sourcing prominent consolidated bedrock units.

1c. Wells located within the Surficial aquifer (SURF) and within the unconsolidated Quaternary deposits (Qt, Qs) in the bedrock geology are Class Ia.

1d. Wells located within the Surficial aquifer (SURF) and within the semi-consolidated Tertiary deposits (Tbm, Tpb) in the bedrock geology are Class Ic.

Rule 2. Carbonate rock aquifers (CARB)

The carbonate rock aquifers of the Piedmont and Valley and Ridge physiographic provinces consist of units that are predominantly limestone, dolomite, or marble. Other units listed in the USGS atlas (Trapp and Horn, 1997) as being carbonate aquifers are also included. In some cases, dolomites been known to behave like confining units.

2a. Wells located within the Carbonate aquifer (CARB) with a lithology description of unconsolidated sand material (USAND) are Class Ia, because they are likely sourcing permeable, unconfined sediments.

2b. Wells located within the Carbonate aquifer (CARB) with a lithology description of unconsolidated clay material (UCLAY) are Class Id, because they are likely sourcing moderately to poorly indurated sand and gravel interbedded with clay and silt units.

2c. Wells located within the Carbonate aquifer (CARB) with a lithology description of carbonate (CARB) or unknown (UNK) are Class Ib, because they are likely sourcing rocks that are soluble and fractured.

2d. Wells located within the Carbonate aquifer (CARB) with a lithology description of bedrock (BEDR) and depths less than or equal to 100 ft are Class IIc, because they are likely sourcing consolidated bedrock units overlain by permeable sediments interbedded with 50 ft or less of confining material.

2e. Wells located within the Carbonate aquifer (CARB) with a lithology description of bedrock (BEDR) and depths greater than 100 ft are Class III, because they are likely sourcing consolidated bedrock units overlain by permeable sediments interbedded with 50 ft or more of confining material.

Rule 3. Sandstone aquifers (SAND)

Water-bearing sandstones of the Valley and Ridge and Appalachian Plateaus physiographic provinces typically have yields varying from 30-300 gpm. The principal water-yielding geologic units are sandstones of the Permian and Pennsylvanian Dunkard Group and the Mississippian/Devonian Pocono Formation.

3a. Wells located within the Sandstone aquifer (SAND) with a lithology description of unconsolidated sand material (USAND) are Class Ia, because they are likely sourcing permeable, unconfined sediments.

3b. Wells located within the Sandstone aquifer (SAND) with a lithology description of unconsolidated clay material (UCLAY) are Class Id, because they are likely sourcing moderately to poorly indurated sand and gravel interbedded with clay and silt units.

3c. Wells located within the Sandstone aquifer (SAND) with a lithology description of carbonate material (CARB) and depths less than or equal to 100 ft are Class Id, because they are likely sourcing rocks that are soluble and fractured overlain by permeable sediments interbedded with 50 ft or less of confining material.

3d. Wells located within the Sandstone aquifer (SAND) with a lithology description of carbonate material (CARB) and depths greater than 100 ft are Class III, because they are likely sourcing rocks that are soluble and fractured overlain by permeable sediments interbedded with 50 ft or more of confining material.

3e. Wells located within the Sandstone aquifer (SAND) with a lithology description of bedrock (BEDR) or unknown (UNK) and pump rates less than or equal to 50 gpm are Class IIb, because they are likely sourcing low-yield bedrock aquifers.

3f. Wells located within the Sandstone aquifer (SAND) with a lithology description of bedrock (BEDR) or unknown (UNK) and pump rates greater than 50 gpm or with no pump rate information are Class IIa, because they are likely sourcing prominent bedrock aquifers.

Rule 4. Crystalline bedrock aquifers (CRYS)

These aquifers consist of crystalline metamorphic and igneous rock units of the Piedmont physiographic province. The Tuscarora Formation of the Valley and Ridge province, composed of quartzite and quartzitic sandstone, is also included as a crystalline aquifer. Unconsolidated material called regolith overlies the crystalline rock aquifers almost everywhere. Because the regolith material varies greatly in thickness, composition, and grain size, its hydraulic properties also vary greatly. The regolith and fractures in the bedrock serve as the principal places for the storage transmission of water.

4a. Wells located within the Crystalline aquifer (CRYS) with a lithology description of unconsolidated sand material (USAND) are Class Ia, because they are likely sourcing permeable, unconfined sediments.

4b. Wells located within the Crystalline aquifer (CRYS) with a lithology description of unconsolidated clay material (UCLAY) are Class Id, because they are likely sourcing moderately to poorly indurated sand and gravel interbedded with clay and silt units.

4c. Wells located within the Crystalline aquifer (CRYS) with a lithology description of carbonate material (CARB) and depths less than or equal to 50 ft are Class Id, because they are likely sourcing rocks that are soluble and fractured overlain by 50 ft or less of confining material.

4d. Wells located within the Crystalline aquifer (CRYS) with a lithology description of carbonate material (CARB) and depths greater than 50 ft are Class III, because they are likely sourcing rocks that are soluble and fractured overlain by 50 ft or more of confining material.

4e. Wells located within the Crystalline aquifer (CRYS) with a lithology description of bedrock (BEDR) or unknown (UNK) and with pump rates less than or equal to 50 gpm are Class IIb, because they are likely sourcing low-yield bedrock aquifers.

4f. Wells located within the Crystalline aquifer (CRYS) with a lithology description of bedrock (BEDR) or unknown (UNK) and with pump rates greater than 50 gpm or with no pump rate information are Class IIa, because they are likely sourcing prominent bedrock aquifers.

Rule 5. Not a principal aquifer (NAPA)

These units are either listed in the USGS atlas (Trapp and Horn, 1997) as confining units or have a lithologic description that indicates the presence of shales or confining units. Little is known about the depth at which water is attained and the thickness of the confining units remains largely unknown.

5a. Wells located within the non-principal aquifers (NAPA) with a lithology description of unconsolidated sand material (USAND) are Class Ia, because they are likely sourcing permeable, unconfined sediments.

5b. Wells located within the non-principal aquifers (NAPA) with a lithology description of unconsolidated clay material (UCLAY) are Class Id, because they are likely sourcing moderately to poorly indurated sand and gravel interbedded with clay and silt units.

5c. Wells located within the non-principal aquifers (NAPA) with a lithology description of carbonate material (CARB) and depths less than or equal to 100 ft are Class Id, because they are likely sourcing rocks that are soluble and fractured overlain by 50 ft or less of confining material.

5d. Wells located within the non-principal aquifers (NAPA) with a lithology description of carbonate material (CARB) and depths greater than 100 ft are Class III, because they are likely sourcing rocks that are soluble and fractured overlain by 50 ft or more of confining material.

5e. Wells located within the non-principal aquifers (NAPA) with a lithology description of bedrock (BEDR) or unknown (UNK) and depths less than or equal to 100 ft or with no depth information and with pump rates less than or equal to 50 gpm are Class IIb, because they are likely sourcing low-yield bedrock aquifers.

5f. Wells located within the non-principal aquifers (NAPA) with a lithology description of bedrock (BEDR) or unknown (UNK) and depths less than or equal to 100 ft or with no depth information and with pump rates greater than 50 gpm or with no pump rate information are Class IIa, because they are likely sourcing prominent bedrock aquifers.

5g. Wells located within the non-principal aquifers (NAPA) with a lithology description of bedrock (BEDR) or unknown (UNK) and depths greater than 100 ft are Class III, because they are likely sourcing low-yield bedrock aquifers overlain by more than 50 ft of confining materials.

Sole Source Aquifers

Pennsylvania contains two EPA-designated sole source aquifers. The Delaware River Streamflow Zone/New Jersey Coastal Plains Aquifer SSA and the Seven Valleys Aquifer, York County SSA. The Delaware River Streamflow Zone/New Jersey Coastal Plains Aquifer SSA is located within multiple aquifers according to the delineations based on geologic units as described above. The Seven Valleys Aquifer, York County SSA is described in Federal Register, vol. 50, as the Conestoga limestone aquifer underlying the Borough of Seven Valleys and a portion of North Codorus Township. Rules for wells in these SSAs are classified based on the aquifer they are most likely sourcing**.**

Metadata Sources References

Berg, T., W. Edmunds, A. Geyer. 1980. Geologic map of Pennsylvania: Pennsylvania survey, 4th series. Map 1, scale 1:250,000.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Trapp, Jr., H. and M.A. Horn, 1997. Ground water atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. Hydrologic Investigations Atlas 730-L, U.S. Geological Survey, Reston, VA, 32 pp.

Rules for Applying the Pettyjohn Classification Scheme in Puerto Rico

15 February 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-M (also called Ground Water Atlas of the United States, Segment 13; Miller et al., 1999) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Well location
2. Pump rate
3. Bedrock geology
4. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology and the Segment 13 Atlas (Miller et al., 1999) as a guide.

There are four principal aquifers in Puerto Rico:

1. Surficial
2. North Coast Limestone aquifer system
3. Igneous and Sedimentary rock
4. Not a principal aquifer

The aquifer features were constructed from the bedrock geology features (BGEO)

Rule 1. Surficial aquifers (SURF)

The unconsolidated sediments of the Surficial aquifer are present throughout the river valleys of Puerto Rico as well as in broad plains along the coasts. The aquifer predominantly consists of Pleistocene to Holocene age sand and gravel alluvium as well as marine sand, silt and clay deposited in thick blankets. The aquifer ranges in thickness from less than 50 ft along the northern coast to more than 1,000 ft near Santa Isabel in the south central portion of the island. The aquifer is generally unconfined and is underlain by volcaniclastic or igneous intrusive rocks except in river valleys along the north and south coast where the surficial aquifer overlies carbonate and siliciclastic rocks. Surficial aquifers along the north coast commonly yield 50 to 150 gallons per minute while wells along the south coast may yield as much as 1,000 gallons per minute.

1a. Wells located within the Surficial aquifer (SURF) are Class Ia because these unconsolidated gravel, sand and silt deposits are predominantly under unconfined conditions.

Rule 2. North Coast Limestone aquifer system (LIME)

The consolidated carbonate rocks of the North Coast Limestone aquifer system outcrop along the north and northwest coast of Puerto Rico. These aquifers are comprised mostly of limestone and dolomite of Oligocene to Miocene age. The aquifer system consists of two limestone aquifers separated by a predominantly mudstone confining unit. The maximum onshore thickness of the limestone aquifers is estimated to be approximately 5,600 ft. The aquifers range from over 1,300 ft in altitude where they overlie volcanic rock to below sea-level along the north coast.

2a. Wells located within the North Coast Limestone aquifer system (LIME) are <u>Class Ib</u> because these wells derive water from rocks that are soluble and fractured.

Rule 3. Igneous and Sedimentary- ock aquifers (IGSE)

The consolidated volcaniclastic, igneous, metamorphic and sedimentary rocks of the igneous and sedimentary rock aquifers are found throughout most of Puerto Rico with the exception of the north and south coasts. The rocks are comprised mostly of volcanic breccias, tuffs and basalts, intrusive igneous rocks such as granodiorite and diorite, metamorphic rocks such as amphibolite and serpentinite and sedimentary rocks such as sandstone and chert of Cretaceous to Eocene age. These rocks store water in fractures and the overlying saprolite. An average yield of only 5 to 10 gallons per minute is common in wells sourcing the igneous and sedimentary rock aquifers.

3a. Wells located within the igneous and sedimentary rock aquifers with pump rates less than or equal to 50 gpm are <u>Class IIb</u> because they are unconfined, consolidated and lower yield.

3b. Wells located within the igneous and sedimentary rock aquifers with pump rates greater than 50 gpm are <u>Class IIa</u> because they are unconfined, consolidated and higher yield.

Rule 4. Not a principal aquifer (NAPA)

The consolidated carbonate rocks along the south and southwest coast as well as the artificial fill and swamp deposits along the north coast of Puerto Rico do not produce enough water to be considered principal aquifers therefore, they receive the ‘not a principal aquifer’ (NAPA) designation. The unconsolidated swamp deposits are of Holocene age while the carbonate deposits are of Oligocene to Pliocene age.

4a. Wells located within the not a principal aquifer (NAPA), located in non-carbonate geologic units, are <u>Class Ia</u> because these wells derive water from sediment that is permeable and unconsolidated.

4b. Wells located within the not a principal aquifer outcrop (NAPA_OUT) located in one of the following carbonate units (Kcot, Kp, Kpe, Tc, Tcb, Tgua, Tjd, Tpo) are <u>Class Ib</u> because these wells derive water from rocks that are soluble and fractured.

Metadata Sources References

Miller, J. A., R.L. Whitehead, D.S. Oki, S.B. Gingerich, and P.G. Olcott. 1999. Ground Water Atlas of the United States: Segment 13, Alaska, Hawaii, Puerto Rico, and the US Virgin Islands (No. 730-N, pp. N1-N36). Geological Survey, Reston, VA, 33 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Rhode Island

23 May 2018

Introduction

The rules defined below were devised using the USGS Ground Water Atlas, Segment 12 (Olcott, 1995), the National Atlas of the United States of America, Principal aquifers, by James A. Miller (1998); the Bedrock Geology Map of Rhode Island (Hermes et al., 1994) and the previously published DW USA reports (RSPA, 2002).

The following data were available digitally at the time these rules were written:

- Well location
- Bedrock geology
- Glacial geology

The principal aquifers in Rhode Island are:

1. Stratified Drift
2. Bedrock

RULE 1. Stratified Drift aquifer (STRA)

The stratified drift aquifer covers a large portion of the state of Rhode Island and incorporates all permeable unconsolidated deposits typically of glacial or fluvial origin.

The units present in the stratified drift aquifer are highly productive and widely used aquifers. Well yields may range from 10-1000 gallons per minute (gpm) and may exceed in some cases 3000 gpm (table 2 of the Segment 12 atlas; Olcott, 1995). Alluvium from Holocene river valleys may overlie the glacial deposits but is usually not the primary source of groundwater.

1. Wells that are located within and derive water from the stratified drift aquifer (STRA) are <u>Class Ia</u>. While the potential for confining units exists, they cannot be individually defined with the data available. The high rates at which the wells produce from these unconsolidated sediments warrant their categorization as preliminary USA's.

Rule 2. Bedrock aquifers

The bedrock of Rhode Island consists mostly of metamorphic and igneous rocks as well as a smaller amount of terrigenous clastic sedimentary rocks. Most bedrock units in Rhode Island are of Paleozoic or Precambrian age. Minor intrusives of Triassic and Jurassic age are present in some areas. The youngest Bedrock unit in the state is the Cretaceous Raritan Formation, which has limited outcrops in the southern portions of the state.

In most cases, a layer of glacial till or outwash covers bedrock. There are relatively few outcrops of bedrock throughout the state. The bedrock aquifer region of the aquifer coverage includes both outcropping bedrock and till-covered bedrock. Wells deriving water from till-covered bedrock or outcropping bedrock are classified below.

Yields of crystalline bedrock aquifers are typically low, ranging from 1 to 20 gpm (table 16 of the Segment 12 atlas; Olcott, 1995). The following descriptions characterize the hydrology of the bedrock.

> "Although the crystalline rocks are geologically complex with a structural fabric that generally trends northeast, movement of water through the rocks is totally dependent on the presence of secondary openings; rock type has little or no effect on ground-water flow." "Spaces between the individual mineral crystals of the crystalline rocks are few, microscopically small, and generally unconnected. Consequently, the intergranular porosity of crystalline rocks is so small as to be insignificant" (Olcott, 1995).

Many of the units referred to as sedimentary rocks have also been affected by minor metamorphism (Cain, 1994**)** and are most likely low yield as well.

2. Wells deriving water from bedrock aquifers covered by till are Class IIc, covered bedrock aquifers.

Metadata Sources References

Hermes, O.D., L.P. Gromet and D.P. Murray. 1994. Bedrock geologic map of Rhode Island. Rhode Island Map Series No. 1, University of Rhode Island, Kingston. Scale = 1:100,000.

Miller, J.A., 1998, The National Atlas of the United States of America, Principal Aquifers, United States Geological Survey, 1:5,000,000 scale.

Olcott, 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in South Carolina

28 June 2018

Introduction

The rules set defined below was devised using the USGS Hydrologic Investigations Atlas 730-G (also called Ground Water Atlas of the United States, Segment 6; Miller, 1990) and the previously published DW USA reports (RSPA, 2002). The data set available to define the rules included:

1. Well location
2. Well depth
3. Surficial geology

The aquifer boundaries were generated using surficial geology and the Segment 6 groundwater atlas (Miller, 1990) as a guide.

There are five principal aquifers in South Carolina:

1. Alluvial valley
2. Non-alluvial valley surficial aquifers (Surficial Aquifer System)
3. Pearl River *
4. Chattahoochee River *
5. Piedmont and Blue Ridge

*The Pearl River and Chattahoochee River aquifers comprise the Southeastern Coastal Plain Aquifer System.

USGS Professional Paper 1773 (Campbell and Coes, 2010) was used in the classification rules to assess the thickness and depth of the permeable and confining units within the hydrogeologic framework. The paper contains several cross sections constructed from well data that constrain the Upper Cretaceous-Quaternary stratigraphy of the South Carolina coastal plain. The cross sections cover the area east of the Fall Line and show that several thick and laterally extensive low permeability units divide the productive aquifer formations that subcrop in the coastal plain. The most important confining units are: the Upper Floridan confining unit, which divides the Floridan aquifer subcrop from the overlying surficial aquifer; the Crouch Branch confining unit, which divides the Floridan Aquifer System or the laterally equivalent Pearl River aquifer from the underlying Chattahoochee River aquifer; and the McQueen Branch confining unit, which divides the upper and lower units of the Chattahoochee River aquifer. In general, these confining units are about 50 ft in thickness, but thin or pinch out toward the Fall Line, and thicken toward the coast. From the South Carolina-Georgia border, the Upper Floridan confining unit pinches out, grading to the west into the Pearl River aquifer outcrop, or to the north, where it is unconformably overlain by the surficial aquifer. From the coastline, the Crouch Branch confining unit pinches out toward the Fall Line from the middle of the state to the South Carolina-North Carolina border. Based on these observations, a depth cut-off was established, below which the aquifers are regarded confined. Wells with depths greater than 300 ft contain at least 50 ft of confining units, and therefore are considered confined (i.e., Class III in the Pettyjohn scheme). This cut-off depth is used throughout the rules set and is applied to the alluvial valley, non-alluvial valley surficial, Pearl River, and Chattahoochee River aquifer outcrops, as well as the Floridan Aquifer System subcrop.

Rule 1. Alluvial Valley aquifer (ALLU)

The unconsolidated sediments of the alluvial valley aquifer are Quaternary in age and are contained within river and stream valleys throughout the Atlantic coastal plain of South Carolina. The alluvial valley aquifer is generally less than 50 ft thick and contains water under unconfined or water table conditions. The aquifer consists of unconsolidated gravel, sand, silt, clay, and peat. This aquifer generally yields small volumes of water and is primarily used for domestic supplies.

1a. Wells located within the alluvial valley aquifer outcrop (ALLU), with well depths less than 50 ft, deriving water from the shallow subsurface, are Class Ia because these sediments form unconsolidated deposits that are under unconfined or water table conditions.

1b. Wells located within the alluvial valley aquifer outcrop (ALLU) most likely deriving water from underlying aquifers with well depths between 50 and 300 ft are Class Id because these aquifers are covered by at least one impermeable unit less than 50 ft in thickness.

1c. Wells located within the alluvial valley aquifer outcrop (ALLU) most likely deriving water from underlying aquifers with well depths greater than 300 ft are Class III because these aquifers are confined by at least one impermeable unit greater than 50 ft in thickness.

Rule 2. Non-Alluvial Valley Surficial Aquifer (SURF)

The unconsolidated sediments of the non-alluvial valley surficial aquifer (surficial aquifer) are Pliocene and younger in age and lie outside of present-day river and stream valleys. These sediments are mostly marine terrace deposits less than 50 ft in thickness and contain water under unconfined conditions. The lithology of the aquifer ranges from unconsolidated sand, with minor shell beds, to sand with silt and clay. This aquifer generally yields small volumes of water and is primarily used for domestic supplies.

2a. Wells located within the non-alluvial valley surficial aquifer outcrop (SURF), with well depths less than 50 ft, deriving water from the shallow subsurface, are Class Ia because these sediments are unconsolidated, and the water is under unconfined or water table conditions.

2b. Wells located within the non-alluvial valley surficial aquifer outcrop (SURF) most likely deriving water from underlying aquifers with well depths between 50 and 300 ft are Class Id because these aquifers are covered by at least one impermeable unit less than 50 ft in thickness.

2c. Wells located within the non-alluvial valley surficial aquifer outcrop (SURF) most likely deriving water from underlying aquifers with well depths greater than 300 ft are Class III because these aquifers are confined by at least one impermeable unit greater than 50 ft in thickness.

Rule 3. Pearl River aquifer (PERL)

The semi-consolidated sediments of the Pearl River aquifer outcrop in the southern upper coastal plain of South Carolina, along the Georgia border, and subcrop to the east, lying stratigraphically below the surficial aquifer and grading laterally into the Floridan Aquifer System. The aquifer consists of sand of Paleocene to Miocene age, with minor sandstone and limestone beds, and contains water under primarily unconfined conditions.

3a. Wells located within the Pearl River aquifer outcrop (PERL), with well depths less than 50 ft, deriving water from the shallow subsurface, are Class Ic because these sediments are semi-consolidated, and the water is under unconfined or water table conditions.

3b. Wells located within the Pearl River aquifer outcrop (PERL) most likely deriving water from underlying aquifers with well depths between 50 and 300 ft are Class Id because these aquifers are covered by at least one impermeable unit less than 50 ft in thickness.

3c. Wells located within the Pearl River aquifer outcrop (PERL) most likely deriving water from underlying aquifers with well depths greater than 300 ft are Class III because these aquifers are confined by at least one impermeable unit greater than 50 ft in thickness.

Rule 4. Chattahoochee River aquifer (CHAT)

The consolidated sediments of the Chattahoochee River aquifer outcrop in the northern upper coastal plain of South Carolina, along the North Carolina border, and subcrop to the east, lying stratigraphically below the Pearl River aquifer and Floridan Aquifer System. The aquifer is separated from these overlying aquifers by a confining unit consisting of silt and clay. The aquifer consists of mostly sandstone of Late Cretaceous to Late Paleocene age, with thin lignitic clay lenses and locally includes glauconitic sand and limestone.

4a. Wells located within the Chattahoochee River aquifer outcrop (CHAT), with well depths less than 50 ft, deriving water from the shallow subsurface, with a yield greater than 50 gpm, are Class IIa because the aquifer sediments are consolidated, and the well is higher yield.

4b. Wells located within the Chattahoochee River aquifer outcrop (CHAT), with well depths less than 50 ft, deriving water from the shallow subsurface, with a yield less than or equal to 50 gpm, are Class IIb because the aquifer sediments are consolidated, and the well is lower yield.

4c. Wells located within the Chattahoochee River aquifer outcrop (CHAT), most likely deriving water from underlying aquifers, with well depths between 50 and 300 ft are Class IIc because the aquifer sediments are consolidated, and these aquifers are covered by at least one impermeable unit less than 50 ft in thickness.

4d. Wells located within the Chattahoochee River aquifer outcrop (CHAT) most likely deriving water from underlying aquifers, with well depths greater than 300 ft are Class III because these aquifers are confined by at least one impermeable unit greater than 50 ft in thickness.

Rule 5. Piedmont and Blue Ridge aquifer (PIED)

The consolidated igneous and metamorphic rocks and local Triassic sedimentary rocks of the Piedmont and Blue Ridge aquifer outcrop from the central part of South Carolina to the northern and western borders of the state. Water is obtained from the regolith and/or fractures in these crystalline rocks, implying unconfined conditions. The aquifer consists of a complex of low- to medium-grade metamorphic rocks and intrusive igneous rocks of Precambrian to Jurassic age. Overall composition is felsic to intermediate with local mafic units in the form of gabbroic plutons and diabase dikes.

5a. Wells located within the Piedmont and Blue Ridge aquifer outcrop (PIED_OUT) with a yield greater than 50 gpm, are Class IIa because the aquifer is consolidated, and the well is higher yield.

5b. Wells located within the Piedmont and Blue Ridge aquifer outcrop (PIED_OUT) with a yield less than or equal to 50 gpm, are Class IIb because the aquifer is consolidated, and the well is lower yield.

Metadata Sources References

Campbell, B.G. and A.L. Coes (eds.). 2010. Groundwater availability in the Atlantic Coastal Plain of North and South Carolina: U.S. Geological Survey Professional Paper 1773, 241 p., 7 pls.

Miller, J. 1997. Ground water atlas of the United States: Segment 6, Alabama, Florida, Georgia South Carolina. Hydrologic Investigations Atlas 730-G, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in South Dakota

15 May 2018

Introduction

The following rules were devised primarily on the basis of information provided in the USGS Hydrologic Investigations Atlas 730-I (Whitehead, 1996) and the previously published DW USA reports (RSPA, 2002). The dataset available at the time these rules were written consisted of:

1. Well location, source, and depth
2. Bedrock geology

Spatial extent of aquifers is generally derived from detailed bedrock geology data (Martin, et al., 2004), using the USGS Hydrologic Investigations Atlas 730-I Segment 8 atlas (Whitehead, 1996) as a guide. Wells are classified primarily on basis of their described source, depth, and the lithology of the bedrock or sedimentology of the unconsolidated material in the area.

The following aquifers of South Dakota were distinguished for this work:

1. Surficial unconsolidated
2. Glacial
3. High Plains
4. Lower Tertiary-Upper Cretaceous
5. Lower Cretaceous
6. Paleozoic
7. Confining unit
8. Not a principle aquifer

Rule 1. Surficial unconsolidated aquifers (SURF)

Surficial non-glacial aquifers in South Dakota consist of Quaternary unconsolidated sand and gravel deposited as alluvium from streams. Stream-valley alluvium is found in and adjacent to most of the larger streams in South Dakota and consists primarily of well-sorted particles that range in size from clay to boulders. Sand and gravel portions of these deposits form the most productive aquifers. Eolian, or wind-blown, sand dunes and deposits can also form locally productive aquifers. Average yield of wells completed in surficial aquifers range from about 1 to 1,000 gallons per minute. However, yields of wells completed in thick sequences of sand and gravel can exceed 3,500 gpm (Whitehead, 1996). Depths of wells completed in glacial outwash deposits are generally less than 300 ft. Wells completed in stream-valley alluvium are generally less than 100 ft deep.

1a. Wells sourcing from surficial Quaternary unconsolidated-deposit aquifers are Class Ia, because these aquifers can have high hydraulic conductivity and contain water primarily under unconfined or water-table conditions.

Rule 2. Glacial aquifers (GLAC)

During the Pleistocene, massive ice sheets covered much of eastern South Dakota. Glacial deposits that were redistributed by glacial meltwater during ice retreats (called glacial outwash) consist of stratified sand and gravel and form productive aquifers. In contrast, clay and silt that were deposited in glacial lakes, and poorly sorted, unstratified deposits of clay, silt, sand, gravel, and boulders (called till) have minimal permeability and form confining units. Permeable lenses of sand and gravel within till can form locally productive aquifers. Outwash deposits are found along stream valleys and in outwash plains. In places, these coarse-grained deposits are as much as 400 ft thick and are important aquifers. Although some of these sand and gravel aquifers are exposed at the land surface, most are buried, ancient channel deposits that formed either in valleys of meltwater streams or valleys incised into the bedrock. These buried valley deposits are commonly covered with confining units consisting of till or fine-grained glacial lake deposits. Most of the continental glacial deposits consist of till, which is a mixture of unsorted clay, silt, sand, gravel and boulders that was deposited beneath or at the margins of the ice.

- 2a. Wells sourcing glacial aquifers shallower than 400 ft, or with unknown depth, and located within the extent of surficial or glacial aquifers, are <u>Class Id,</u> because these wells are commonly covered with confining units consisting of till or fine-grained glacial lake deposits.
- 2b. Wells sourcing glacial aquifers deeper than 400 ft and located within the extent of surficial or glacial aquifers, are of <u>Class III</u>.

Rule 3. High Plains aquifer (HPLA)

The High Plains aquifer covers an area of ~4,800 square miles in south-central South Dakota. The aquifer consists of upper Tertiary and Quaternary unconsolidated sand and gravel deposits. Fine-grained deposits of clay and silt commonly are interbedded or mixed with the sand and gravel. Most wells completed in the High Plains aquifer obtain water from upper Tertiary aquifers in the Miocene Ogallala Formation and the Oligocene-Miocene Arikaree Formation. The unconsolidated sand and gravel beds of the Ogallala yield water much more readily than the more consolidated beds of the Arikaree. Siltstone and sandstone of the Oligocene White River Group (Brule Formation) yield highly variable volumes of water (Whitehead, 1996). The upper Tertiary aquifers consist of broad, extensive sheets of alluvium that were deposited by a network of braided streams that flowed eastward from the Rocky Mountains and constantly shifted their channels across a broad, gently sloping plain. The permeability of the upper Tertiary aquifers is variable and directly related to the grain size and sorting of the deposits. Where the aquifers consist of sand and gravel, they are extremely permeable and, thus, susceptible to contamination. Permeability decreases as clay content increases. Generally, the upper Tertiary aquifers become more clayey and less permeable with depth. Quaternary valley-fill and dune deposits (Sand Hills) are hydraulically connected to the underlying Tertiary aquifers and are included in the High Plains aquifer. These permeable deposits are important recharge areas because they readily absorb and temporarily store precipitation before it percolates downward to recharge the underlying Tertiary aquifers. Except for the wind-deposited dune sands, all deposits that compose the High Plains aquifer were deposited by streams. The High Plains aquifer contains water primarily under unconfined or water-table conditions, though clay beds and lenses of fine-grained material locally create confined conditions. The High Plains aquifer is as much as 1,000 ft thick in southeastern Wyoming, but is generally thinner in South Dakota. In South Dakota, depth to water in the High Plains aquifer is generally less than 200 ft and its saturated thickness generally is less than 600 ft. Most wells completed in the High Plains aquifer are less than 600 ft deep. Well yields that range from 250 to 750 gallons per minute are typical of the High Plains aquifer over about 80% of its extent in South Dakota.

3a. Wells sourcing the High Plains aquifer and located within the outcrop of this aquifer, or within surficial Quaternary unconsolidated-deposit aquifers that overlie it, are Class Ia

Rule 4. Lower Tertiary aquifers (LTRT)

In South Dakota, lower Tertiary aquifers consist of sandstone beds within the Paleocene Fort Union Formation or Group. Most of the lower Tertiary rocks were deposited in continental environments and consist of alternating beds of sandstone, siltstone, and claystone and commonly contain beds of lignite and subbituminous coal. Water in the lower Tertiary aquifers commonly is under unconfined conditions, though clay beds in the upper parts of the aquifers can create locally confined conditions. In South Dakota, most wells completed in the lower Tertiary aquifers are generally 300 to 900 ft deep and typically yield from 1 to 50 gallons per minute, though maximum yields can exceed 500 gallons per minute (Whitehead, 1996).

4a. Wells sourcing lower Tertiary aquifers and located within the outcrop of these aquifers are Class IIa.

4b. Wells sourcing lower Tertiary aquifers, but covered by unconsolidated material, that are less than 50 ft deep or with unknown depth, are Class IIc.

4c. Wells sourcing lower Tertiary aquifers and located outside of the outcrop of these aquifers, or covered by unconsolidated material and greater than 50 ft deep, are generally confined, and are Class III.

Rule 5. Upper Cretaceous aquifers (UCRT)

Upper Cretaceous aquifers of South Dakota are exposed as a wide band that surrounds the lower Tertiary aquifers. Although these aquifers are widespread in the subsurface, they contain freshwater only where they crop out and for a short distance downdip of where they are covered by younger rocks. The upper Cretaceous aquifers consist of sandstone beds in the Hell Creek Formation and Fox Hills Sandstone. The Hell Creek Formation consists of interbedded sandstone, siltstone, claystone, and local thin beds of coal or lignite, all of which were deposited in a continental environment. The underlying Fox Hills sandstone consists primarily of sandstone that was deposited in mostly a deltaic to marine environment and contains local beds of siltstone and shale. Water in the upper Cretaceous aquifers is under unconfined conditions in most places. The permeability of the upper Cretaceous aquifers is somewhat variable, but generally not as great as that of the aquifers in younger rocks. Wells completed in the Hell Creek Formation and Fox Hills Sandstone generally are less than 800 ft deep and have yields that range from 5 to 50 gallons per minute (Whitehead, 1996).

5a. Wells sourcing upper Cretaceous aquifers and located within the outcrop of these aquifers are Class IIb.

5b. Wells sourcing upper Cretaceous aquifers, but covered by unconsolidated material, that are less than 50 ft deep or with unknown depth, are Class IIc.

5c. Wells sourcing upper Cretaceous aquifers and located outside of the outcrop of these aquifers, or covered by unconsolidated material and greater than 50 ft deep, are generally confined, and are Class III.

Rule 6. Lower Cretaceous aquifers (LCRT)

Lower Cretaceous aquifers extend over most of South Dakota, but are exposed at the land surface only as a narrow band around the Black Hills Uplift. The lower Cretaceous aquifers are separated from the overlying upper Cretaceous aquifers by several thick shales that form an effective confining unit (described below). In South Dakota, consolidated sandstones in the Dakota Sandstone, Fuson Formation, and Lakota Formation form the lower Cretaceous aquifers. Locally, permeable sandstones of the Jurassic Sundance Formation yield small to moderate quantities of water to wells. Most of the water-yielding sandstones in the lower Cretaceous aquifers are of fluvial or deltaic origin. Water in the lower Cretaceous aquifers is confined except in aquifer outcrop areas around the Black Hills. In eastern South Dakota, the aquifers contain water under confined to semi-confined conditions. Low-permeability till and glacial-lake deposits overlie the aquifers in this region. Yields of most wells completed in these aquifers range from ~5 to 60 gallons per minute. However, yields of some wells completed in the lower Cretaceous aquifers may exceed 500 to 1,000 gallons per minute (Whitehead, 1996).

6a. Wells sourcing lower Cretaceous aquifers and located within the outcrop of these aquifers are Class IIa.

6b. Wells sourcing lower Cretaceous aquifers, but covered by unconsolidated material, that are less than 50 ft deep or with unknown depth, are Class IIc.

6c. Wells sourcing lower Cretaceous aquifers, and located outside of the outcrop of these aquifers, or covered by unconsolidated material and greater than 50 ft deep, are generally confined and are Class III.

Rule 7. Paleozoic aquifers (PALE)

Paleozoic aquifers extend over about three-fourths of South Dakota in the subsurface, but are exposed at the land surface only in a small area around the Black Hills. The Paleozoic aquifers consist mostly of limestone and dolomite, but some Paleozoic sandstones also yield water. Confining units that overlie and separate the aquifers consist of shale and siltstone with some beds of anhydrite and halite. Most of these Paleozoic rocks were deposited in marine environments. In South Dakota, Paleozoic aquifers consist of Pennsylvanian sandstones in the Minnelusa Formation, Mississippian limestones and dolomites of the Madison Group, Ordovician dolomite and limestone of the Red River Formation and sandstones and limestones of the Deadwood Formation. Limestones and dolomites of the Madison Group are the most productive aquifers and may represent the most important bedrock aquifers in South Dakota (Howells, 1979; Whitehead, 1996). In places, large solution cavities have developed in these limestones, through which large volumes of water can flow. Wells that penetrate these solution cavities can yield very large volumes of water, especially where several solution cavities are interconnected. In addition, springs commonly issue from solution openings in Madison limestones. Where these limestones are exposed at the surface, dissolution has created karst topography. These solution openings at the land surface allow surface water to move into the underlying limestone. Except for recharge/outcrop areas around the Black Hills, the Paleozoic aquifers are overlain by confining units in most places and contain water under high artesian pressure.

7a. Wells sourcing Paleozoic aquifers and located within the outcrop of these aquifers are Class Ib.

7b. Wells sourcing Paleozoic aquifers, but covered by unconsolidated material, that are less than 50 ft deep or with unknown depth, are Class Id.

7c. Wells sourcing Paleozoic aquifers, and located outside of the outcrop of these aquifers, or covered by unconsolidated material and greater than 50 ft deep are generally confined and are Class III.

Rule 8. Confining units (CONF)

Several thick Cretaceous shales form an effective confining unit that separates the lower Cretaceous aquifers from overlying aquifers. The Pierre Shale is the thickest and most extensive of the confining units. The Pierre Shale is as much as 3,000 ft thick and subcrops over about two-thirds of eastern South Dakota. Locally, the Pierre Shale yields small volumes of water from thin interbedded sandstones or from highly weathered or fractured zones in the uppermost shale beds. Other Cretaceous confining units include the Niobrara Formation, Carlile Shale, Greenhorn Limestone, and Graneros Shale. In eastern South Dakota, small volumes of water are obtained from wells completed in calcareous lenses of the chalky, shaly Niobrara Formation, the Greenhorn Limestone, and Codell Sandstone Member of the Carlile Shale (Whitehead, 1996). However, these are not considered principal aquifers. The Jurassic Morrison Formation, Triassic Spearfish Formation and Permian Minnekahta and Opeche Formations form confining units that separate the Paleozoic aquifers from the overlying lower Cretaceous aquifers.

8a. Wells sourcing confining units and located within the outcrop of those confining units are Class IIb.

8b. Wells sourcing confining units, but covered by unconsolidated material, that are less than 50 ft deep or with unknown depth, are Class IIc.

8c. Wells sourcing confining units and located outside of the outcrop of these confining units, or covered by unconsolidated material and greater than 50 ft deep, are Class III.

Rule 9. Not a principle aquifer (NAPA)

Outcrop belts of igneous and metamorphic rocks in South Dakota are designated as ‘not a principal aquifer’ (NAPA). This designation covers areas where aquifers either do not exist, yield too little water to be significant, or yield sufficient water to supply only local requirements, but are not extensive enough to be considered major aquifers. The rocks are chiefly Precambrian slate, schist, quartzite, and granite that form the core of the Black Hills Uplift, scattered outcrops of the Precambrian Sioux Quartzite in eastern South Dakota, and Cenozoic igneous rocks of the northern Black Hills.

9a. Wells sourcing these units and located within the outcrop of those units are Class IIb.

9b. Wells sourcing these units, but covered by unconsolidated material, that are less than 50 ft deep or with unknown depth, are Class IIc.

9c. Wells sourcing these units and located outside of the outcrop of these units, or covered by unconsolidated material and greater than 50 ft deep, are Class III.

Metadata Sources References

Howells, L. 1979. Geohydrology of the Cheyenne River Indian Reservation, South Dakota: U.S. Geological Survey, Hydrologic Investigations Atlas HA-585, 1:250,000 and 1:500,000 scale.

Martin, J.E., J.F. Sawyer, M.D. Fahrenbach, D.W. Tomhave, and L.D. Schulz. 2004. Geologic map of South Dakota. South Dakota Geological Survey, General Map 10. 1 sheet, scale 1:500,000.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Whitehead, R.L. 1996. Ground water atlas of the United States: Segment 8, Montana, North Dakota, South Dakota, Wyoming. Hydrologic Investigations Atlas 730-I, U.S. Geological Survey, Reston, VA, 24 pp.

Rules for Applying the Pettyjohn Classification Scheme in Tennessee

9 April 2019

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-K (also called Ground Water Atlas of the United States, Segment 10; Lloyd and Lyke, 1995) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Well location
2. Bedrock geology
3. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology and the Segment 10 Atlas (Lloyd and Lyke, 1995) as a guide.

Due to the lack of source or depth data, classification of all wells is based solely on the location of the well within the aquifer coverage.

There are nine principal aquifers in the state of Tennessee:

1. Alluvial
2. Mississippi Embayment aquifer system
3. Black Warrior River
4. Pennsylvanian
5. Mississippian
6. Silurian-Devonian
7. Ordovician
8. Valley and Ridge
9. Blue Ridge

The aquifer features were constructed from the bedrock geology features (BGEO).

Rule 1. Alluvial aquifer (ALLU)

The unconsolidated sediments of the Alluvial aquifer are present within the major river valleys of Tennessee such as the Mississippi, Hatchie, Tennessee and Cumberland rivers as well as on the flanks of these river valleys in the form of high terrace deposits. The aquifer predominantly consists of sand and gravel from Pleistocene age to modern fluvial deposition. The aquifer is unconfined throughout the entire state of Tennessee.

1a. Wells located within the Alluvial aquifer outcrop (ALLU) are <u>Class Ia</u> because these unconsolidated sand and gravel deposits are predominantly under unconfined conditions.

Rule 2. Mississippi Embayment aquifer system (EMBA)

The unconsolidated to semi-consolidated sediments of the Mississippi Embayment aquifer system (EMBA) outcrop across western Tennessee with the exception of the major river valleys in the area. The five aquifers that make up the EMBA predominantly consist of massive sand beds with two silt and clay units confining the lower aquifers within the system. Where no confining units are present, aquifers are differentiated on the basis of changes in lithology and hydrologic head between aquifers. The sediments that make up the EMBA are Cretaceous to Eocene in age.

2a. Wells located within the Mississippi Embayment aquifer system outcrop (EMBA) excluding those located in the McNairy-Nacatoch aquifer (Km, Ko) are conservatively Class Ia because without depth data it is not possible to determining if a given well is sourcing an unconfined surficial aquifer or a deeper confined aquifer.

2b. Wells located within the Mississippi Embayment aquifer system outcrop (EMBA) located in the McNairy-Nacatoch aquifer (Km, Ko) are Class Ic because the sand and clay which makes up this aquifer was deposited during the Cretaceous period therefore old enough to be considered semi-consolidated.

Rule 3. Black Warrior River aquifer (BLAC)

The unconsolidated to semi-consolidated sediments of the Black Warrior River aquifer outcrop in a north-south trending band in southwest Tennessee. The Black Warrior River aquifer consists of sand and clay deposited in fluvial deltaic and marine environments during the Cretaceous period. Where not exposed at the surface, the aquifer is overlain by the Black Warrior confining unit. The Black Warrior River aquifer is underlain by crystalline basement rock.

3a. Wells located within the Black Warrior River aquifer outcrop (BLAC) are Class Ic because the sand and clay which makes up this aquifer was deposited during the Cretaceous period therefore old enough to be considered semi-consolidated.

Rule 4. Pennsylvanian aquifers (PENN)

The consolidated siliciclastic rocks of the Pennsylvanian aquifers outcrop in a northeast trending band across east-central Tennessee. The Pennsylvanian aquifers consists of sandstone, conglomerate with interbedded siltstone, shale and coal of Pennsylvanian age. The conglomerate aquifers can range from a few feet to approximately 200 ft in thickness while the sandstone aquifers range from 100 to 300 ft thick in Tennessee. Wells sourcing the Pennsylvanian aquifers in Tennessee commonly yield between 5 and 50 gallons per minute (gpm).

4a. Wells located within the Pennsylvanian aquifers outcrop (PENN) are Class IIb because these aquifers are consolidated, generally unconfined and commonly lower yield according to the Pettyjohn classification system.

Rule 5. Mississippian aquifers (MISS)

The consolidated carbonate rocks of the Mississippian aquifers outcrop in north-central Tennessee as part of the Interior Low Plateaus Province and in a northwest trending band across east-central

Tennessee as part of the Appalachian Plateaus Province. The Mississippian aquifers consist primarily of limestone, sandstone and chert of Mississippian age. Fresh water circulates to depths as great as 500 ft below land surface within the Mississippian aquifers.

5a. Wells located within the Mississippian aquifers outcrop (MISS) are <u>Class Ib</u> because the aquifers consist of karstic limestone containing solution cavities.

Rule 6. Silurian-Devonian aquifers (SILD)

The consolidated carbonate rock of the Silurian-Devonian aquifers outcrop along valley walls in central and western Tennessee. The Silurian-Devonian aquifers consist of predominantly limestone with shale and chert lenses of Silurian to Devonian age. Where these aquifers are in the subsurface, they are confined from the Mississippian aquifers by the Upper Devonian Shale.

6a. Wells located within the Silurian-Devonian aquifers outcrop (SILD) are <u>Class Ib</u> because the aquifers consist of karstic limestone containing solution cavities.

Rule 7. Ordovician aquifers (ORDO)

The consolidated carbonate rock of the Ordovician aquifers outcrop in the central portion of the state. The Ordovician aquifers consist of predominantly limestone with interbedded shale, calcarenite, breccia and bentonite of Ordovician age. Wells sourcing the Ordovician aquifers in Tennessee obtain water between 50 and 1,200 ft below land surface.

7a. Wells located within the Ordovician aquifers outcrop (ORDO) are <u>Class Ib</u> because the aquifers consist of karstic limestone containing solution cavities.

Rule 8. Valley and Ridge aquifers (VALL)

The consolidated carbonate rocks of the Valley and Ridge aquifers outcrop in northeast trending bands in eastern Tennessee. The Valley and Ridge aquifers consist of limestones, dolomites and chert of Cambrian to Mississippian age. Wells sourcing the Valley and Ridge aquifers yield between 1 and 2,500 gpm with the largest yields coming from the lower portions of the Chickamauga Group, Knox Group and Shady Dolomite.

8a. Wells located within the Valley and Ridge aquifers outcrop (VALL) are <u>Class Ib</u> because the aquifers consist of karstic limestone containing solution cavities.

Rule 9. Blue Ridge aquifers (BLUE)

The consolidated sedimentary, metasedimentary, igneous and metamorphic rocks of the Blue Ridge aquifers outcrop in northeast trending bands along the Tennessee-North Carolina border. The Blue Ridge aquifers consist of primarily sandstone, shale, siltstone, conglomerate, granite, gabbro and gneiss of Pre-Cambrian to Cambrian age. Most of the available water within the Blue Ridge aquifers is present in fractures within a few hundred feet of land surface. The median yield of wells sourcing the Blue Ridge aquifers in Tennessee is 6 gpm.

9a. Wells located within the Blue Ridge aquifers outcrop (BLUE) are Class IIb because the aquifer is consolidated, generally unconfined and commonly lower yield according to the Pettyjohn classification system.

Rule 10. Not a principal aquifer (NAPA)

The Not a Principal aquifer units consist of unconsolidated and semi-consolidated sediments outcropping in the western portion of the state as well as consolidated sedimentary and metamorphic rocks outcropping in the central and eastern portion of the state. The Not a Principal aquifer consists of clays and sands of Cretaceous to Tertiary age, chert and shale of Mississippian age and shale, sandstone and quartzite of Cambrian to Silurian age.

10a. Wells located within the Not a Principal aquifer outcrop (NAPA), located in the Tertiary age Midway Group (Tm) are Class Id because the lithology of the Midway Group is predominantly low permeability clay.

10b. Wells located within the Not a Principal aquifer outcrop (NAPA), located in the Cretaceous age semi-consolidated sediments (Kcc, Kd and Ks) are Class Ic because the sand and clay which makes up these units was deposited during the Cretaceous period therefore old enough to be considered semi-consolidated.

10c. Wells located within the Not a Principal aquifer outcrop (NAPA) excluding those located in the formations mentioned in Rules 10a. and 10b. are Class IIb because these formations are generally composed of consolidated non-carbonate bedrock that is most likely lower yield.

Metadata Sources References

Lloyd Jr., O.B. and W.K. Lyke. 1995. Ground water atlas of the United States: Segment 10, Illinois, Indiana, Kentucky, Ohio, Tennessee. Hydrologic Investigations Atlas 730-K, U.S. Geological Survey, Reston, VA, 32 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Texas

16 March 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-E (Ryder, 1996) and information provided on the Texas Water Development Board website, https://www.twdb.texas.gov/groundwater/aquifer/ and published in Aquifers of Texas (George et al.; Report 380, Texas Water Development Board (TWDB), 2011) and the previously published DW USA reports (RSPA, 2002). The available data sets included:

1. Wells: location, depth, source aquifer
2. Bedrock geology
3. Aquifer boundaries

Classification of all wells should be based on the shallowest sourced interval in the well. However, because screen depth data is not currently available for the state of Texas, the classification of wells is based on their total depth and the source information provided. The maximum depth at which the classification changes to "unknown" is based upon the maximum thickness of each aquifer. The aquifer thickness was determined from the measurements and figures provided in Ryder (1996). An additional 50 ft was added for thinner aquifers (less than or equal to 400 ft) and 200 ft for thicker aquifers (greater than 400 ft) resulting in the estimated maximum thickness. The addition of 50 or 200 ft is to allow for uncertainty in the measurement of well depth, and the situations where wells were drilled a short distance into the underlying unit before drilling was terminated. The objective is to identify the wells that most likely have an error in at least one of the parameters of location, depth, or source.

The following aquifers of Texas were distinguished for this work:

1. *(An artifact from the previous effort, left blank here)*
2. Alluvial
   - General Alluvium
   - Brazos River Alluvium
3. Rio Grande
   - Hueco–Mesilla Bolsons
   - West Texas Bolsons
4. Pecos Valley (Cenozoic)
5. Seymour
6. High Plains
   - Ogallala
   - Rita Blanca
7. Gulf Coast
8. Texas Coastal Uplands
   - Carrizo–Wilcox
   - Queen City
   - Sparta
   - Yegua–Jackson

9. Nacatoch
10. Blossom
11. Woodbine
12. Edwards
13. Edwards−Trinity
14. Trinity
15. Dockum
16. Capitan Reef Complex
17. Blaine
18. Marble Falls
19. Ellenburger−San Saba
20. Hickory
21. Igneous
22. Bone Spring−Victorio Peak
23. Lipan
24. Marathon

Rule 1. (An artifact from the previous effort, left blank here and in the table)

The previous effort had no actual rule 1 and the information listed here was moved to the introduction, so we have intentionally left this rule blank.

Rule 2. Alluvial aquifers (ALLU, BRAZ)

General alluvial aquifers (ALLU): Groundwater is contained in alluvial floodplain and terrace deposits associated with the major river systems. The floodplain alluvium consists of fine to coarse sand, gravel, silt, and clay deposited in a complex geometry.

Brazos River Alluvium aquifer (BRAZ): The thickness of the Brazos River Alluvium ranged from negligible to 168 ft.

2a. Wells that derive water from the alluvial aquifer outcrops of the valleys and terraces associated with the major river systems (e.g., Brazos) at depths less than or equal to 200 ft are Class Ia, because these aquifers are permeable sands and gravels.

2b. Wells deriving water from depths greater than 200 ft are classified as unknown. The 200 ft cut-off is based on reported maximum thicknesses of 150 ft or less for Rio Grande alluvium (Ryder, 1996) and of 168 ft for Brazos river alluvium (Report 380, TWDB, 2011).

Rule 3. Rio Grande aquifers (HUEC, WEST)

Hueco-Mesilla Bolsons aquifer (HUEC): This aquifer is composed of basin-fill deposits of silt, sand, gravel, and clay. These sediments crop out at the surface in El Paso and Hudspeth counties and occur within two basins: the Hueco Bolson, which has a maximum thickness of 9,000 ft, and the Mesilla Bolson, which has a maximum thickness of 2000 ft (Report 380, TWDB, 2011).

West Texas Bolsons aquifer (WEST): This aquifer is composed of basin-fill deposits that range from the fine-grained silt and clay of lake deposits to the coarse-grained volcanic rock and limestone of alluvial fans. These sediments crop out at the surface in Culberson, Hudspeth, Jeff Davis, and Presidio counties and occur within one of the following structural basins: Salt, Eagle, Red Light, and Presidio. The maximum reported thickness is 3000 ft (Report 380, TWDB, 2011).

3a. Wells that derive water from the Rio Grande aquifer outcrops and are less than or equal to 1000 ft deep are Class Ia, because these late Tertiary/Quaternary sediments are permeable sands and gravels.

3b. Wells deeper than 1000 ft are Class III, because of the presence of confining units and artesian conditions.

Rule 4. Pecos Valley (Cenozoic) aquifer (PECO)

Alluvial and windblown deposits that make up the Pecos Valley aquifer fill several basins including the Pecos Trough and the Monument Draw Trough. Maximum thickness of these sediments is 1500 ft (Report 380, TWDB, 2011). This aquifer outcrops in the counties of Andrews, Crane, Ector, Loving, Pecos, Reeves, Ward, and Winker.

4a. Any wells that derive water from the Pecos River Basin (Cenozoic) Alluvial aquifer of the upper Pecos River region from depths less than or equal to 1700 ft are Class Ia, because these surficial Cenozoic Alluvial deposits are permeable sands and gravels.

4b. Wells within this aquifer deriving water from depths greater than 1700 ft are classified as unknown based on a reported maximum thickness equal to 1500 ft and the aquifer description of aquifer conditions as “generally unconfined” (Ryder, 1996).

Rule 5. Seymour aquifer (SEYM)

The Seymour aquifer is a surficial Pleistocene erosional remnant that occurs in 22 separate areas in parts of 20 counties in the upper Red and Brazos River Basins. The thickness of the Seymour aquifer ranges from less than 100 ft to as much as 360 ft in isolated northern portions of the aquifer (George et al, 2011). The most intensely developed part of this aquifer is located in Haskell and Knox counties, which lie within the central portion of the aquifer.

5a. Wells that derive water from the Seymour aquifer at depths less than or equal to 150 ft are Class Ia, because these alluvial deposits are permeable sands and gravels.

5b. Wells deeper than 150 ft are unknown, because with the data available, it is not possible to identify those areas as deep as 360 ft, thus the 150 ft cut-off is viewed as a reasonable compromise.

Rule 6. High Plains aquifers (OGAL, RITA)

Ogallala aquifer (OGAL): Located in the high plains aquifer outcrop belt in the Ogallala Formation, the Ogallala aquifer is the largest aquifer in the United States. The aquifer consists of sand, gravel, clay, and silt. It has a total thickness of 650 ft and is overlain by 150 ft of windblown sands and alluvium (Ryder, 1996). A 200 ft overlying buffer is included because some units below the Ogallala are not hydraulically isolated from the Ogallala.

Rita Blanca aquifer (RITA): Some of the units hydraulically connected to the Ogallala aquifer form the Rita Blanca aquifer in the northwestern most part of the state which includes the coarse-grained sand and gravel layers of the Lytle and Dakota formations as well as in the Exeter Sandstone and the Morrison Formation.

6a. Wells that derive water from the High Plains aquifers at depths less than or equal to 1000 ft are Class Ic because these Tertiary sandstones are semi-consolidated, high-yield aquifers.

6b. Wells deriving water from depths greater than 1000 ft are unknown. The 1000 ft cut-off is based on the total thickness (650 + 150 + 200 ft) of all units as described above.

Rule 7. Gulf Coast aquifer (GULF)

The Gulf Coast aquifer is the outcrop belt of the coastal lowlands aquifer system [coastal plain seaward of Jackson/Vicksburg (Eocene/early Oligocene) outcrop belt] consisting of several aquifers including the Jasper, Evangeline, and Chicot aquifers. The aquifer is composed of discontinuous sand, silt, clay, and gravel beds (TWDB website). A 400 ft cut-off for shallow well source is based on the fact that most of the sands from which water is derived are deltaic, barrier island/inlet and coastal plain units, which are typically no thicker than 200 ft. To account for wells that may derive water from only their lower half this number is doubled, resulting in a 400 ft cut-off. Additional support for the 400 ft depth limit is found in Weiss (1992), in which it is shown that the percentage of sand is most commonly less than 60% in the costal lowlands aquifer system. Therefore, at a maximum, within a thickness of 400 ft, approximately 240 ft of the sediments are permeable sand and the remaining 160 ft are low-permeability clays and silts, which may act as confining units.

7a. Wells that derive water from shallow depths (less than or equal to 400 ft) are Class Ia if the source is Pliocene or younger in age (Goliad Sand; Willis Sand; Bentley Formation; Montgomery Formation; Beaumont Formation), because these sediments are unconsolidated and highly permeable. Aquifer and rock names include: (1) Evangeline aquifer (Pliocene) – Goliad Sand; and (2) Chicot aquifer (Pleistocene/Holocene) – Willis Sand, Bentley Formation, Montgomery Formation, Beaumont Formation, alluvium.

7b. Wells that derive water from shallow depths (less than or equal to 400 ft) are Class Ic if the source is Oligocene/Miocene in age, because these rocks are semi-consolidated, high-yield aquifers. Aquifer and rock names include: Jasper aquifer (late Oligocene/Miocene) – Frio Formation, Anahuac Formation, Catahoula Sandstone, Oakville Sandstone, Fleming Sandstone, Burkeville aquiclude, and Lagarto Clay.

7c. Wells deeper than 400 ft producing from either of these systems (Pliocene or Oligocene/Miocene) or the Jackson subcrop penetrate confining units and are Class III.

Rule 8. Texas Coastal Uplands aquifers (CARR, QUEE, SPAR, YEGU)

The outcrop belts of the Texas Coastal Uplands aquifer system include the (1) Upper Claiborne aquifer (Eocene; Yegua Formation); (2) Middle Claiborne aquifer [Eocene (also called Sparta and Queen City aquifers); Sparta Sand; Weches Formation; Queen City Sand; Reklaw Formation; and Bigfoot Formation]; (3) Lower Claiborne-upper Wilcox aquifer (Eocene; Carrizo sand); and (4)

Middle Wilcox aquifer (Paleocene). (Note: Units 3 and 4 are collectively referred to as the Carrizo-Wilcox aquifer.)

Carrizo-Wilcox aquifer (CARR): This aquifer consists of the Wilcox Group and the overlying Carrizo Formation of the Claiborne Group and is primarily composed of sand locally interbedded with gravel, silt, clay, and lignite (TWDB website).

Queen City aquifer (QUEE): This aquifer is composed of sand, loosely cemented sandstone, and interbedded clay layers with a maximum thickness of 2,000 ft and freshwater saturated thickness averaging ~140 ft.

Sparta aquifer (SPAR): This aquifer is contained within the Sparta Formation which is a part of the Claiborne Group. It is composed of a sand-rich unit interbedded with silt and clay layers and with massive sand beds in the bottom section (TWDB website). The thickness ranges from 200-700 ft with freshwater saturated thickness averaging ~120 ft.

Yegua-Jackson aquifer (YEGU): This aquifer includes water-bearing parts of the Yegua Formation (part of the upper Claiborne Group) and the Jackson Group (comprising the Whitsett, Manning, Wellborn, and Caddell formations) and is composed of interbedded sand, silt, and clay layers originally deposited as fluvial and deltaic sediments (TWDB website).

8a. Wells that derive water from the outcrop belts of the Texas Coastal Uplands aquifer system are <u>Class Ic</u>, because these Tertiary sandstones are semi-consolidated, high-yield aquifers.

8b. Wells in any of these outcrop belts that derive water from deeper horizons (greater than 400 ft) are <u>Class III</u>, because these formations are all underlain by confining units. It is not possible to determine which wells are <u>Class III-v</u>, because the local thickness of confining units is unknown.

8c. Wells deriving water from the subcrop of the aquifer systems defined above are <u>Class III</u>, because each aquifer is overlain and underlain by confining units at depth.

Rule 9. Nacatoch aquifer (NACA)

The Nacatoch aquifer is part of the Upper Cretaceous Navarro Group and is consists of the sequences of marine-derived sandstone separated by impermeable layers of mudstone or clay that compose the Nacatoch Sand. The number of sand layers varies throughout the Nacatoch's extent, and the thickness of individual sand units ranges from more than 100 ft in the north to less than 20 ft to the south. Thickness of intervening mudstone units similarly ranges from more than 100 ft to only a few feet (TWDB website).

9a. Wells in the Nacatoch aquifer outcrop belt of the northeast area that derive water from that unit at depths less than or equal to 700 ft are <u>Class Ic</u>, because these sedimentary rocks are semi-consolidated, high-yield aquifers.

9b. Wells deeper than 700 ft are unknown. The 700 ft cutoff is based on a reported maximum thickness of 500 ft (Ryder, 1996) plus 200 ft as a conservative buffer.

9c. Wells deriving water from the subcrop of the aquifer are Class III (or Class III-v if the confining unit thickness is less than 50 ft or unknown), because younger overlying units create confining conditions.

Rule 10. Blossom aquifer (BLOS)

The Blossom aquifer consists of the Blossom Sand Formation of the Austin Group, composed of alternating sequences of sand and clay (TWDB website). It outcrops in Bowie, Red River, and Lamar counties. The reported maximum thickness is 400 ft (Ryder, 1996).

10a. Wells in the Blossom aquifer outcrop belt that derive water from that unit at depths less than or equal to 450 ft are Class Ic, because these sedimentary rocks are semi-consolidated, high-yield aquifers.

10b. Wells deeper than 450 ft are unknown. The 450 ft cutoff is based on the maximum thickness of 400 ft plus 50 ft as a conservative buffer.

10c. Wells deriving water from the subcrop of the aquifer are Class III (or Class III-v if the confining unit thickness is less than 50 ft or unknown), because of confining units within the Austin Group.

Rule 11. Woodbine aquifer (WOOD)

The Woodbine aquifer (Upper Cretaceous) overlies the Trinity aquifer and consists of sandstone interbedded with shale and clay. Common rock names include: Templeton, Lewisville, Red Branch, and Dexter members. The reported thickness of the Woodbine aquifer is 600-700 ft (Ryder, 1996) “near the down-dip limit of slightly saline water”.

11a. Wells in the Woodbine aquifer outcrop belt that derive water from that unit at depths less than or equal to 900 ft are Class IIa, because the sedimentary rocks in this aquifer typically yield well over 50 gpm.

11b. Wells deeper than 900 ft are unknown. This 900 ft cut-off is based on the maximum thickness of the aquifer of 700 ft and 200 ft as a conservative buffer.

11c. Wells deriving water from the subcrop of the aquifer are Class III (or Class III-v if the confining unit thickness is less than 50 ft or unknown) because of confining units above and below the aquifer at depth.

Rule 12. Edwards aquifer (EDWA)

The Edwards (Balcones Fault Zone) aquifer is a highly permeable Cretaceous aquifer composed primarily of partially dissolved limestone (TWDB website), and it is highly faulted and fractured. The reported maximum thickness is 600-800 ft (Report 380, TWDB, 2011; Ryder, 1996). The outcrop belt of the Edwards is located in the following counties (north to south): Bell, Williamson, Travis, Hays, Comal, Bexar, Medina, Uvalde, and Kinney. Common rock names for the aquifer are: Georgetown Formation, and Person and Kainer Formations of the Edwards Group.

12a. Wells in the Edwards aquifer outcrop that derive water from that aquifer are <u>Class Ib</u> because of the faulting and fracturing.

12b. Wells deriving water from the aquifer with depths greater than 1000 ft are unknown. This 1000 ft cut-off is the result of the maximum thickness of 800 ft plus a 200 ft conservative buffer.

12c. Wells deriving water from the subcrop of the aquifer are <u>Class III</u> (or <u>Class III-v</u> if the confining unit thickness is less than 50 ft or unknown), because younger overlying units create confining conditions.

Rule 13. Edwards-Trinity aquifer (EDWT)

The Edwards-Trinity (Plateau) aquifer is a Cretaceous aquifer in the Trans-Pecos or Edwards Plateau geographic regions. The water-bearing units are composed predominantly of limestone and dolomite (TWDB website). A maximum thickness is derived from a published cross section (Fig. 87, Ryder, 1996) and a general description of the aquifer thickness in the same publication which states "thickness ranges from a few tens of ft to more than 1000 ft." Common rock names: Boracho, Fort Lancaster, Finlay, Fort Terrett, and Segovia Formations; also possibly referred to as Edwards Group.

13a. Wells deriving water from the Edwards-Trinity aquifer outcrop belt at depths less than or equal to 1200 ft are <u>Class Ib</u>, because the upper portion of the aquifer is composed of limestones that contain secondary porosity (jointing and caverns).

13b. Wells deriving water from deeper horizons are unknown. The 1200 ft cut-off is derived from the maximum thickness of 1000 ft and a 200 ft conservative buffer.

13c. Wells deriving water from the subcrop of the aquifer are <u>Class III</u> (or <u>Class III-v</u> if the confining unit thickness is less than 50 ft or unknown), because younger overlying units create confining conditions.

Rule 14. Trinity aquifer (TRIN)

The Trinity aquifer (Cretaceous) is composed of several smaller aquifers contained within the Trinity Group and consists of sandstones and limestones that typically yield well over 50 gpm. The aquifer also has clays, gravels, and conglomerates. Published cross sections (Figs. 110, 111, 112, Ryder, 1996) were used to determine a cutoff thickness of 2000 ft. Common rock names: Antlers, Travis Peak, Glen Rose, Hensell, Hosston, Paluxy, and Twin Mountains Formations.

14a. Wells in the Trinity aquifer outcrop belt that derive water from the Trinity at depths less than or equal to 1200 ft are <u>Class IIa</u> because of the high-yield sandstones and limestones.

14b. Wells within the outcrop belt and deeper than 1200 ft are unknown.

14c. Wells outside the Trinity aquifer outcrop belt that derive water from the Trinity at a depth less than or equal to 2000 ft are <u>Class III</u> (or <u>Class III-v</u> if confining unit thickness is less than 50 ft or is unknown), because the Trinity aquifer is confined by an overlying unit.

14d. An exception to rule 14.c is where wells in the Edwards outcrop derive water from the Trinity subcrop (in the Balcones Fault Zone). These wells, if shallower than 2000 ft, are Class IIa.

14e. Wells in the Edwards outcrop that derive water from the Trinity subcrop (in the Balcones Fault Zone) with a depth greater than 2000 ft are unknown.

Rule 15. Dockum aquifer (DOCK)

The Dockum aquifer (Triassic) of the west-central and panhandle areas consists of the following formations that make up the Dockum Group: the Santa Rosa Formation, the Tecovas Formation, the Trujillo Sandstone, and the Cooper Canyon Formation. The aquifer contains sandstones and conglomerates that typically yield well over 50 gpm, as well as gravel, siltstone, mudstone, and shale. A 900 ft cut-off is based on a reported saturated thickness of as much as 700 ft (Ryder, 1996).

15a. Wells that derive water from the Dockum aquifer at depths less than or equal to 900 ft are Class IIa.

15b. Wells deeper than 900 ft are unknown.

15c. Wells deriving water from the subcrop of the aquifer are considered Class IIa, because the aquifer is not hydraulically isolated from the surface.

Rule 16. Capitan Reef Complex aquifer (CAPI)

The Capitan Reef Complex aquifer (Permian) is composed of "cavernous dolomite" (TWDB website) and a highly porous limestone. The aquifer outcrops in in Culberson, Hudspeth, Jeff Davis, Brewster, Pecos, Reeves, Ward, and Winkler counties. Common rock names: Capitan Limestone, Goat Seep Dolomite, and most of the Carlsbad facies of the Artesia Group, including the Grayburg, Queen, Seven Rivers, Yates, and Tansill formations. A 1200 ft cut-off is based on a statement according to Ryder (1996) that the aquifer has been "penetrated by wells to depths >1000 ft," and reports of water levels that "range between 280 to 1000 ft below the surface" in the same publication.

16a. Wells in the outcrop belt of the Capitan Reef Complex aquifer that derive water from that aquifer at depths up to 1200 ft are Class Ib.

16b. Wells deeper than 1200 ft are unknown.

Rule 17. Blaine aquifer (BLAI)

The Blaine aquifer is part of the Permian Blaine Formation, which is composed of red silty shale, cavernous gypsum and anhydrite, salt, and dolomite. A reported maximum thickness of the Blaine aquifer is 400 ft (Ryder, 1996).

17a. Wells in the Blaine aquifer outcrop belt that derive water from that aquifer at depths less than or equal to 450 ft are Class Ib because of the cavernous formations.

17b. Wells within the Blaine deeper than 450 ft are unknown. This is based on the maximum thickness of 400 ft plus a conservative buffer of 50 ft.

17c. Wells deriving water from the subcrop of the aquifer are Class III (or Class III-v if the confining unit thickness is less than 50 ft or unknown), because younger overlying units create confining conditions.

Rule 18. Marble Falls aquifer (MARB)

The Marble Falls aquifer (Pennsylvanian: Marble Falls Limestone of the Bend Group) outcrop belt is located in a circular pattern around the Llano Uplift in center of the state. It is a limestone unit that contains numerous fractures, cavities, and solution channels. The reported maximum thickness is 600 ft (Ryder, 1996).

18a. Wells in the Marble Falls aquifer outcrop belt that derive water from that aquifer at depths less than or equal to 800 ft are Class Ib.

18b. Wells deeper than 800 ft are classed as unknown. The 800 ft cut-off is based on the 600 ft maximum thickness and a 200 ft buffer in order to be conservative.

Rule 19. Ellenburger-San Saba aquifer (ELLE)

The Ellenburger-San Saba aquifer consists of the Tanyard, Gorman, and Honeycut formations of the Ellenburger Group (Ordovician) and the San Saba Limestone Member of the Wilberns Formation (Cambrian/Ordovician). The aquifer outcrop consists of a sequence of limestone and dolomite and is located in a circular pattern around the Llano Uplift in center of the state. The limestones contain numerous fractures, cavities, and solution channels.

19a. Wells in the Ellenburger-San Saba aquifer outcrop belt that derive water from that aquifer at depths less than or equal to 2200 ft are Class Ib.

19b. Wells deeper than 2200 ft are classed as unknown.

19c. Wells deriving water from the subcrop of the aquifer are Class III (or Class III-v if the confining unit thickness is less than 50 ft or unknown), because younger overlying units create confining conditions.

19d. An exception to rule 19.c occurs when the subcrop of the Ellenburger-San Saba aquifer lies below the Marble falls outcrop. In this case, aquifer conditions are still unconfined and wells are Class Ib.

Rule 20. Hickory aquifer (HICK)

The Hickory aquifer consists of parts of the Hickory Sandstone Member of the Riley Formation containing sandstones and conglomerates that typically yield over 50 gpm. The maximum thickness is reported to be 480-500 ft (Report 380, TWDB, 2011; Ryder, 1996).

20a. Wells in the Hickory aquifer outcrop that derive water from the Hickory at depths less than or equal to 700 ft are Class IIa.

20b. Wells deeper than 700 ft are classed as unknown. The 700 ft cut-off is derived from the maximum thickness of 500 ft and a 200 ft conservative buffer.

20c. Wells that derive water from the subcrop of the Hickory aquifer are treated the same as the outcrop because these units are often in hydraulic continuity with overlying units.

Rule 21. Igneous aquifer (IGNE)

The Igneous aquifer consists of volcanic rocks made up of a complex series of welded pyroclastic rock, lava, and volcaniclastic sediments and includes more than 40 different named units.

21. Wells located in the Igneous aquifer outcrop belt that derive water from that aquifer are <u>Class Ib</u>, because of the high yield of wells in this aquifer. A depth at which it becomes unreasonable for a well to be deriving water from this aquifer is unknown. The vertical extent of igneous intrusive rocks can be quite great and in this case the water is poorly constrained.

Rule 22. Bone Spring-Victorio Peak aquifer (BONE)

The principal water-bearing units in the Bone Spring-Victorio Peak aquifer are the Bone Spring and Victorio Peak limestones (Permian) which contain numerous fractures, cavities, and solution channels.

22a. Wells in the Bone Spring-Victorio Peak aquifer outcrop belt that derive water from that aquifer at depths less than or equal to 2200 ft are <u>Class Ib</u>.

22b. Wells deeper than 2200 ft are classed as unknown. The 2200 ft cutoff is based on an estimation of aquifer thickness of "as much as 2000 ft." (Ryder, 1996).

Rule 23. Lipan aquifer (LIPA)

The Lipan Aquifer includes water-bearing alluvium consisting mostly of gravels and conglomerates cemented with sandy lime and layers of clay and the updip portions of older, underlying strata including the San Angelo Sandstone of the Pease River Group and the Choza Formation, Bullwagon Dolomite, Vale Formation, Standpipe Limestone, and Arroyo Formation of the Clear Fork Group. The limestone in this unit contains numerous fractures, cavities, and solution channels.

23a. Wells in the Lipan aquifer outcrop belt that derive water from that aquifer at depths less than or equal to 175 ft are <u>Class Ib</u>.

23b. Wells deeper than 175 ft are classed as unknown. This is based on a reported aquifer thickness of 125 ft (Ryder, 1996), plus 50 ft as a conservative buffer.

Rule 24. Marathon aquifer (MARA)

The Marathon aquifer consists of tightly folded and faulted rocks of the Gaptank Formation, the Dimple Limestone, the Tesnus Formation, the Caballos Novaculite, the Maravillas Chert, the Fort

Pena Formation, and the Marathon Limestone. The Marathon Limestone is the most productive part of the aquifer and contains numerous fractures, cavities, and solution channels.

24a. Wells in the Marathon aquifer outcrop belt that derive water from that aquifer at depths less than or equal to 1100 ft are <u>Class Ib</u>.

24b. Wells deeper than 1100 ft are classed as unknown. This is based on a reported aquifer thickness of 900 ft (Ryder, 1996), plus 200 ft as a conservative buffer.

Metadata Sources References

George, P.G., R.E. Mace, and R. Petrossian. 2011. Aquifers of Texas. Texas Water Development Board Report 380.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Ryder, P.D. 1996. Ground water atlas of the United States: Segment 4, Oklahoma, Texas. Hydrologic Investigations Atlas 730-E, U.S. Geological Survey, Reston, VA, 32 pp.

Weiss, J.S. 1992. Geohydrologic units of the coastal lowlands aquifer system, south central United States, U.S. Geological Survey Professional paper 1416-C, 32 pp.

Rules for Applying the Pettyjohn Classification Scheme in Utah

16 October 2018

Introduction

The rule set below is based on information published in the USGS Hydrologic Investigations Atlas 730-C (Robson and Banta, 1995) and the previously published DW USA reports (RSPA, 2002). The data available for Utah included:

1. Wells: location, pump rate
2. Bedrock geology

Well classification is based on the shallowest aquifer that could potentially be sampled at a well location. If source-aquifer data become available, well classifications could change.

There are four principal aquifer systems in Utah in addition to a region that is considered not a principal aquifer (NAPA). Unconsolidated sand and gravel aquifers include surficial aquifers in stream valleys and basin-fill deposits of the Basin and Range aquifers. Carbonate rocks also form important aquifers in the Basin and Range Physiographic Province. The Colorado Plateaus aquifers are primarily sandstone aquifers. The NAPA-designated region is underlain by a variety of rock types.

Codes used below to identify bedrock geology map formations refer to those used in the digital version of the Geologic Map of Utah.

The following aquifers of Utah were distinguished for this work:

1. Surficial
2. Carbonate and basaltic rock
3. Colorado Plateaus
4. Consolidated bedrock
5. Not a principal aquifer

Rule 1. Surficial aquifer systems (SURF)

Utah's surficial aquifers consist of Quaternary deposits of alluvial gravel, sand, silt, and clay or Quaternary deposits of eolian sand and silt. Some of the larger alluvial deposits, such as those near the Sevier River in central Utah and in the Uinta Basin of northeastern Utah, contain locally important surficial aquifers.

The Basin and Range basin-fill surficial aquifers extend through most of the Basin and Range Physiographic Province in the western United States, including much of western Utah. The aquifers are present in alluvium-filled basins interspersed between ranges of mountains. The Basin and Range basin-fill aquifers are the principal sources of ground water in western Utah. Basin fill primarily consists of unconsolidated to moderately consolidated, well- to poorly sorted beds of gravel, sand, silt, and clay deposited on alluvial fans, pediments, floodplains, and playas. More cemented or compact sediments in the older basin fill and finer grained sediments near the center of basins are less permeable than coarser grained sediments near the margins of basins. Evaporites are present in the deeper, fine-grained sediments in the centers of some basins. The thickness of basin fill typically ranges from 1,000 to 5,000 ft and may exceed 10,000 ft in a few deep basins. Stream alluvium is present within most of the larger stream valleys.

Other surficial aquifers in lesser stream valleys are generally small and isolated from each other.

1a. Wells located within the more cemented or compact sediments in the older Basin and Range fill, finer grained sediments near the center of basins, glacial deposits, and landslide deposits of the surficial aquifers (map formations playa, Qg, Ql, Qls, Qs, T4;3, T4;4, T4;5) are presumably deriving water from shallow unconsolidated sand and gravel aquifers that are covered by low permeability unconsolidated material. Thus, these wells are <u>Class Id</u>.

1b. Wells located within all other areas of the surficial aquifers are presumably deriving water from shallow, unconfined, unconsolidated sand and gravel aquifers and, thus, are <u>Class Ia</u>.

Rule 2. Carbonate and basaltic rock aquifers (CARB)

Soluble and fractured bedrock units have carbonate or basaltic lava lithology. Carbonate units may contain solution cavities and other karst features. Basalt flow units commonly can be highly permeable as they contain open spaces associated with fractures and joints, rubble zones and vesicular basalt at the top and bottom of flows, and unconsolidated-deposit interbeds.

In the Basin and Range Physiographic Province, carbonate rocks predominate in a thick sequence of Paleozoic and Lower Mesozoic rocks. The carbonate rocks can contain fractures and solution-enlarged rock openings creating solution-altered zones of increased permeability.

Basalt flow units commonly can be highly permeable as they contain open spaces associated with fractures and joints, rubble zones and vesicular basalt at the top and bottom of flows, and unconsolidated-deposit interbeds.

2. Because of the potential for high permeability associated with fracture and solution porosity, all wells in the carbonate and basaltic rock aquifers are <u>Class Ib</u>.

Rule 3. Colorado Plateaus aquifers (COLO)

The Colorado Plateaus aquifers underlie an area of ~110,000 square miles in western Colorado, northwestern New Mexico, Northeastern Arizona, and eastern Utah. This area is roughly coincident with the Colorado Plateaus Physiographic Province. The Colorado Plateaus aquifers consist of a thick Permian to Oligocene sequence of poorly to well-consolidated conglomerate, sandstone, and shale. Volcanic rocks, carbonate rocks, and evaporite deposits also form locally productive aquifers. The principal aquifers are the Uinta-Animas aquifer, the Mersaverde aquifer, the Dakota-Glen Canyon aquifer system, and the Coconino-De Chelly aquifer. Relatively impermeable confining units separate each of the four principal aquifers. The two thickest of these confining units are the Mancos Shale that underlies the Mesaverde aquifer, and the Chinle-Moenkopi confining unit that underlies the Dakota-Glen Canyon aquifer system.

The Uinta-Animas aquifer in the Uinta Basin is primarily composed of Lower Tertiary beds of sandstone, conglomerate, and siltstone in the Duchesne River, Uinta, Wasatch, and Green River Formations.

The Mesaverde aquifer comprises water-yielding units, primarily sandstone with interbedded shale and coal in the Upper Cretaceous Mesaverde Group. In the western Uinta Basin and parts of the Wasatch Plateau, the overlying Tertiary and Cretaceous North Horn Formation is also considered part of the aquifer. In the Kaiparowits Basin the aquifer is in the Cretaceous Straight Cliffs Sandstone, Waheap Sandstone, and Kaiparowits Formation, which together are approximate equivalents of the Mesaverde Group, and the overlying Tertiary-Cretaceous Canaan Peak Formation.

The Dakota-Glen Canyon aquifer system consists of water-yielding Jurassic and Cretaceous rocks which underlie most of the Colorado Plateaus area. The aquifer system includes four permeable zones that are referred to as the Dakota aquifer, Morrison aquifer, Entrada aquifer, and Glen Canyon aquifer. The geologic units that form the bulk of these aquifers are: (1) the Dakota Sandstone, (2) the lower part of the Morrison Formation, (3) the Entrada Sandstone and its equivalent, the Preuss Sandstone, and (4) the Glen Canyon Sandstone or Group and its equivalent, the Nugget Sandstone. Sandstone, conglomerate, and conglomeratic sandstone are the principal water-yielding materials. Low-permeability layers of mudstone, claystone, siltstone, shale, and limestone form confining units that separate individual aquifers in the Dakota-Glen Canyon aquifer system.

The Coconino-De Chelly aquifer consists of water-yielding Permian rocks (P1) that underlie the southern part of the Colorado Plateaus. In Utah, the Coconino Sandstone and the De Chelly Sandstone of the Cutler Group form the bulk of this aquifer. The Coconino and De Chelly Sandstones generally consist of well-sorted quartz sandstone with thin interbeds of siltstone, mudstone, and carbonates.

- 3a. The Chinle-Moenkopi confining unit forms a thick upper confining unit over portions of the Coconino-De Chelly aquifer (Robson and Banta, 1995, Figures 121, 122, & 130). Wells in the Colorado Plateaus aquifers that also fall within the map formations TR2;8 (Chinle Formation) or TR1;8 (Moenkopi Formation) of the bedrock geology coverage are presumed to derive water from confined portions of the underlying Coconino-De Chelly aquifer and are Class IIc.
- 3b. Wells that derive water from unconfined portions of the Colorado Plateaus aquifers and have a pump rate less than or equal to 50 gpm are Class IIb.
- 3c. Wells that derive water from unconfined portions of the Colorado Plateaus aquifers and have a pump rate greater than 50 gpm, or where no pump rate is given, are Class IIa.

Rule 4. Consolidated bedrock aquifers (BEDR)

Consolidated bedrock aquifers consist of igneous, metamorphic and sedimentary rocks and are not considered to be principal groundwater sources.

4a. Wells that fall within the consolidated bedrock aquifers and have a pump rate less than or equal to 50 gpm are Class IIb.

4b. Wells that fall within the consolidated bedrock aquifers and have a pump rate greater than 50 gpm, or where no pump rate is given, are Class IIa.

Rule 5. Not a principal aquifer (NAPA)

Formations in the NAPA region are confining units consisting of shale or mudstone.

5. Wells that fall within the NAPA aquifers are Class III covered aquifers.

Sole Source Aquifers

Utah contains three EPA-designated sole source aquifers: The Glen Canyon - Moab, Utah aquifer system in San Juan and Grand Counties; the Castle Valley aquifer system in San Juan County; and the Western Uinta Arch Paleozoic aquifer system in Summit County. All of these sole source aquifers are contained within the coverage of one of the larger principal aquifers described above. The Castle Valley aquifer system is contained within the Surficial aquifers. The Glen Canyon - Moab, Utah and Western Uinta Arch Paleozoic aquifer systems are part of the Colorado Plateaus aquifers. Inclusion of the sole source aquifers within the larger principal aquifers of Utah does not affect the Pettyjohn classification of wells within the sole source aquifers.

Metadata Sources References

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Robson, S.G. and E.R. Banta. 1995. Ground water atlas of the United States: Segment 2, Arizona, Colorado, New Mexico, Utah. Hydrologic Investigations Atlas 730-C, U.S. Geological Survey, Reston, VA, 34 pp.

Rules for Applying the Pettyjohn Classification Scheme in Vermont

9 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-M (Olcott, 1995) and the previously published DW USA reports (RSPA, 2002). The datasets available to define the rules include:

1. Well location
2. Well total depth
3. Well casing depth
4. Pump rate
5. Bedrock geology
6. Surficial geology
7. Aquifer boundaries

The aquifer boundaries were generated using bedrock geology, surficial geology, and the USGS Hydrologic Investigations Atlas 730-M, Segment 12 atlas (Olcott, 1995) as a guide.
Classification of all wells is based on the shallowest interval in the well from which water is derived.
There are four principal aquifers in the state of Vermont:

1. Alluvial and Glacial Outwash*
2. Paleozoic Carbonate
3. Crystalline
4. Not a principal aquifer

* The Alluvial and Glacial Outwash aquifer was constructed using the "LITHCODE" field in the SGEO feature class and is a combination of both glacial and fluvial deposition.

The aquifer features were constructed from the bedrock geology features (BGEO) and the surficial geology (SGEO).

It is important to note that when casing depth is not available, total depth is used to determine which aquifer the well is sourcing and therefore which rule applies.

Rule 1. Alluvial and Glacial Outwash aquifer (GLAC)

The unconsolidated sediments of the Alluvial and Glacial Outwash aquifer are present along the shores of Lake Champlain and throughout the glacial carved valleys of Vermont. The aquifer predominantly consists of sand and gravel from glacial deposition and modern alluvial deposition. The aquifer ranges in thickness from less than 50 ft to more than 150 ft. The Alluvial and Glacial Outwash Aquifer is predominantly used in the glacial valleys throughout the state where surface resources do not yield enough water to sustain local populations. The aquifer is generally unconfined and is underlain by the Paleozoic Carbonate aquifer in western Vermont, and the Crystalline aquifer throughout the remainder of the state.

1a. Wells located within the Alluvial and Glacial Outwash aquifer outcrop (GLAC_OUT), with casing depths less than or equal to 150 ft are Class Ia because these unconsolidated sand gravel deposits are predominantly under unconfined conditions.

1b. Wells located within the Alluvial and Glacial Outwash aquifer outcrop (GLAC_OUT), located in the Paleozoic Carbonate aquifer subcrop with casing depths greater than 150 ft are Class Ib because the wells are sourcing carbonate, potentially cavernous rock.

1c. Wells located within the Alluvial and Glacial Outwash aquifer outcrop (GLAC_OUT), located in the Crystalline aquifer subcrop with casing depths greater than 150 ft with pump rates less than or equal to 50 gpm are Class IIb because they are unconfined, consolidated and lower yield.

1d. Wells located within the Alluvial and Glacial Outwash aquifer outcrop (GLAC_OUT), located in the Crystalline aquifer subcrop with casing depths greater than 150 ft with pump rates greater than 50 gpm are Class IIa because they are unconfined, consolidated and higher yield.

1e. Wells located within the Alluvial and Glacial Outwash aquifer outcrop (GLAC_OUT), located within the Not a Principal aquifer subcrop, with casing depths greater than 150 ft with pump rates less than or equal to 50 gpm are Class IIb because they are unconfined, consolidated and lower yield.

1f. Wells located within the Alluvial and Glacial Outwash aquifer outcrop (GLAC_OUT), located within the Not a Principal aquifer subcrop, with casing depths greater than 150 ft with pump rates greater than 50 gpm are Class IIa because they are unconfined, consolidated and higher yield.

Rule 2. Paleozoic Carbonate aquifer (CARB)

The consolidated carbonate rocks of the Paleozoic carbonate aquifer outcrop along the western border of Vermont. These are comprised mostly of limestone, dolomite and marble, and are Cambrian to Ordovician in age. The deformation of these carbonate beds has caused parting along bedding planes and has created joints, fractures and faults which are the major water yielding openings in the rock. The Paleozoic carbonate aquifer is bound on the west by siliciclastic rocks and on the east by low to medium-grade metaphoric rocks. The aquifer is generally unconfined in the upper 200 ft.

2a. Wells located within the Paleozoic carbonate aquifer outcrop (CARB_OUT) are Class Ib because these wells derive water from rocks that are soluble and fractured.

Rule 3. Crystalline aquifer (CRYS)

The consolidated crystalline rocks of the crystalline aquifer system are found throughout most of the state of Vermont. The rocks are comprised of mostly granite, schist, gneiss, and quartzite, and are Pre-Cambrian to Devonian in age. The crystalline aquifer primarily moves through secondary openings such as joints, fractures, and bedding or cleavage planes. These openings decrease with depth therefore most wells are drilled no deeper than 600 ft. The volume water stored in these fractures is generally small therefore an average yield of only a few gallons per minute is common in wells sourcing the crystalline aquifer.

3a. Wells located within the crystalline aquifer outcrop (CRYS_OUT) with pump rates less than or equal to 50 gpm are <u>Class IIb</u> because they are unconfined, consolidated and lower yield.

3b. Wells located within the crystalline aquifer outcrop (CRYS_OUT) with pump rates greater than 50 gpm are <u>Class IIa</u> because they are unconfined, consolidated and higher yield.

Rule 4. Not a principal aquifer (NAPA)

The consolidated siliciclastic and metamorphic rocks along the western border of Vermont do not produce enough water to be considered significant therefore they receive the 'not a principal aquifer' (NAPA) designation. The outcrop predominantly consists of rocks of Cambrian and Ordovician age.

4a. Wells located within the not a principal aquifer outcrop (NAPA_OUT) with pump rates less than or equal to 50 gpm are <u>Class IIb</u> because they are unconfined, consolidated and lower yield.

4b. Wells located within the not a principal aquifer outcrop (NAPA_OUT) with pump rates greater than 50 gpm are <u>Class IIa</u> because they are unconfined, consolidated and higher yield.

Metadata Sources References

Olcott, P.G. 1995. Ground water atlas of the United States: Segment 12, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont. Hydrologic Investigations Atlas 730-M, U.S. Geological Survey, Reston, VA, 30 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Rules for Applying the Pettyjohn Classification Scheme in Virginia

9 August 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-L (also called Ground Water Atlas of the United States, Segment 11; Trapp and Horn, 1997), USGS Professional Paper 1829 entitled Assessment of Groundwater Availability in the Northern Atlantic Coastal Plain Aquifer System From Long Island, New York, to North Carolina (Masterson et al., 2016), the USGS Data Series 996 entitled Digital Elevations and Extents of Regional Hydrogeologic Units in the Northern Atlantic Coastal Plain Aquifer System From Long Island, New York, to North Carolina (Pope et al., 2016) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Screen depth
3. Casing depth
4. Well depth
5. Pump rate
6. Surficial geology
7. Aquifer boundaries

The aquifer boundaries were generated using surface geology and the Segment 11 Atlas (Trapp and Horn, 1997) as a guide. Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are seven principal aquifers in Virginia:

1. Alluvial
2. Atlantic coastal plain *
3. Potomac *
4. Crystalline and undifferentiated sedimentary rock +
5. Early Mesozoic basin +
6. Appalachian sandstone
7. Appalachian carbonate

*The Atlantic coastal plain and Potomac aquifers comprise the Northern Atlantic Coastal Plain Aquifer System.

+The crystalline rock and undifferentiated sedimentary rock and the early Mesozoic basin aquifers comprise the Piedmont and Blue Ridge Aquifer System.

USGS Professional Paper 1829 (Masterson et al., 2016) and USGS Data Series 996 (Pope et al., 2016) were used in the classification rules to assess the thickness and depth of the permeable and confining units within the hydrogeologic framework. The documents contain several cross sections, as well as digital elevations and extents for units that constrain the Upper Cretaceous-Quaternary stratigraphy of the Virginia coastal plain. These data cover the area east of the Fall

Line and show that several thick and laterally extensive low permeability units divide the productive aquifer formations that subcrop in the coastal plain. The most important confining units are: The upper Chesapeake confining unit, which divides the surficial aquifer from the upper Chesapeake aquifer; the lower Chesapeake confining unit, which divides the upper Chesapeake aquifer from the lower Chesapeake aquifer; and the Calvert confining unit, which divides the lower Chesapeake aquifer from the Castle Hayne-Aquia aquifer. In general, these confining units are 50 ft or greater in thickness, but thin or pinch out toward the Fall Line, and thicken toward the coast. Based on these observations, a depth cut-off was established, below which the aquifers are regarded confined. The combination of the three confining units mentioned above are required to produce a confined interval for the entire coastal plain of Virginia, so the depth cut-off used in this rule set is established based on the depth of the Calvert confining unit. The digital elevation raster of the top of Calvert confining unit and the land surface Digital Elevation Model from USGS Data Series 996 were used to obtain the depth to top of Calvert confining unit. A buffer of 50 ft was added to this depth to ensure confinement. Because the depth to the top of the Calvert confining unit plus 50 ft (hereafter referred to as "Depth Top Calvert") ranges from 500 to 1400 ft, the coastal plain of Virginia is divided into three zones (model field THICK_SGEO) in order to apply the depth cut-off to better achieve an optimal Pettyjohn classification for water wells in Virginia. The depth information from wells is used for rulemaking in the following order of precedence: screen depth, case depth, and well depth.

Rule 1. Alluvial aquifer (ALLU)

The unconsolidated sediments of the alluvial valley aquifer are Quaternary in age and are contained within river and stream valleys throughout the Atlantic coastal plain of Virginia. The alluvial valley aquifer is generally less than 50 ft thick and contains water under unconfined or water table conditions. A buffer of 50 ft is added to this average thickness in order to establish a conservative rule for the classification of wells. The aquifer consists of unconsolidated gravel, sand, silt, clay, and peat. This aquifer generally yields small volumes of water and is primarily used for domestic supplies.

1a. Wells located within the alluvial valley aquifer outcrop (ALLU), with well depths less than 100 ft, deriving water from the shallow subsurface, are <u>Class Ia</u> because these sediments form unconsolidated deposits that are under unconfined or water table conditions.

1b. Wells located within the alluvial valley aquifer outcrop (ALLU) most likely deriving water from underlying aquifers with well depths between 100 ft and Depth Top Calvert are <u>Class Id</u> because these aquifers are covered by at least one impermeable unit less than 50 ft in thickness.

1c. Wells located within the alluvial valley aquifer outcrop (ALLU) most likely deriving water from underlying aquifers with well depths greater than Depth Top Calvert are <u>Class III</u> because these aquifers are confined by at least one impermeable unit greater than 50 ft in thickness.

1d. Wells located within the alluvial valley aquifer outcrop (ALLU), close to the fall line, where alluvial sediments are onlapping consolidated rocks of the crystalline rock and undifferentiated sedimentary rock aquifer, with well depths greater than 100 ft, are <u>Class IIc</u> because these wells most likely derive water from covered bedrock aquifers.

Rule 2. Atlantic Coastal Plain aquifer (ACPA)

The Atlantic coastal plain aquifer comprises all of the aquifers in the North Atlantic Coastal Plain Aquifer System, except the Potomac aquifer, and includes the surficial aquifer, Chesapeake aquifer, Castle Hayne-Aquia aquifer, and portions of the Severn-Magothy and the laterally equivalent Peedee-upper Cape Fear aquifers. The unconsolidated sediments of the surficial aquifer are exposed at the land surface in the coastal plain of Virginia, principally along the coast near the border with North Carolina and on the Delmarva Peninsula. These sediments consist of sand and gravel, mostly of Quaternary age. The average thickness of the surficial aquifer in Virginia is generally 50 ft or less, and contains water predominately under unconfined conditions. A buffer of 50 ft is added to this average thickness in order to establish a conservative rule for the classification of wells. The unconsolidated sediments of the Chesapeake aquifer outcrop over much of the coastal plain of Virginia from the North Carolina border to the Potomac River, and subcrop to the east, lying stratigraphically below the surficial aquifer. The Chesapeake aquifer consists of shelly sand, silty sand, and shell beds, and fine to medium phosphatic sand of Miocene age. The maximum thickness of the Chesapeake aquifer in Virginia is about 600 ft, although only the upper part of the aquifer is an important source of water. The aquifer underlies the surficial aquifer, and is mostly confined by a clay-rich unit. The unconsolidated to semi-consolidated sediments of the Castle Hayne-Aquia aquifer outcrops in the northern coastal plain of Virginia, and subcrops to the south and east, lying stratigraphically below the Chesapeake aquifer. The Castle Hayne-Aquia aquifer is confined, except where it outcrops, and consists of an upper unit of medium to coarse glauconitic sand and a lower unit of fine to medium glauconitic sand. The maximum thickness of the aquifer is 460 ft, and the average thickness is about 140 ft. Taken together, the individual aquifers that comprise the Atlantic coastal plain aquifer are an important source of water for public water supplies in the coastal plain of Virginia.

2a. Wells located within the Atlantic coastal plain aquifer outcrop (ACPA), with well depths less than 100 ft, deriving water from the shallow subsurface, are <u>Class Ia</u> because these sediments are unconsolidated, and the water is under unconfined or water table conditions.

2b. Wells located within the Atlantic coastal plain aquifer outcrop (ACPA) most likely deriving water from underlying aquifers with well depths between 100 ft and Depth Top Calvert are <u>Class Id</u> because these aquifers are covered by at least one impermeable unit less than 50 ft in thickness.

2c. Wells located within the Atlantic coastal plain aquifer outcrop (ACPA) most likely deriving water from underlying aquifers with well depths greater than Depth Top Calvert are <u>Class III</u> because these aquifers are confined by at least one impermeable unit greater than 50 ft in thickness.

2d. Wells located within the Atlantic coastal plain aquifer outcrop (ACPA), close to the fall line, where coastal plain sediments are onlapping consolidated rocks of the crystalline rock and undifferentiated sedimentary rock aquifer, with well depths greater than 100 ft, are <u>Class IIc</u> because these wells most likely derive water from covered bedrock aquifers.

Rule 3. Potomac aquifer (PTMC)

The semi-consolidated sediments of the Potomac aquifer outcrop along the Fall Line in the upper coastal plain of Virginia, and subcrop to the east, lying stratigraphically below the Severn-

Mogothy and Peedee-upper Cape Fear aquifers. Because the Potomac aquifer outcrop lies along the Fall Line, this portion of the aquifer is generally unconfined, except where it is covered by the Calvert confining unit. Because of the onlap of coastal plain sediments, within the aquifer outcrop Depth Top Calvert is no greater than 50 ft, and the thickness of the aquifer is generally less than 50 ft. A buffer of 50 ft is added to this average for Depth Top Calvert and average thickness in order to establish a conservative rule for the classification of wells.

3a. Wells located within the Potomac aquifer outcrop (PTMC), with well depths less than 100 ft, deriving water from the shallow subsurface, are Class Ic because these sediments are semi-consolidated, and the water is under unconfined or water table conditions.

3b. Wells located within the Potomac aquifer outcrop (PTMC), where coastal plain sediments are onlapping consolidated rocks of the crystalline rock and undifferentiated sedimentary rock aquifer, with well depths greater than 100 ft, are Class IIc because these wells most likely derive water from covered bedrock aquifers.

3c. Wells located within the Potomac aquifer outcrop (PTMC) that are covered by the Calvert confining unit are Class III because these aquifers are confined by at least one impermeable unit greater than 50 ft in thickness.

Rule 4. Crystalline rock and undifferentiated sedimentary rock aquifer (CRYS)

The crystalline and consolidated sedimentary rocks of the crystalline rock and undifferentiated sedimentary rock aquifer outcrop in central Virginia, in the Piedmont and Blue Ridge physiographic provinces of the state. The aquifer consists of pre-Cretaceous age crystalline igneous and metamorphic rocks and tightly cemented, predominantly clastic sedimentary rocks. Water is obtained from the regolith and/or fractures in these rocks.

4a. Wells sourcing the crystalline rock and undifferentiated sedimentary rock aquifer and located within the outcrop of the aquifer (CRYS), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

4b. Wells sourcing the crystalline rock and undifferentiated sedimentary rock aquifer and located within the outcrop of the aquifer (CRYS), with a pump rate less than or equal to 50 gpm are Class IIb because they are unconfined and lower yield.

Rule 5. Early Mesozoic Basin aquifer (MESO)

The Triassic- and Jurassic-age consolidated sedimentary rocks and minor crystalline rocks of the Early Mesozoic basin aquifers outcrop in elongate rift basins developed within crystalline rocks of the Piedmont physiographic province and located in central Virginia, and along the North Carolina border. The aquifer is comprised predominately of interbedded shale, sandstone, and siltstone, and is commonly intruded by basalt and diabase dikes and sills. Water yields from Early Mesozoic basin aquifers is highly variable, depending on lithology, cementation, and proximity to igneous intrusions, and ranges from eight to 75 gpm.

5a. Wells sourcing the Early Mesozoic basin aquifers and located within the aquifer (MESO), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

5b. Wells sourcing the Early Mesozoic basin aquifers and located within the aquifer (MESO), with a pump rate less than or equal to 50 gpm are Class IIb because they are unconfined and lower yield.

Rule 6. Appalachian sandstone aquifer (ASSA)

The consolidated siliciclastic sedimentary rocks of the Appalachian sandstone aquifer outcrop in the Valley and Ridge and Appalachian Plateau physiographic provinces of Virginia. These rocks are composed mostly of sandstone, with subordinate conglomerate, shale, and coal, and are Cambrian to Pennsylvanian in age. Permeable units are relatively flat-lying in the Appalachian Plateau province, but are folded and faulting in the Valley and Ridge. Yields of wells completed in Permian and Pennsylvanian sandstones of the Appalachian Plateau province are mainly used for domestic supply because well yields are generally less than 12 gallons per minute, while wells deriving water from Ordovician to Mississippian sandstones of the Valley and Ridge yield up to 155 gallons per minute.

6a. Wells sourcing the Appalachian sandstone aquifer and located within the aquifer (ASSA), with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

6b. Wells sourcing the Appalachian sandstone aquifer and located within the aquifer (ASSA), with a pump rate less than or equal to 50 gpm are Class IIb because they are unconfined and lower yield.

Rule 7. Appalachian carbonate aquifer (ACOA)

The consolidated carbonate rocks of the Appalachian carbonate aquifer outcrop in the Valley and Ridge and Appalachian Plateau physiographic provinces of Virginia. These rocks are composed mostly of limestone and dolomite, and are Cambrian to Mississippian in age. Permeable units are relatively flat-lying in the Appalachian Plateau province, but are folded and faulting in the Valley and Ridge. The principal water-yielding geologic unit in the Appalachian Plateau is the Mississippian Greenbrier Limestone, while in the Valley and Ridge many units ranging in age from Cambrian to Devonian yield water primarily in the valleys of the fold and thrust belt. Yields of wells completed in the Greenbrier Limestone are typically less than 50 gallons per minute. Aquifers in Cambrian and Ordovician carbonate rocks commonly yield from 150 to 1,000 gallons per minute to wells. Yields of wells completed in Silurian and Devonian limestones are typically only 20 gallons per minute or less.

7a. Wells located within the outcrop boundary of the Appalachian carbonate aquifer (ACOA) are Class Ib because these wells derive water from rocks that are soluble and fractured.

Metadata Sources References

Masterson, J.P., J.P. Pope, M.N. Fienen, J. Monti, M.R. Nardi, and J.S. Finkelstein. 2016. Assessment of groundwater availability in the Northern Atlantic Coastal Plain aquifer system from Long Island, New York, to North Carolina. USGS Professional Paper 1829, U.S. Geological Survey, Reston, VA, 76 pp.

Pope, J.P., D.C. Andreasen, E.R. McFarland, and M.K. Watt. 2016. Digital elevations and extents of regional hydrogeologic units in the Northern Atlantic Coastal Plain aquifer system from Long Island, New York, to North Carolina. USGS Data Series 996, U.S. Geological Survey, Reston, VA, 28 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc. for the Research and Special Programs Administration, Washington, D.C.

Trapp, H. and M.A. Horn. 1997. Ground water atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. Hydrologic Investigations Atlas 730-L, U.S. Geological Survey, Reston, VA, 26 pp.

Rules for Applying the Pettyjohn Classification Scheme in Washington

30 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-H (also called Ground Water Atlas of the United States, Segment 7; Whitehead., 1994) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well total depth
3. Well screen depth
4. Pump rate
5. Bedrock geology
6. Aquifer boundaries

The aquifer boundaries were generated using the Segment 7 Atlas (Whitehead., 1994) as a guide.

Classification of all wells is based on the shallowest interval in the well from which water is derived.

The following aquifers of Washington were distinguished for this work:

1. Unconsolidated Deposit
2. Volcanic and sedimentary rock
3. Miocene basaltic rock
4. Pre-Miocene rock
5. Not a principal aquifer

The aquifer features were constructed from the bedrock geology features (BGEO).
It is important to note that when screen depth is not available, total depth is used to determine which aquifer the well is sourcing and therefore which rule applies.

Rule 1. Unconsolidated Deposit aquifer (UNCO)

The unconsolidated sediments of the Unconsolidated Deposit aquifer are found in a north-south trending basin in the Seattle/Tacoma region, in former glacial valleys throughout the state, and in large plains in the center of the state. This aquifer is associated with erosional or structural basins that were filled with glacial and or alluvial sediments predominantly within in the last 3 million years. The Unconsolidated Deposit aquifer consists of predominantly unconfined surficial sediments ranging in size from sand to cobble. The sediments of the Unconsolidated Deposit aquifer can be as much as 3,000 ft thick in the Puget Sound Lowlands but the most permeable units are usually found in the upper 500 ft in cases where only well depth is available, a buffer of 100 ft was added to the aquifer thickness to allow for uncertainty in the measurement of the well depth, resulting in a maximum permeable thickness of 600 ft.

1a. Wells located within the Unconsolidated Deposit aquifer outcrop (UNCO), with well screens less than or equal to 500 ft are Class Ia because the aquifer is surficial, unconsolidated and permeable. If only well depth is available, then an additional 100 ft buffer was added.

1b. Wells located within the Unconsolidated Deposit aquifer outcrop (UNCO), with well screens greater than 500 ft, are classified as unknown (UNK) because the well is sourcing water greater than the known permeable depth of the Unconsolidated Deposit aquifer and the underlying aquifer cannot be determined.

Rule 2. Volcanic and sedimentary rock aquifer (VOLC)

The unconsolidated sediments and consolidated volcanic and sedimentary rocks of the volcanic and sedimentary rock aquifer outcrops in the Cascades Range of west central Washington as well as in valleys in central and eastern Washington. The aquifer consists of Pliocene and younger age volcanic rocks such as basalt, andesite, and dacite as well as sedimentary rocks and unconsolidated sands and gravel. The thickness of the volcanic and sedimentary rock aquifer is largely unknown because it is located in a very remote area of the state and has a limited outcrop area, however, some wells access the geothermal waters within the aquifer which can be as deep as 2,000 ft below land surface.

2a. Wells located within the volcanic and sedimentary rock aquifer outcrop (VOLC), excluding those located in formations with unconsolidated sediments (PLcg (t),PLMcg, QMc, QMcg, QMs, QPLc, QPLcg), with a pump rates less than or equal to 50 gpm are Class IIb because they are sourcing consolidated sediments and have a lower yield.

2b. Wells located within the volcanic and sedimentary rock aquifer outcrop (VOLC), excluding those located in formations with unconsolidated sediments (PLcg (t),PLMcg, QMc, QMcg, QMs, QPLc, QPLcg),with a pump rate greater than 50 gpm are Class IIa because they are sourcing consolidated sediments and have a higher yield.

2c. Wells located within the volcanic and sedimentary rock aquifer outcrop (VOLC), in formations with unconsolidated sediments (PLcg (t), PLMcg, QMc, QMcg, QMs, QPLc, QPLcg), are Class Ia because these sediments are surficial, unconsolidated and permeable.

Rule 3. Miocene basaltic rock aquifer (BSLT)

The unconsolidated sediments and consolidated volcanic and sedimentary rocks of the Miocene basaltic rock aquifer outcrop throughout central and eastern Washington. The aquifer consists of basalt, andesite, rhyolite and dacite as well as interbedded sedimentary rocks and unconsolidated sands and gravel of Miocene age. The thickness of the Miocene basaltic rock aquifer can be as much as 15,000 ft in the southern portion of the Columbia Plateau.

3a. Wells located within the Miocene basaltic rock aquifer outcrop (BSLT), with a pump rates less than or equal to 50 gpm are Class IIb because they are sourcing consolidated sediments and have a lower yield.

3b. Wells located within the Miocene basaltic rock aquifer outcrop (BSLT), with a pump rate greater than 50 gpm are Class IIa because they are sourcing consolidated sediments and have a higher yield.

3c. Wells located within the Miocene basaltic rock aquifer outcrop (BSLT), in formations with unconsolidated sediments (Mc, Mc(2), Mc(d), Mc(e), Mc(h), Mc(l), Mc(m), Mw(w), are Class Ia because these sediments are surficial, unconsolidated and permeable.

Rule 4. Pre-Miocene rock aquifer (PRMI)

The consolidated volcanic, sedimentary, igneous and metamorphic rocks of the Pre-Miocene Rock aquifer outcrop throughout northern and western Washington. The aquifer consists of predominantly pre-Miocene age volcanic rocks such as basalt and rhyolite, sedimentary rocks such as sandstone and siltstone, intrusive igneous rocks such as granite and gabbro and metamorphic rocks such as schist and marble. The Pre-Miocene rock aquifer, like the volcanic and sedimentary Rock aquifer, is located in remote areas of the state, therefore, the thickness of the aquifer is largely unknown. But it is safe to say that with increased depth, fracture void space decreases, therefore the volume of water pumped in most cases, decreases with depth.

4a. Wells located within the Pre-Miocene rock aquifer outcrop (PRMI), in non-carbonate lithologies, with a pump rate less than or equal to 50 gpm are Class IIb because they are consolidated and lower yield.

4b. Wells located within the Pre-Miocene rock aquifer outcrop (PRMI), in non-carbonate lithologies, with a pump rate greater than 50 gpm are Class IIa because they are consolidated and higher yield.

4c. Wells located within the Pre-Miocene rock aquifer outcrop (PRMI), in carbonate lithologies (marble, metacarbonate) are Class Ib because these wells derive water from rocks that are soluble and fractured.

Rule 5. Not a principal aquifer (NAPA)

The Pliocene to Holocene age unconsolidated sediments that receive the ‘Not a principal aquifer’ designation are found throughout the state of Washington. In the central and eastern portion of the state, the ‘Not a principal aquifer’ predominantly consists of the Palouse Formation, which is comprised of loess, which covers the Miocene Basaltic Rock aquifer and is generally less than 50 ft thick (Groundwater Atlas of the United States, Segment 7, Pg. 19). Other sediments that receive the ‘Not a Principal Aquifer’ designation are glacial tills and mass wasting deposits found throughout the state of Washington. These deposits vary greatly in thickness.

5a. Wells located within the ‘Not a principal aquifer’ outcrop (NAPA), excluding wells in the Palouse Formation and peat deposits (Qf, Qp), are conservatively Class Ia because the sediments that makes up this aquifer are surficial, unconsolidated and permeable.

5b. Wells located within the ‘Not a principal aquifer’ outcrop (NAPA), within the Palouse Formation (Ql), and peat deposits (Qf, Qp), with screen depths less than or equal to 50 ft are Class Id because the thickness of the low permeability loess or peat is less than 50 ft.

5c. Wells located within the 'Not a principal aquifer' outcrop (NAPA), within the Palouse Formation (Ql), with screen depths greater than 50 ft, are Class IIc because these wells are sourcing the underlying Micocene Basaltic Rock aquifer covered by less than 50 ft of low permeability, unconsolidated material.

5d. Wells located within the 'Not a principal aquifer' outcrop (NAPA), within the peat deposits (Qf, Qp), with screen depths greater than 50 ft are classified as unknown because the well is likely sourcing water greater than the average thickness of peat deposits in the area and the underlying aquifer is cannot be determined.

Sole source Aquifers

The Whidbey Island aquifer predominantly consists of interbedded sand, gravel, silt and clay. The thickness of the aquifer varies greatly from place to place on the island. Wells sourcing the Whidbey Island aquifer are classified the same as wells sourcing the Unconsolidated Sediment aquifer. See Rules 1a and 1b.

Metadata Sources References

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Whitehead, R.L. 1994. Ground water atlas of the United States: Segment 7, Idaho, Oregon, Washington. Hydrologic Investigations Atlas 730-H, U.S. Geological Survey, Reston, VA, 33 pp.

Rules for Applying the Pettyjohn Classification Scheme in Washington, D.C.

31 January 2019

The public water system data (PWS) for Washington, D.C. were extracted from the EPA Safe Drinking Water Information System (SDWIS) database. The SDWIS data contained two surface water intakes. Because groundwater wells are not present in the data, rules for applying the Pettyjohn classification scheme are not required for the DW USA model.

**** Rules are not Required and Intentionally Left Blank****

Rules for Applying the Pettyjohn Classification Scheme in West Virginia

13 July 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-L (also called Ground Water Atlas of the United States, Segment 11; Trapp and Horn, 1997), the Aquifer-Characteristics Data for West Virginia (Kozar and Mathes, 2001) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well Location
2. Surficial Geology

Because no depth or source information existed, wells were classified on the basis of their location and surface geology.

The aquifer boundaries were generated using surface geology and the Segment 11 Atlas (Trapp and Horn, 1997) as a guide.

Classification of all wells is based the location of the well only.

There are four principal aquifers in West Virginia:

1. Alluvial aquifers
2. Paleozoic Sandstone Aquifers
3. Paleozoic Carbonate Aquifers
4. Not a Principal Aquifer

Rule 1. Alluvial Aquifer (ALLU)

The unconsolidated sediments of the alluvial aquifer are exposed at the land surface in major stream and river valleys in West Virginia, and consist of mostly sand and gravel of Quaternary age. The texture and mineralogy of these sediments, as well as their hydrogeologic characteristics, vary depending on whether the stream valley belongs to a northward or southward flowing stream. Alluvium in southward flowing stream valleys is principally reworked glacial material from deposits that were eroded during and after the retreat of Pleistocene continental ice sheets. Aquifers comprised of glacially derived alluvium are typically highly productive. Alluvium in northward flowing stream valleys is derived from the crystalline and consolidated sedimentary rocks that form the Valley and Ridge and Appalachian Plateau physiographic provinces. These sediments are comparatively fine grained, and thus aquifers comprised of these sediments typically yield less water. Alluvial aquifers contain water primarily under unconfined or water table conditions.

1a. Wells located within the outcrop boundary of the alluvial aquifer (ALLU) are <u>Class Ia</u> because water in these unconsolidated sand and gravel deposits are under unconfined conditions.

Rule 2. Paleozoic Sandstone Aquifer (PZSS)

The consolidated siliciclastic sedimentary rocks of the Paleozoic sandstone aquifer outcrop in the Valley and Ridge and Appalachian Plateau physiographic provinces of West Virginia. These rocks are composed mostly of sandstone, with subordinate conglomerate, shale, and coal, and are Devonian to Permian in age. Permeable units are relatively flat-lying in the Appalachian Plateau province, but are folded and faulting in the Valley and Ridge. Yields of wells completed in Permian and Pennsylvanian sandstones of the Appalachian Plateau province range from 5 to 400 gallons per minute, while wells deriving water from Devonian and Mississippian sandstones of the Valley and Ridge commonly yield about 15 gallons per minute.

2a. Wells located within the outcrop boundary of the Paleozoic sandstone aquifer (PZSS) are <u>Class IIa</u> because these wells derive water from rocks that are consolidated and unconfined.

Rule 3. Paleozoic Carbonate Aquifer (PZCO)

The consolidated carbonate rocks of the Paleozoic carbonate aquifer outcrop in the Valley and Ridge and Appalachian Plateau physiographic provinces of West Virginia. These rocks are composed mostly of limestone and dolomite, and are Cambrian to Mississippian in age. Permeable units are relatively flat-lying in the Appalachian Plateau province, but are folded and faulting in the Valley and Ridge. The principal water-yielding geologic unit in the Appalachian Plateau is the Mississippian Greenbrier Limestone, while in the Valley and Ridge many units ranging in age from Cambrian to Devonian yield water primarily in the valleys of the fold and thrust belt. Yields of wells completed in the Greenbrier Limestone range from 5 to 100 gallons per minute, but some springs that issue from the Greenbrier discharge 1,000 gallons per minute or more. Aquifers in Cambrian and Ordovician carbonate rocks typically yield about 35 gallons per minute, though some wells completed in these rocks yield as much 600 gallons per minute. Some springs that issue from the Cambro-Ordovician carbonates discharge from 1,000 to 5,000 gallons per minute. Yields of wells completed in Silurian and Devonian limestones commonly only range from 10 to 20 gallons per minute; however, some springs that issue from these rocks discharge as many as 15,000 gallons per minute.

3a. Wells located within the outcrop boundary of the Paleozoic carbonate aquifer (PZCO) are <u>Class Ib</u> because these wells derive water from rocks that are soluble and fractured.

Rule 4. Not a Principal Aquifer (NAPA)

Some outcrop belts of Paleozoic sedimentary and metamorphic rocks in West Virginia, mostly outcropping in the Valley and Ridge, are designated as ‘not a principal aquifer’ (NAPA). This designation covers areas where aquifers either do not exist, yield too little water to be significant, or yield sufficient water to supply only local requirements, but are not extensive enough to be considered major aquifers. The rocks are chiefly shale, but also include minor outcrops of metamorphic quartzite, phyllite, and greenstone.

4a. Wells located within the outcrop boundary of not a principal aquifer (NAPA) are <u>Class IIb</u> because these wells derive water from rocks that are consolidated and unconfined.

Metadata Sources References

Kozar, M.D. and M.V. Mathes. 2001. Aquifer-characteristics data for West Virginia. Water-resources investigations report, 1, 4036.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Trapp, Jr., H. and M.A. Horn, 1997. Ground water atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. Hydrologic Investigations Atlas 730-L, U.S. Geological Survey, Reston, VA, 32 pp.

Rules for Applying the Pettyjohn Classification Scheme in Wisconsin

25 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-J (also called Ground Water Atlas of the United States, Segment 9; Olcott, 1993) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well location
2. Well depth
3. Casing depth
4. Screen depth
5. Pump rate
6. Surficial geology
7. Aquifer boundaries

The aquifer coverage for Wisconsin was produced from bedrock geology received from the state, and glacial sediment extents (Soller, 1992), using the Segment 10 Atlas (Olcott, 1993) as a guide. Glacial sediment permeability and thickness are recorded in THICK_SGEO according to the following coding scheme. THICK_SGEO codes are a two character alpha-numeric combination where the first letter indicates permeability (P – permeable, C – non-permeable), and the single digit number, which appears last, indicates the sedimentary thickness (0 – no sedimentary cover, 1 – 0-50 ft, 2 – 50-100 ft, 3 – 100-200 ft, 4 – 200-400 ft, 5 – 400-600 ft).

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are three principal aquifers in Wisconsin:

1. Silurian-Devonian
2. Cambrian-Ordovician
3. Crystalline rock

Rule 1. Silurian-Devonian aquifer (SILD)

The consolidated sedimentary rocks of the Silurian-Devonian aquifer outcrop in eastern Wisconsin, where aquifer water exists under unconfined water table conditions. The lithology of the aquifer is mostly limestone and dolomite, with minor shale and evaporate beds. The aquifer thickness ranges from 300-400 ft and yields from wells completed in the aquifer range from 100 to 500 gpm.

1a. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing permeable glacial deposits above the bedrock surface, are <u>Class Ia</u> because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

1b. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing non-permeable glacial deposits above the bedrock surface, with well depth less than 50 ft, or bedrock aquifers covered by less than 50 ft of low permeability material, are Class Id because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

1c. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing water below the bedrock surface in areas with permeable sedimentary cover or areas with no sedimentary cover, are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

1d. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing water at depths greater than 50 ft, in areas with non-permeable sedimentary cover greater than 50 ft thick, are Class III because the aquifer unit is confined.

1e. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing water at depths greater than 400 ft below the bedrock surface, are Class III because the wells are most likely sourcing the underlying Cambrian-Ordovician aquifer, which is confined.

Rule 2. Cambrian-Ordovician aquifer (CORD)

The consolidated sedimentary rocks of the Cambrian-Ordovician aquifer outcrop in central and southern Wisconsin and wrap around the Wisconsin Dome to the east and west. The Cambrian-Ordovician aquifer includes the Precambrian Lake Superior Sandstone, which is present in Wisconsin along the southern shore of Lake Superior. Within the aquifer's outcrop water exists under unconfined conditions, whereas within the aquifer subcrop, which is limited to eastern Wisconsin, the aquifer is confined. The lithology of the aquifer is dominantly sandstone, limestone, dolomite, and shale; and aquifer water exists under unconfined conditions. The aquifer thickness ranges from 200 ft to over 900 ft.

2a. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing permeable glacial deposits above the bedrock surface, are Class Ia because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

2b. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing non-permeable glacial deposits above the bedrock surface, with well depth less than 50 ft, are Class Id because these unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

2c. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing carbonate bedrock aquifers, with formation codes Op and Osi, covered by less than 50 ft of low permeability material, are Class Id because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

2d. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing bedrock aquifers covered by less than 50 ft of low permeability material, are Class IIc because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

2e. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing carbonate bedrock aquifers, with formation codes Op and Osi, in areas with permeable sedimentary cover are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

2f. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

2g. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate less than 50 gpm are Class IIb because they are unconfined and lower yield.

2h. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing water at depths greater than 50 ft, in areas with non-permeable sedimentary cover greater than 50 ft thick, are Class III because the aquifer unit is confined.

Rule 3. Crystalline rock aquifer (CRYS)

The consolidated rocks of the Archean-Middle Proterozoic crystalline rock aquifer outcrop in northern Wisconsin, where the aquifer is unconfined. The lithology of the aquifer is a combination of igneous and metamorphic rocks, and tightly cemented mostly siliciclastic sedimentary rocks. Water generally moves through secondary openings, such as joints, fractures, and faults.

3a. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing permeable glacial deposits above the bedrock surface, are Class Ia because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

3b. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing non-permeable glacial deposits above the bedrock surface, with well depth less than 50 ft, are Class Id because these unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

3c. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing bedrock aquifers covered by less than 50 ft of low permeability material, are Class IIc because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

3d. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

3e. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate less than 50 gpm are Class IIb because they are unconfined and lower yield.

3f. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing water at depths greater than 50 ft, in areas with non-permeable sedimentary cover greater than 50 ft thick, are Class III because the aquifer unit is confined.

Metadata Sources References

Olcott, P.G. 1992. Ground water atlas of the United States: Segment 9, Iowa, Michigan, Minnesota, Wisconsin. Hydrologic Investigations Atlas 730-J, U.S. Geological Survey, Reston, VA, 33 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Soller, D.R. 1992. Text and references to accompany "Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains": U.S. Geological Survey Bulletin 1921, 54 p.

Rules for Applying the Pettyjohn Classification Scheme in Wisconsin

25 October 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-J (also called Ground Water Atlas of the United States, Segment 9; Olcott, 1993) and the previously published DW USA reports (RSPA, 2002). The dataset available to define the rules included:

1. Well Location
2. Well Depth
3. Casing Depth
4. Screen Depth
5. Pump Rate
6. Surficial Geology
7. Aquifer Boundaries

The aquifer coverage for Wisconsin was produced from bedrock geology received from the state, and glacial sediment extents (Soller, 1992), using the Segment 10 Atlas (Olcott, 1993) as a guide. Glacial sediment permeability and thickness are recorded in THICK_SGEO according to the following coding scheme. THICK_SGEO codes are a two character alpha-numeric combination where the first letter indicates permeability (P – permeable, C – non-permeable), and the single digit number, which appears last, indicates the sedimentary thickness (0 – no sedimentary cover, 1 – 0-50 ft., 2 – 50-100 ft., 3 – 100-200 ft., 4 – 200-400 ft., 5 – 400-600 ft.).

Classification of all wells is based on the shallowest interval in the well from which water is derived.

There are three principal aquifers in Wisconsin:

1. Silurian-Devonian aquifer
2. Cambrian-Ordovician aquifer
3. Crystalline rock aquifer

Rule 1. Silurian-Devonian aquifer (SILD)

The consolidated sedimentary rocks of the Silurian-Devonian aquifer outcrop in eastern Wisconsin, where aquifer water exists under unconfined water table conditions. The lithology of the aquifer is mostly limestone and dolomite, with minor shale and evaporate beds. The aquifer thickness ranges from 300-400 ft. and yields from wells completed in the aquifer range from 100 to 500 gallons per minute.

1a. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing permeable glacial deposits above the bedrock surface, are <u>Class Ia</u> because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

1b. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing non-permeable glacial deposits above the bedrock surface, with well depth less than 50 ft., or bedrock aquifers covered by less than 50 ft. of low permeability material, are Class Id because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

1c. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing water below the bedrock surface in areas with permeable sedimentary cover or areas with no sedimentary cover, are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

1d. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing water at depths greater than 50 ft., in areas with non-permeable sedimentary cover greater than 50 ft. thick, are Class III because the aquifer unit is confined.

1e. Wells located within the Silurian-Devonian aquifer boundary (SILD), sourcing water at depths greater than 400 ft. below the bedrock surface, are Class III because the wells are most likely sourcing the underlying Cambrian-Ordovician aquifer, which is confined.

Rule 2. Cambrian-Ordovician aquifer (CORD)

The consolidated sedimentary rocks of the Cambrian-Ordovician aquifer outcrop in central and southern Wisconsin and wrap around the Wisconsin Dome to the east and west. The Cambrian-Ordovician aquifer includes the Precambrian Lake Superior Sandstone, which is present in Wisconsin along the southern shore of Lake Superior. Within the aquifer's outcrop water exists under unconfined conditions, whereas within the aquifer subcrop, which is limited to eastern Wisconsin, the aquifer is confined. The lithology of the aquifer is dominantly sandstone, limestone, dolomite, and shale; and aquifer water exists under unconfined conditions. The aquifer thickness ranges from 200 ft. to over 900 ft.

2a. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing permeable glacial deposits above the bedrock surface, are Class Ia because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

2b. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing non-permeable glacial deposits above the bedrock surface, with well depth less than 50 ft., are Class Id because these unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

2c. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing carbonate bedrock aquifers, with formation codes Op and Osi, covered by less than 50 ft. of low permeability material, are Class Id because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

2d. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing bedrock aquifers covered by less than 50 ft. of low permeability material, are Class IIc because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

2e. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing carbonate bedrock aquifers, with formation codes Op and Osi, in areas with permeable sedimentary cover are Class Ib because the aquifer unit is comprised of soluble carbonate rocks.

2f. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

2g. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate less than 50 gpm are Class IIb because they are unconfined and lower yield.

2h. Wells located within the Cambrian-Ordovician aquifer boundary (CORD), sourcing water at depths greater than 50 ft., in areas with non-permeable sedimentary cover greater than 50 ft. thick, are Class III because the aquifer unit is confined.

Rule 3. Crystalline Rock Aquifer (CRYS)

The consolidated rocks of the Archean-Middle Proterozoic crystalline rock aquifer outcrop in northern Wisconsin, where the aquifer is unconfined. The lithology of the aquifer is a combination of igneous and metamorphic rocks, and tightly cemented mostly siliciclastic sedimentary rocks. Water generally moves through secondary openings, such as joints, fractures, and faults.

3a. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing permeable glacial deposits above the bedrock surface, are Class Ia because water in these unconsolidated, surficial gravel and sand deposits is in hydraulic continuity with the water table.

3b. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing non-permeable glacial deposits above the bedrock surface, with well depth less than 50 ft., are Class Id because these unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

3c. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing bedrock aquifers covered by less than 50 ft. of low permeability material, are Class IIc because the overlying unconsolidated, unstratified, low permeability surficial deposits impede the vertical flow of water.

3d. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate greater than 50 gpm are Class IIa because they are unconfined and higher yield.

3e. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing water below the bedrock surface in areas with permeable sedimentary cover, with a pump rate less than 50 gpm are Class IIb because they are unconfined and lower yield.

3f. Wells located within the crystalline rock aquifer boundary (CRYS), sourcing water at depths greater than 50 ft., in areas with non-permeable sedimentary cover greater than 50 ft. thick, are Class III because the aquifer unit is confined.

Metadata Sources References

Olcott, P.G. 1992. Ground water atlas of the United States: Segment 9, Iowa, Michigan, Minnesota, Wisconsin. Hydrologic Investigations Atlas 730-J, U.S. Geological Survey, Reston, VA, 33 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Soller, D.R. 1992. Text and references to accompany "Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains": U.S. Geological Survey Bulletin 1921, 54 p.

Rules for Applying the Pettyjohn Classification Scheme in Wyoming

12 February 2018

Introduction

The rule set defined below is based on information published in the USGS Hydrologic Investigations Atlas 730-I (referred to as Segment 8 atlas in Whitehead, 1996 below) and the previously published DW USA reports (RSPA, 2002). The available data set included:

1. Wells: location
2. Surface geology (unconsolidated units)
3. Bedrock geology (with Quaternary Alluvium)

The Alluvial, Volcanic, Northern Great Plains, High Plains, and Upper Colorado River Basin aquifer systems were interpreted from the bedrock geology coverage provided by the USGS. This is done primarily for presentation, because the geology of Wyoming is very complex. Minor unnamed Tertiary, Cretaceous, and Paleozoic aquifers exist in the central portion of the state but were not included in the aquifer coverages created. This does not mean that wells deriving water from these units were neglected, however. Because well data consisted of well location only, each well in the state of Wyoming was classified according to the lithology of the unit it was located within. Therefore, the rules listed below will refer in most cases to specific formations within a given aquifer system.

The following aquifer regions of Wyoming were distinguished for this work:

1. Alluvial
2. High Plains and High Plains Confining Unit
3. Northern Great Plains/Upper Colorado River Basin Tertiary Permeable Unit
4. Northern Great Plains/Upper Colorado River Basin Mesozoic Permeable Unit
5. Northern Great Plains/Upper Colorado River Basin Confined
6. Northern Great Plains/Upper Colorado River Basin Carbonate Units
7. Volcanic and Igneous
8. Not a principal aquifer
9. Sole Source Aquifers

Rule 1. Alluvial aquifers (ALLU)

The alluvial sediments that compose these aquifers fill stream valleys or broad tectonic lowlands of mountainous areas. These lowland basins were formed by faulting, erosion, or both. The alluvium was deposited primarily as coalescing alluvial fans built by streams that flowed into the valleys from the surrounding mountains. The alluvial sediments are unconsolidated, permeable materials. Locally, sand and gravel beds of late Tertiary age compose aquifers beneath the Quaternary deposits that form most of the basin fill. Basin-fill deposits typically are coarse grained near basin margins and finer grained toward basin centers. Because no depth information is available, wells are classified with no regard to well depth. Typically, wells within the modern alluvium associated with river valleys should have maximum depths of around 200 ft, because that is the approximate maximum thickness of the alluvium. Wells within the broad valleys of western, central, and southeastern Wyoming may be as deep as 900 ft, with Pettyjohn classification switching from Ia to III at 200 ft, due to the high probability of confining units.

1a. Wells that derive water from the surficial (Holocene) sediments anywhere within the Alluvial aquifer [which includes alluvial valley sediments as well as modern intermontane valley and basin fill (unit abbreviations QTc, QTg, Qa, Qg, Qls, Qs, Qt, and Qu) are Class Ia, unless they are within the relatively limited number of playa and lacustrine deposits in the south-central portion of the state.

1b. Wells located in playa or lacustrine sediments (Unit abbreviation: Ql) are Class III due to the confining nature of these fine-grained deposits.

Rule 2. High Plains Permeable (HPPM) and Confining (HPCN) aquifers

The High Plains aquifers are located in southeastern Wyoming. Most wells obtain water from upper Tertiary aquifers that consist of the Ogallala Formation (unconsolidated sand and gravel) of Miocene age and the Arikaree Formation (sandstone) of Miocene and Oligocene age. Valley-fill and dune deposits of Quaternary age are hydraulically connected to the aquifers in Tertiary rocks. Except for the dune sands, which were deposited by wind, all the rocks and deposits that compose the High Plains aquifer system were deposited by streams.

2a. Wells within the broad sheets of Tertiary braided stream deposits (unit abbreviations: Tmo, Tmu, Twr, Twrb, and Twru) are Class Ic, because these sands and gravels are semi-consolidated.

2b Wells located within the Chadron member of the White River Formation (Twrc) are Class III, because this is a locally confining unit.

Rule 3. Northern Great Plains/Upper Colorado River Basin Tertiary Permeable aquifers (GCTE)

The Northern Great Plains aquifers are located in northeastern Wyoming. The majority of these aquifers are sandstones of Tertiary and Cretaceous age and carbonate rocks of Paleozoic age. These aquifers, along with regional confining units that separate some of them, form one of the largest confined aquifer systems in the United States. Open spaces in the sandstone aquifers are mostly pores between individual sand grains, but local larger openings include bedding planes, fractures, and faults. Large open spaces (solution cavities) are common in carbonate rocks.

The Upper Colorado River Basin aquifers are located in southwestern Wyoming. Layered sedimentary rocks in numerous geologic formations that range in age from Cenozoic to Paleozoic compose the aquifers. The formations can be grouped into five principal aquifers: Laney aquifer (Eocene, fractured sandstone beds); Wasatch-Fort Union aquifer (lower Tertiary, sandstones); Mesaverde aquifer (Upper Cretaceous, sandstone); Dakota through Nugget aquifers (Jurassic, sandstones); and Paleozoic aquifers (Cambrian to Pennsylvanian, sandstones and carbonates).

Lower Tertiary (Paleocene to Oligocene) sandstones make up portions of the Northern Great Plains and Upper Colorado River Basin aquifer systems. These crop out over a large area of Wyoming [southern ends of the Big Horn and Powder River Basins; much of the southern half of the state

(Figs. 7, 8, 11, and 31; Segment 8 atlas; Whitehead, 1996)]. Unit names include Fort Union, Wasatch, and Brule Formations, and Laney member of the Green River Formation (Unit abbreviations: Tf, Tfu, Tfl, Tflt, Tft, Tftl, Tftr, Tgl, Tm, Tw, Twk, Twlc, Twm, Twmo, Twn, Twg, Th, Twc, Toe, Twd, Tgrw, Tbs, Tbw, Tp).

3. Most of the wells that derive water from these units are low producers (<50 gpm) and, thus, are Class IIb. If depth data were available, wells deeper than 500 ft would be Class III, due to interbedded shales at depth.

Rule 4. Northern Great Plains/Upper Colorado River Basin Mesozoic Permeable aquifers (GCME)

The Northern Great Plains and Upper Colorado River Basin aquifer systems also incorporate Upper and Lower Cretaceous, as well as Jurassic consolidated sandstones. These crop out mostly around the edges of the major structural basins (e.g., Big Horn and Powder River). Units in this category include Hell Creek and Lance Formations; Fox Hills Sandstone, Mesaverde Group, Sundance and Gypsum Spring Formations, Nugget Sandstone, Pruess Sandstone (Unit abbreviations: Kav, Kfb, Kfh, Kfl, KJ, KJg, KJs, Kl, Klm, Kns, Kmt, K@, Kmv, Kr, Kbl, Ke, Kal, Jsg, Js, Jst, J@, J@gc, J@gn, J@n, and J@nd).

4. Most of the wells that derive water from these units are low producers (< 50 gpm), and are therefore Class IIb. If depth data were available, wells deeper than 500 ft would be Class III, due to interbedded shales at depth.

Rule 5. Northern Great Plains/Upper Colorado River Basin Confined aquifers (GCCN)

Both the Northern Great Plains and Upper Colorado River Basin aquifer systems include confining units, which separate individual aquifers within the system. Major confining units include the Lewis, Pierre, and Mowry shales. Unit abbreviations are: Kle, Kn, Knc, Knt, Kp, Ks, Ksn, Kgb, Kgbm, Kc, Km, Kmr, Ka, Kft, Kf, Kcl, Kcf, @Ps, @Pjs, @Pg, @Pcg, @c, @cd, P&M, P&Ma, Pfs, Pm, Pmo, Tb, Tgw, Tgt, Tgwt, Kba, Kbr, Pp, Tglu.

5. Wells occurring in the outcrop belt of these confining units are Class III.

Rule 6. Northern Great Plains/Upper Colorado River Basin Carbonate aquifers (GCCA)

Paleozoic carbonate aquifers make up portions of the Northern Great Plains aquifer, as well as minor outcrops in uplifted areas within the Upper Colorado River basin. The principle rock name for the Mississippian units is the Madison Limestone. Unit names for the Cambrian/Ordovician rocks include Bighorn Dolomite, Whitewood Dolomite, Stonewall Formation, Red River Formation, and Gallatin Limestone (Unit abbreviations: Mm, MD, MO, PM, P&m, P&h, DO, MDO, MDe, _r, Pzr, O_, and Ob). These units are aggregate of permeable horizons and low-permeability, semiconfining material.

6. Wells that derive water from these carbonate and karst units are Class Ib.

Rule 7. Volcanic and Igneous aquifers (VOLC)

Volcanic rock aquifers are located in small areas in northwestern Wyoming. These aquifers consist of extrusive igneous rocks, beds of tuff and volcanic ash, and beds of semiconsolidated to consolidated sedimentary rocks that contain large to small amounts of volcanic material. Outcrops of crystalline igneous rocks of any age and from PreCambrian units of any rock type are also incuded in this aquifer category and exist throughout the state. The permeability in these aquifers is extremely variable, because they are complexly interbedded and consist of numerous rock types. Unit abbreviations are: Qb, Qi, Qr, !W, Ta, Tai, Taw, Teml, Thp, Thr, Ti, Tii, Tie, Ts, Tt, Ttl, Ttp, Tts, Twl, Twp, Ugn, Ugn +, WVg, WVsv, Wg, Wgd, Wgn, Wmu, Wp, Wqm, Ws, Xdl, Xgo, Xgy, Xlc, Xm, Xsv, Xqd, Yla, Yls, Ys, and shear.

7. Any wells that derive water from these units are Class IIb, because these are highly consolidated, low yield rocks.

Rule 8. Not a principal aquifer (NAPA)

Mostly low yield bedrocks are grouped as not a principal aquifer. These formations include a large variety of rocks from Precambrian bedrocks to Quaternary volcanic rocks. The NAPA outcrops form a northwest-southeast trending wide zone across Wyoming. Wells that are located within the remaining "not a principle aquifer" region derive water from a range of lithologies.

8a. The intermontane basins of central and western Wyoming in the NAPA region contain semi-consolidated deposits of upper Tertiary (Miocene/Pliocene) sands and gravels. These deposits usually occur as terraces around basin margins, or are buried under Holocene basin-fill. Wells located in the outcrop belts (unit abbreviations: Tcg, Tcr, Tcs, Tep, Tgc, and Tr) of these aquifers, which derive water from them, are <u>Class Ic</u>. If depth information were available, the general guideline that wells deeper than 500 ft are Class III could be applied.

8b. Wells located within confining units are <u>Class III</u>. Unit abbreviations are: @Pcg, @ad, @c, Kbr, Kc, Kh, Kn, P&M, and P&Ma.

8c. Wells located within consolidated bedrock units are <u>Class IIb</u>. Unit abbreviations are as follows: J@n, J@nd, Jst, Kb, Kha, Kl, Kmv, Kso, Kss, P&c, P&cf, Ugn, WVsv, and Wg.

8d. Wells located within carbonate aquifers are <u>Class Ib</u>. Unit abbreviations are as follows: Tcd (Camp Davis Formation), Tte (Teewinot Formation), MD, and MDg.

8e. Wells located in semi-consolidated units are <u>Class Ic</u>. Unit abbreviations are as follows: Tha, Tsl, Twb, Twdr, and Twim.

Rule 9. Sole Source Aquifers

Two sole source aquifers are defined in Wyoming by EPA: (1) Eastern Snake River Plain aquifer stream flow source area, which extends from Idaho; (2) Elk Mountain aquifer, located in southeastern Wyoming. Much of the Eastern Snake River Plain and all of the Elk Mountain are contained within the coverage of the larger principal aquifers and therefore, inclusion of these sole source aquifers does not affect the Pettyjohn classification of the majority of wells that fall within their boundaries.

9. For wells that fall within the boundary of these sole source aquifers but do not fall within any other principal aquifer boundaries, the class is unknown because the description is too vague for interpretation.

Metadata Sources References

Whitehead, R.L. 1996. Ground water atlas of the United States: Segment 8, Montana, North Dakota, South Dakota, Wyoming. Hydrologic Investigations Atlas 730-I, U.S. Geological Survey, Reston, VA, 24 pp.

Research and Special Programs Administration (RSPA). 2002. A model for defining unusually sensitive areas. Prepared by Research Planning, Inc., for the Research and Special Programs Administration, Washington, D.C.

Appendix D

Example Aquifer Vulnerability Rules for North Carolina
RULES_LUT

Vulnerability Lookup Table – RULES_LUT for North Carolina

VAL_AQUIF	CLASS	FM	SOURCE	MIN_DEPTH	MAX_DEPTH	MIN_YIELD	MAX_YIELD	RULE
SURF_OUT	Ia			0	100	0	0	1a
SURF_OUT	III		S,Kpd	100	0	0	0	1b
SURF_OUT	UNK			100	0	0	0	1c
SURF_OUT	Ia			0	0	0	0	1a
CHPK_OUT	Ia			0	0	0	0	2a
CHPK_SUB	Ia			0	0	0	0	2b
CHAQ_OUT	Ia	Tpa		0	0	0	0	3a
CHAQ_OUT	Ib			0	0	0	0	3b
CHAQ_SUB	III			0	0	0	0	3c
PDCF_OUT	Ic			0	0	0	0	4a
PDCF_SUB	III			0	0	0	0	4b
PTMC_SUB	III			0	0	0	0	5a
CRYS_OUT	IIb			0	0	0	50	6b
CRYS_OUT	IIa			0	0	0	0	6a
CRYS_SUB	IIb			0	0	0	50	6d
CRYS_SUB	IIa			0	0	0	0	6c
MESO_OUT	IIb			0	0	0	50	7b
MESO_OUT	IIa			0	0	0	0	7a
CARB_OUT	Ib			0	0	0	0	8a
NAPA_OUT	IIb			0	0	0	50	9b
NAPA_OUT	IIa			0	0	0	0	9a

Appendix E

Open Water Lookup Table
OW_NHD_LUT

CLASS	FCODE	DESCRIPTION
OPEN WATER	30700	Area to be Submerged
OTHER	31200	Bay/Inlet
OPEN WATER	31800	Bridge
NOT APPL	33400	Connector
OPEN WATER	33600	Canal/Ditch
OPEN WATER	33601	Canal/Ditch: Canal/Ditch Type = Aqueduct
OTHER	33603	Canal Ditch: Canal Ditch Type = Stormwater
NOT APPL	34300	Dam/Weir
NOT APPL	34305	Dam/Weir: Construction Material = Earthen
NOT APPL	34306	Dam/Weir: Construction Material = Nonearthen
OTHER	36100	Playa
OPEN WATER	36200	Flume
OTHER	36400	Foreshore
NOT APPL	36700	Gaging Station
NOT APPL	36701	Gaging Station Status=Active; Record=Continuous
NOT APPL	36900	Gate
OTHER	37800	Ice Mass
OPEN WATER	39000	Lake/Pond
OTHER	39001	Lake/Pond: Hydrographic Category = Intermittent
OPEN WATER	39004	Lake/Pond: Hydrographic Category = Perennial
OTHER	39005	Lake/Pond: Hydrographic Category = Intermittent; Stage = High Water Elevation
OTHER	39006	Lake/Pond: Hydrographic Category = Intermittent; Stage = Date of Photography
OPEN WATER	39009	Lake/Pond: Hydrographic Category = Perennial; Stage = Average Water Elevation
OPEN WATER	39010	Lake/Pond: Hydrographic Category = Perennial; Stage = Normal Pool
OPEN WATER	39011	Lake/Pond: Hydrographic Category = Perennial; Stage = Date of Photography
OPEN WATER	39012	Lake/Pond: Hydrographic Category = Perennial; Stage = Spillway Elevation
OPEN WATER	39800	Lock Chamber
OTHER	40300	Inundation Area
OTHER	40307	Inundation Area: Inundation Control Status = Not Controlled
OTHER	40308	Inundation Area: Inundation Control Status = Controlled
OTHER	40309	Inundation Area: Inundation Control Status = Controlled; Stage = Flood Elevation
NOT APPL	41100	Nonearthen Shore
OTHER	42000	Underground Conduit
OTHER	42001	Underground Conduit: Positional Accuracy = Definite
OTHER	42002	Underground Conduit: Positional Accuracy = Indefinite
OTHER	42003	Underground Conduit: Positional Accuracy = Approximate
OTHER	42800	Pipeline
OTHER	42801	Pipeline: Pipeline Type = Aqueduct; Relationship to Surface = At or Near
OTHER	42802	Pipeline: Pipeline Type = Aqueduct; Relationship to Surface = Elevated
OTHER	42803	Pipeline: Pipeline Type = Aqueduct; Relationship to Surface = Underground
OTHER	42804	Pipeline: Pipeline Type = Aqueduct; Relationship to Surface = Underwater
OTHER	42805	Pipeline: Pipeline Type = General Case; Relationship to Surface = At or Near
OTHER	42806	Pipeline: Pipeline Type = General Case; Relationship to Surface = Elevated
OTHER	42807	Pipeline: Pipeline Type = General Case; Relationship to Surface = Underground
OTHER	42808	Pipeline: Pipeline Type = General Case; Relationship to Surface = Underwater
OTHER	42809	Pipeline: Pipeline Type = Penstock; Relationship to Surface = At or Near
OTHER	42810	Pipeline: Pipeline Type = Penstock; Relationship to Surface = Elevated

CLASS	FCODE	DESCRIPTION
OTHER	42811	Pipeline: Pipeline Type = Penstock; Relationship to Surface = Underground
OTHER	42812	Pipeline: Pipeline Type = Penstock; Relationship to Surface = Underwater
OTHER	42813	Pipeline: Pipeline Type = Siphon
OTHER	42814	Pipeline: Pipeline Type = General Case
OTHER	42815	Pipeline: Pipeline Type = Penstock
OTHER	42816	Pipeline: Pipeline Type = Aqueduct
OTHER	42820	Pipeline: Pipeline Type = Stormwater
OTHER	42821	Pipeline: Pipeline Type = Stormwater; Relationship to Surface = At or Near
OTHER	42822	Pipeline: Pipeline Type = Stormwater; Relationship to Surface = Elevated
OTHER	42823	Pipeline: Pipeline Type = Stormwater; Relationship to Surface = Underground
OTHER	42824	Pipeline: Pipeline Type = Stormwater; Relationship to Surface = Underwater
OPEN WATER	43100	Rapids
NOT APPL	43400	Reef
OPEN WATER	43600	Reservoir
OTHER	43601	Reservoir: Reservoir Type = Aquaculture
OTHER	43603	Reservoir: Reservoir Type = Decorative Pool
OTHER	43604	Reservoir: Reservoir Type = Tailings Pond; Construction Material = Earthen
OTHER	43605	Reservoir: Reservoir Type = Tailings Pond
OTHER	43606	Reservoir: Reservoir Type = Disposal
OTHER	43607	Reservoir: Reservoir Type = Evaporator
OTHER	43608	Reservoir: Reservoir Type = Swimming Pool
OTHER	43609	Reservoir: Reservoir Type = Cooling Pond
OTHER	43610	Reservoir: Reservoir Type = Filtration Pond
OTHER	43611	Reservoir: Reservoir Type = Settling Pond
OTHER	43612	Reservoir: Reservoir Type = Sewage Treatment Pond
OPEN WATER	43613	Reservoir: Reservoir Type = Water Storage; Construction Material = Nonearthen
OTHER	43614	Reservoir: Reservoir Type = Water Storage; Construction Material = Earthen; Hydrographic Category = Intermittent
OPEN WATER	43615	Reservoir: Reservoir Type = Water Storage; Construction Material = Earthen; Hydrographic Category = Perennial
OPEN WATER	43617	Reservoir: Reservoir Type = Water Storage
OPEN WATER	43618	Reservoir: Construction Material = Earthen
OPEN WATER	43619	Reservoir: Construction Material = Nonearthen
OPEN WATER	43621	Reservoir: Reservoir Type = Water Storage; Hydrographic Category = Perennial
OTHER	43623	Reservoir: Reservoir Type = Evaporator; Construction Material = Earthen
OTHER	43624	Reservoir; Reservoir Type = Treatment
OTHER	43625	Reservoir: Reservoir Type = Disposal; Construction Material = Earthen
OTHER	43626	Reservoir: Reservoir Type = Disposal; Construction Material = Nonearthen
NOT APPL	44100	Rock
NOT APPL	44101	Rock: Relationship to Surface = Abovewater
NOT APPL	44102	Rock: Relationship to Surface = Underwater
OTHER	44500	Sea/Ocean
NOT APPL	45000	Sink/Rise
OTHER	45500	Spillway
NOT APPL	45800	Spring/Seep
OPEN WATER	46000	Stream/River
OTHER	46003	Stream/River: Hydrographic Category = Intermittent
OPEN WATER	46006	Stream/River: Hydrographic Category = Perennial
OTHER	46007	Stream/River: Hydrographic Category = Ephemeral

CLASS	FCODE	DESCRIPTION
NOT APPL	46100	Submerged Stream
OTHER	46600	Swamp/Marsh
OTHER	46601	Swamp/Marsh: Hydrographic Category = Intermittent
OTHER	46602	Swamp/Marsh: Hydrographic Category = Perennial
NOT APPL	47800	Tunnel
NOT APPL	48300	Wall
OTHER	48400	Wash
NOT APPL	48500	Water Intake/Outflow
OPEN WATER	48700	Waterfall
NOT APPL	48800	Well
OTHER	49300	Estuary
NOT APPL	50300	Sounding Datum Line
NOT APPL	50301	Sounding Datum Line: Positional Accuracy = Approximate
NOT APPL	50302	Sounding Datum Line: Positional Accuracy = Definite
OPEN WATER	53700	Area of Complex Channels
NOT APPL	55800	Artificial Path
NOT APPL	56600	Coastline
NOT APPL	56700	Shoreline
NOT APPL	56800	Levee

Appendix F

Data Processing QA/QC Checklist

Preliminary Checks

Check the data processing document, to ensure that the final data can be recreated following the instructions in the data processing document. Make sure there are no assumed or implied steps. Every step must be documented. If there are any questions about the final data, they should be able to be answered by reading the processing document.

Make sure the following required feature classes are present and in their appropriate datasets.

Feature Dataset	Feature Class	Feature Type
welldata	pws	Points
state	bnd	Polygons
state	bnd_10mi	Polygons
hydro	nhd_area	Polygons
hydro	nhd_flowline	Lines
hydro	nhd_waterbody	Polygons
geology	bgeo	Polygons
aquifers	aquifer	Polygons
	rules_lut	Table
	ow_nhd_lut	Table

Check if the optional feature classes are present and in their appropriate feature datasets.

Feature Dataset	Feature Class	Feature Type
swpa	swpa	Polygons
ssa	ssa	Polygons
geology	sgeo	Polygons
geology	sedthick	Polygons
geology	drift	Polygons
geology	basins	Polygons
	source_lut	Table

Start checking individual feature classes based on the information in the Data Processing document and Data Processing Guidelines and the requirements in the data dictionary. Field names are case sensitive. All model related fields need to be uppercase.

Detailed Checks by Feature Class

BND

- Detailed checks are not done on this feature class, because it was created by a script and is not edited during the preprocessing.

BND_10MI

- Detailed checks are not done on this feature class, because it was created by a script and is not edited during the preprocessing.

NHD_AREA

- Detailed checks are not done on this feature class, because it was created by a script and is not edited during the preprocessing.

NHD_FLOWLINE

- Detailed checks are not done on this feature class, because it was created by a script and is not edited during the preprocessing.

NHD_WATERBODY

- Detailed checks are not done on this feature class, because it was created by a script and is not edited during the preprocessing.

AQUIFER

- The feature class name is aquifer.
- There is a field named OBJECTID that is of type Object ID.
- Contains the field AQUIF that is of type TEXT and length 10.
- AQUIF does not contain any NULL or Blank values.
- The feature class was dissolved on AQUIF.
- All the codes in AQUIF are in the Aquifer Guidelines document for that state.
- If there are both outcrops and subcrops in the feature class, then the code for AQUIF includes the suffix "_OUT" for outcrop or "_SUB" for subcrop.
- AQUIF does not have a water feature.

SSA

- The feature class name is ssa.
- There is a field named OBJECTID that is of type Object ID.
- It contains the field KARST of type TEXT and length 1.
- KARST is updated with Y for karst aquifers or is NULL. Check with the geologist to determine if the aquifer is karst.
- It contains the field RECHARGE of type TEXT and length 1.
- RECHARGE is updated with Y for recharge areas or is NULL. Recharge areas are identified by the Sole Source Aquifer Name or in the Federal Register entry for that aquifer.
- It contains NAME of type TEXT and length 75.
- The source data for NAME is from the field SSA_NAME in the feature class.
- NAME is the same as the value in SSA_NAME with " SSA" truncated from the value.
- It contains field AQUIF of type TEXT and length 10.
- It is updated with an 8-letter code ending in "_SSA" unless the aquifer is the same as one in the AQUIFER feature class. In that case AQUIF should have the same code as in the AQUIFER feature class.

BGEO

- The feature class name is bgeo.
- There is a field named OBJECTID that is of type Object ID.

- It contains the field FM and is type TEXT.
- From the data processing document, determine the source of the values for FM.
- Length of FM is long enough for all the values in the source field.
- Compare FM values to source field values to ensure all rows were updated correctly.
- It contains the field BGEO_DESC and is type TEXT.
- From the data processing document, determine the source of the values for BGEO_DESC.
- Length of BGEO_DESC is long enough for all the values in the source field.
- Compare BGEO_DESC values to source field values to ensure all rows were updated correctly.
- Fields FM and BGEO_DESC should not have any blank values. They may contain NULL values.

SGEO

- The feature class name is sgeo.
- There is a field named OBJECTID that is of type Object ID.
- It contains the field SGEO_DESC and is type TEXT.
- From the data processing document, determine the source of the values for SGEO_DESC.
- Length of SGEO_DESC is long enough for all the values in the source field.
- Compare SGEO_DESC values to source field values to ensure all rows were updated correctly.
- Field SGEO_DESC cannot not have any blank values. It can have NULL values.

SEDTHICK

- The feature class name is sedthick.
- There is a field named OBJECTID that is of type Object ID.
- It contains the field THICK_SGEO and is type TEXT and length 1.
- The value of THICK_SGEO is 0 to 9 based on information in the processing document (e.g. 1: < 50 feet, 2: 50 to 100 feet).
- Field THICK_SGEO cannot have any blank values. It can have NULL values.

DRIFT

- The feature class name is drift.
- There is a field named OBJECTID that is of type Object ID.
- It contains the field THICK_GLAC and is type TEXT and length 1.
- The value of THICK_GLAC is 0 to 9 based on information in the processing document (e.g. 1: < 50 feet, 2: 50 to 100 feet).
- Field THICK_GLAC cannot have any blank values. It can have NULL values.

BASINS

- The feature class name is basins
- There is a field named OBJECTID that is of type Object ID.
- It contains the field BASIN and is type TEXT.

- From the data processing document, determine the source of the values for BASIN.
- Length of BASIN is long enough for all the values in the source field.
- Compare BASIN values to source field values to ensure all rows were updated correctly.
- Field BASIN cannot have any blank values. It can have NULL values.

SWPA

- The feature class name is swpa.
- There is a field named OBJECTID that is of type Object ID.
- It contains the field PWS_ID and is type TEXT of length 10.
- From the data processing document, determine the source of the values for PWS_ID.
- PWS_ID should have a 2-letter state code or 2-digit EPA region code, followed by a 7-digit number (e.g. ND1800049).
- Check that the value in PWS_ID equals the value in the source field. If the source values had to be manipulated to get the PWS_ID, check to make sure that manipulation was documented in the data processing document. Redo the manipulation and make sure the results match the PWS_ID.
- It contains the field SWPAUNIQUE of type TEXT and length 20.
- SWPAUNIQUE format should be ST-PWSID-######. Where ST is the 2-digit state code, PWSID is the 7-digit numeric portion of PWS_ID and ###### is a sequential 6 digit number (example: ND-18000049-000023).
- SWPAUNIQUE has all unique values.
- SWPAUNIQUE has no NULL or blank values.
- Join SWPA to PWS on SWPAUNIQUE. There should be no SWPA records that don't have a matching PWS record. The Selection "PWS.SWPAUNIQUE IS NULL" should return 0 records.

PWS

- The feature class name is pws.
- There is a field named OBJECTID that is of type Object ID.
- It contains the field PWS_ID and is type TEXT of length 10.
- From the data processing document, determine the source of the values for PWS_ID.
- PWS_ID should have a 2-letter state code or 2 digit EPA region code, followed by a 7 digit number (e.g. ND1800049).
- Check that the value in PWS_ID equals the value in the source field. If the source values had to be manipulated to get the PWS_ID, check to make sure that manipulation was documented in the data processing document. Redo the manipulation and make sure the results match the PWS_ID.
- ACTIVITY_CODE is type TEXT of length 1.
- Valid values for ACTIVITY_CODE are "A", "I", or NULL. There should be no blanks.
- From the data processing document, determine the source of the values for ACTIVITY_CODE.
- Check that the values in ACTIVITY_CODE match the values in the source field. If the source values are not "Active" or "A" and "Inactive" or "I", check the definitions of the

source values and make sure the ACTIVITY_CODE column is updated correctly based on the definition.

- SYSTEM_TYPE is type TEXT of length 1.
- Valid values for SYSTEM_TYPE are “C”, “P”, “N”, or NULL. There should be no blanks.
- From the data processing document, determine the source of the values for SYSTEM_TYPE.
- Check that the values in SYSTEM_TYPE match the values in the source field. If the source values are not “C”, “P”, “N” check the definitions of the source values and make sure the SYSTEM_TYPE column is updated correctly based on the definition.
- SOURCE_TYPE is type TEXT of length 2.
- Valid values for SOURCE_TYPE are “GW”, “SW”, “SP” or NULL. There should be no blanks.
- From the data processing document, determine the source of the values for SOURCE_TYPE.
- Check that the values in SOURCE_TYPE match the values in the source field. If the source values are not “GW”, “SW”, or “SP” check the definitions of the source values and make sure the SOURCE_TYPE column is updated correctly based on the definitions.
- DEPTH_WELL is a numeric type either LONG or DOUBLE, based on the source data.
- From the data processing document, determine the source of the values for DEPTH_WELL.
- The values for DEPTH_WELL are in feet.
- Valid values for DEPTH_WELL are numeric greater than 0 or 0. There should be no blank or NULL values. A value of 0 is assumed to be no value.
- Check that the value in DEPTH_WELL match the values in the source field. If the values in the source field needed to be converted check that the processing document describes the conversion. Replicate the conversion to check if DEPTH_WELL is correct.
- DEPTH_SCREEN is a numeric type either LONG or DOUBLE, based on the source data.
- From the data processing document, determine the source of the values for DEPTH_SCREEN.
- The values, for DEPTH_SCREEN, are in feet.
- Valid values, for DEPTH_SCREEN, are numeric greater than 0 or 0. There should be no blank or NULL values. A value of 0 is assumed to be no value.
- Check that the value in DEPTH_SCREEN match the values in the source field. If the values in the source field needed to be converted check that the processing document describes the conversion. Replicate the conversion to check if DEPTH_SCREEN is correct.
- DEPTH_CASE is a numeric type either LONG or DOUBLE, based on the source data.
- From the data processing document, determine the source of the values for DEPTH_CASE.
- The values for, DEPTH_CASE, are in feet.

- Valid values, for DEPTH_CASE, are numeric greater than 0 or 0. There should be no blank or NULL values. A value of 0 is assumed to be no value.
- Check that the value in DEPTH_CASE match the values in the source field. If the values in the source field needed to be converted check that the processing document describes the conversion. Replicate the conversion to check if DEPTH_CASE is correct.
- PUMP_RATE is a numeric type either LONG or DOUBLE, based on the source data.
- From the data processing document, determine the source of the values for PUMP_RATE.
- The values, for PUMP_RATE, are in gallons per minute.
- Valid values, for PUMP_RATE, are numeric greater than 0 or 0. There should be no blank or NULL values. A value of 0 is assumed to be no value.
- Check if all the values in the source field for PUMP_RATE have the same units.
- Check that the value in PUMP_RATE match the values in the source field. If the values in the source field needed to be converted check that the processing document describes the conversion. Replicate the conversion to check if PUMP_RATE is correct. If the units vary in the source field check that the value for PUMP_RATE was converted according to the units in the source field for that record.
- SOURCE is type TEXT.
- From the data processing document, determine the source field of the values for SOURCE. SOURCE is the name of the aquifer from which the well is deriving water.
- SOURCE length should be the same as the source field for SOURCE.
- SOURCE should be free text or NULL. There should be no blank values.
- Check if the values in SOURCE match the values in the source field. There should be no conversion at this point.
- THICK_CONF is a numeric type either LONG or DOUBLE, based on the source field data.
- From the data processing document, determine the source of the values for THICK_CONF.
- The values, for THICK_CONF, are in feet.
- Check that the value in THICK_CONF match the values in the source field. If the values in the source field needed to be converted check that the processing document describes the conversion. Replicate the conversion to check if THICK_CONF is correct.
- LITHOLOGY is type TEXT.
- From the data processing document, determine the source field of the values for LITHOLOGY. LITHOLOGY is the description of the aquifer from which the well is deriving water.
- LITHOLOGY length should be the same as the source field for LITHOLOGY.
- LITHOLOGY should be free text or NULL. There should be no blank values.
- Check if the values in LITHOLOGY match the values in the source field. If the source data is converted, check that the conversion is documented in the data processing document. Convert the source field data following the data processing document and confirm the LITHOLOGY values are correct.

- SWPBUFF is a numeric type either LONG or DOUBLE.
- SWPABUFF is in meters.
- Check processing document to determine what the values of SWPABUFF should be.
- Values for SWPABUFF should be numeric or 0. There should be no blanks or NULL values.
- SWPABUFF should be 0 if SOURCE_TYPE is “SW”.
- SWPABUFF should be 0 if SWPAUNIQUE is not NULL.
- If protection areas for springs are treated the same as protection areas for surface water intakes, then SWPABUFF should be 0 if SOURCE_TYPE is “SP”.
- Check that all SWPABUFF values that are not 0 match the values identified in the processing document.
- SWPAUNIQUE is of type TEXT with a length of 20.
- SWPAUNIQUE format should be ST-PWSID-######. Where ST is the 2-digit state code, PWSID is the 7-digit numeric portion of PWS_ID and ###### is a sequential 6 digit number (example: ND-18000049-000023).
- All SWPAUNIQUE values should be unique.
- SWPAUNIQUE has either a valid value or NULL. There should be no blanks.
- Join PWS to SWPA on SWPAUNIQUE. There should be no PWS records with a SWPAUNIQUE value that don’t have a matching SWPA record. The Selection “PWS.SWPAUNIQUE IS NOT NULL AND SWPA.SWPAUNIQUE IS NULL” should return 0 records.
- There should be a state supplied unique identifier between the PWS record and SWPA record. Or PWS and SWPA feature classes both have matching state supplied PWS_IDs.
- If there is a state supplied unique identifier, check that the well is within the boundary of the matching protection area. For surface water intakes check that the intake is inside the boundary, or within 100 meters of the boundary of the matching protection area.
- If the well/intakes are matched on PWS_ID, check that the well falls within 1 and only 1 wellhead protection area with the same PWS_ID. Check that the surface water intake is in, or within 100 meters of 1 and only 1 surface water protection area with the same PWS_ID.

OW_NHD_LUT

- Detailed checks are not done on this table, because it was created by a script and is not edited during the preprocessing.

RULES_LUT

- The table name is rules_lut.
- There is a field named OBJECTID that is of type Object ID.
- It contains the required field VAL_AQUIF and is type TEXT of length 10.
- The field does not contain any blank or NULL values.
- If there is no SOURCE field in the PWS feature class, the values are the 4 letter AQUIF_CODE used in the AQUIFER feature class.

- If there is an SSA feature class and rules are written for the SSA aquifers, there should be values in VAL_AQUIF to match the values in the AQUIF field of the SSA feature class.
- If there is a SOURCE field in the PWS feature class, the values in VAL_AQUIF are the 4 letter AQUIF_CODE used in the AQUIFER feature class. with either _OUT or _SUB appended to it. If AQUIFER contains outcrops and subcrops, then VAL_AQUIF values are the same as the AQUIF_CODE used in the AQUIFER feature class.
- It contains the required field CLASS and is type TEXT of length 10.
- The field does not contain any blank or NULL values.
- Valid values are Ia, Ib, Ic, Id, IIa, IIb, IIc III.
- Make sure they are the letter Capital I, not the number One, or the letter lowercase L.
- Optionally contains the field FM of type TEXT and length is long enough to contain the longest character string in the field.
- FM contains text from the FM field in the BGEO feature class or is NULL. It cannot be blank.
- Optionally contains the field BGEO_DESC of type TEXT and length is long enough to contain the longest character string in the field.
- BGEO_DESC contains text from the BGEO_DESC field in the BGEO feature class or is NULL. It cannot be blank.
- Optionally contains the field SGEO_DESC of type TEXT and length is long enough to contain the longest character string in the field.
- SGEO_DESC contains text from the SGEO_DESC field in the SGEO feature class or is NULL. It cannot be blank.
- Optionally contains the field THICK_SGEO of type TEXT and length 1.
- THICK_SGEO contains text from the THICK_SGEO field in the SEDTHICK feature class or is NULL. It cannot be blank.
- Optionally contains the field THICK_GLAC of type TEXT and length 1.
- THICK_GLAC contains text from the THICK_GLAC field in the DRIFT feature class or is NULL. It cannot be blank.
- Optionally contains the field AQUIF of type TEXT and length 10.
- AQUIF contains the 4 or 8 letter aquifer codes in the AQUIF field of the AQUIFER feature class or is NULL. It cannot be blank.
- Optionally contains the field SOURCE of type TEXT and length is long enough to contain the longest character string in the field.
- SOURCE contains text from the SOURCE field in the PWS feature class or is NULL. It cannot be blank.
- Optionally contains the field LITHOLOGY of type TEXT and length is long enough to contain the longest character string in the field.
- LITHOLOGY contains text from the LITHOLOGY field in the PWS feature class or is NULL. It cannot be blank.
- It contains the required field MIN_DEPTH and is a numeric type either LONG or DOUBLE, based on the source data.

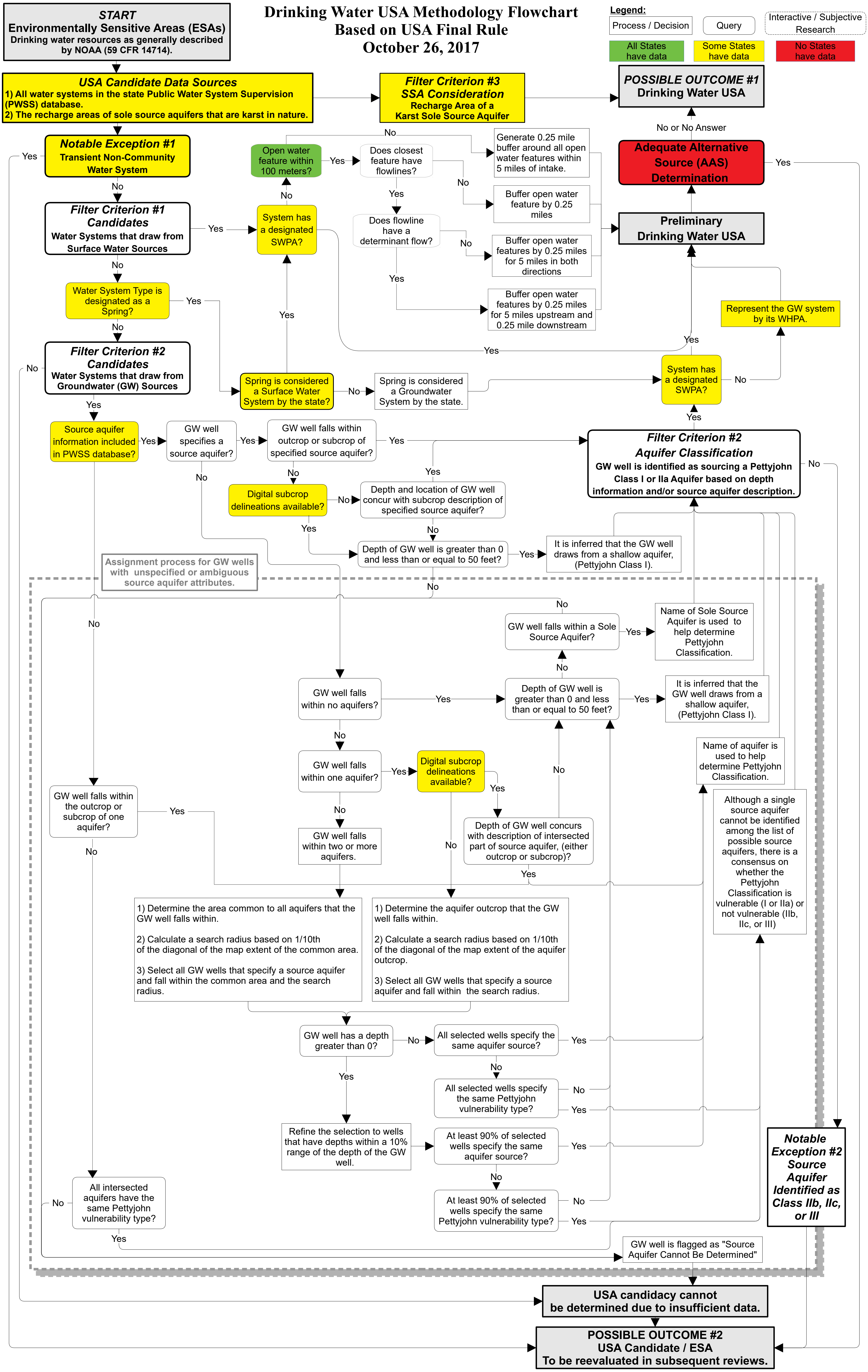
- MIN_DEPTH must be a number or 0. The field does not contain any blank or NULL values.
- It contains the required field MAX_DEPTH and is a numeric type either LONG or DOUBLE, based on the source data.
- MAX_DEPTH must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MIN_CONF and is a numeric type either LONG or DOUBLE, based on the source data.
- MIN_CONF must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MAX_CONF and is a numeric type either LONG or DOUBLE, based on the source data.
- MAX_CONF must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MIN_YIELD and is a numeric type either LONG or DOUBLE, based on the source data.
- MIN_YIELD must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MAX_YIELD and is a numeric type either LONG or DOUBLE, based on the source data.
- MAX_YIELD must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MIN_CASE and is a numeric type either LONG or DOUBLE, based on the source data.
- MIN_CASE must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MAX_CASE and is a numeric type either LONG or DOUBLE, based on the source data.
- MAX_CASE must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MIN_SCREEN and is a numeric type either LONG or DOUBLE, based on the source data.
- MIN_SCREEN must be a number or 0. The field does not contain any blank or NULL values.
- Optionally contains the field MAX_SCREEN and is a numeric type either LONG or DOUBLE, based on the source data.
- MAX_SCREEN must be a number or 0. The field does not contain any blank or NULL values.
- Contains the required field RULE of type TEXT and length 3.
- RULE contains the Rule number. It cannot be blank or NULL.

SOURCE_LUT

- The table name is source_lut.
- There is a field named OBJECTID that is of type Object ID.
- It contains the required field SOURCE and is type TEXT and is long enough to contain the longest character string in the field.
- The field cannot be blank, but it can contain 1 and only 1 NULL.
- It contains the required field AQUIF_CODE of type TEXT and is long enough to contain the longest character string in the field.
- It contains one or a comma separated string of aquifer codes that match the aquifer codes in the AQUIF field of the AQUIFER feature class.

Appendix G

Drinking Water USA Methodology Flowchart


Drinking Water USA Methodology Flowchart
Based on USA Final Rule
October 26, 2017
Legend:
Process / Decision
Query
Interactive / Subjective Research
All States have data
Some States have data
No States have data
START
Environmentally Sensitive Areas (ESAs)
Drinking water resources as generally described by NOAA (59 CFR 14714).
USA Candidate Data Sources
1) All water systems in the state Public Water System Supervision (PWSS) database.
2) The recharge areas of sole source aquifers that are karst in nature.
Filter Criterion #3
SSA Consideration
Recharge Area of a Karst Sole Source Aquifer
POSSIBLE OUTCOME #1
Drinking Water USA
No or No Answer
Adequate Alternative Source (AAS) Determination
Notable Exception #1
Transient Non-Community Water System
Open water feature within 100 meters?
Does closest feature have flowlines?
Generate 0.25 mile buffer around all open water features within 5 miles of intake.
Buffer open water feature by 0.25 miles
Does flowline have a determinant flow?
Buffer open water features by 0.25 miles for 5 miles in both directions
Buffer open water features by 0.25 miles for 5 miles upstream and 0.25 mile downstream
Preliminary Drinking Water USA
Filter Criterion #1
Candidates
Water Systems that draw from Surface Water Sources
System has a designated SWPA?
Water System Type is designated as a Spring?
Represent the GW system by its WHPA.
Filter Criterion #2
Candidates
Water Systems that draw from Groundwater (GW) Sources
Spring is considered a Surface Water System by the state?
Spring is considered a Groundwater System by the state.
System has a designated SWPA?
Source aquifer information included in PWSS database?
GW well specifies a source aquifer?
GW well falls within outcrop or subcrop of specified source aquifer?
Filter Criterion #2
Aquifer Classification
GW well is identified as sourcing a Pettyjohn Class I or IIa Aquifer based on depth information and/or source aquifer description.
Digital subcrop delineations available?
Depth and location of GW well concur with subcrop description of specified source aquifer?
Depth of GW well is greater than 0 and less than or equal to 50 feet?
It is inferred that the GW well draws from a shallow aquifer, (Pettyjohn Class I).
Assignment process for GW wells with unspecified or ambiguous source aquifer attributes.
GW well falls within a Sole Source Aquifer?
Name of Sole Source Aquifer is used to help determine Pettyjohn Classification.
GW well falls within no aquifers?
Depth of GW well is greater than 0 and less than or equal to 50 feet?
It is inferred that the GW well draws from a shallow aquifer, (Pettyjohn Class I).
Name of aquifer is used to help determine Pettyjohn Classification.
GW well falls within one aquifer?
Digital subcrop delineations available?
GW well falls within the outcrop or subcrop of one aquifer?
Depth of GW well concurs with description of intersected part of source aquifer, (either outcrop or subcrop)?
GW well falls within two or more aquifers.
Although a single source aquifer cannot be identified among the list of possible source aquifers, there is a consensus on whether the Pettyjohn Classification is vulnerable (I or IIa) or not vulnerable (IIb, IIc, or III)
1) Determine the area common to all aquifers that the GW well falls within.
2) Calculate a search radius based on 1/10th of the diagonal of the map extent of the common area.
3) Select all GW wells that specify a source aquifer and fall within the common area and the search radius.
1) Determine the aquifer outcrop that the GW well falls within.
2) Calculate a search radius based on 1/10th of the diagonal of the map extent of the aquifer outcrop.
3) Select all GW wells that specify a source aquifer and fall within the search radius.
GW well has a depth greater than 0?
All selected wells specify the same aquifer source?
All selected wells specify the same Pettyjohn vulnerability type?
Refine the selection to wells that have depths within a 10% range of the depth of the GW well.
At least 90% of selected wells specify the same aquifer source?
At least 90% of selected wells specify the same Pettyjohn vulnerability type?
All intersected aquifers have the same Pettyjohn vulnerability type?
Notable Exception #2
Source Aquifer Identified as Class IIb, IIc, or III
GW well is flagged as "Source Aquifer Cannot Be Determined"
USA candidacy cannot be determined due to insufficient data.
POSSIBLE OUTCOME #2
USA Candidate / ESA
To be reevaluated in subsequent reviews.

Appendix H

Geospatial Extent Comparisons:

Source Water Protection Areas (SWPA)
Upstream/Downstream Buffers
Sole Source Aquifers (SSA)

Due to the content of Appendix H, it is designated ***For Official Use Only*** *and managed as a standalone document by PHMSA*