Secondary Hydrogeologic Regions of the Conterminous United States
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Abstract

The U.S. Geological Survey (USGS) previously identified and mapped 62 Principal Aquifers (PAs) in the U.S., with 57 located in the conterminous states. Areas outside of PAs, which account for about 40% of the conterminous U.S., were collectively identified as "other rocks." This paper, for the first time, subdivides this large area into internally-consistent features, defined here as Secondary Hydrogeologic Regions (SHRs). SHRs are areas of other rock within which the rocks or deposits are of comparable age, lithology, geologic or physiographic setting, and relationship to the presence or absence of underlying PAs or overlying glacial deposits. A total of 69 SHRs were identified. The number and size of SHRs identified in this paper are comparable to the number and size of PAs previously identified by the USGS. From a two-dimensional perspective, SHRs are complementary to PAs, mapped only where the PAs were not identified on the USGS PA map and not mapped where the PAs were identified. SHRs generally consist of low permeability rocks or deposits, but can include locally productive aquifers. The two maps, taken together, provide a comprehensive, national-scale hydrogeologic framework for assessing and understanding groundwater systems.

Introduction

Regional-scale classification of groundwater systems provides a basis for understanding and management of groundwater resources (Barthel 2014; Dennehy et al. 2015). In the United States (U.S.), two classification systems have been widely used: an approach developed by Heath (1982, 1984, 1988), and subsequent work by the U.S. Geological Survey (USGS) presented in “The Ground Water Atlas of the United States” (Miller 2000). The Ground Water Atlas included a map of Principal Aquifers, which was subsequently updated by the USGS (2003). In the five paragraphs that follow, the work of Heath and the USGS are reviewed. Those studies provide the foundation for the work presented in this paper. The review of previous work is followed by two paragraphs describing the purpose and potential value of the current work.

Heath (1982 and 1984) provided a classification system for identifying groundwater regions, which were defined as areas in which the composition, arrangement, and structure of rock units are similar. Heath, building upon the work of Meinzer (1923) and Thomas (1952), identified 15 groundwater regions in the U.S., Puerto Rico, and the Virgin Islands. Heath’s classification system has been widely used. For example, it provided the framework for describing the hydrogeology of North America (Back et al. 1988) and provided a foundation for the initial development of the widely cited DRASTIC method for assessing vulnerability to pollution (Aller et al. 1987). Heath’s classification system has been widely used. For example, it provided the framework for describing the hydrogeology of North America (Back et al. 1988) and provided a foundation for the initial development of the widely cited DRASTIC method for assessing vulnerability to pollution (Aller et al. 1987). Heath’s groundwater regions are large and focus on the general characteristics of groundwater systems that provide water supply. Heath did not explicitly identify specific aquifers or aquifer systems within those regions.

The USGS (Miller 2000) subsequently published “The Ground Water Atlas of the United States” which described the “location, extent, and geologic and hydrologic characteristics of the most productive aquifers in the United States.” The productive aquifers were identified as principal aquifers (PAs) and were characterized as belonging to one of six lithologic categories (Figure 1A). Areas outside of PAs were simply identified as “not a principal aquifer” by Miller (2000) and as “other” on the USGS PA map.
Principal aquifer outcrop or subcrop
Other rocks not underlain by a Principal Aquifer
Other rocks underlain by a Principal Aquifer
Extent of Laurentide ice sheet

Unconsolidated sand and gravel aquifers
Sandstone and carbonate-rock aquifers
Semiconsolidated sand and gravel aquifers
Carbonate-rock aquifers
Sandstone aquifers
Igneous- and metamorphic-rock aquifers

A total of 62 PAs were identified in the 50 states, Puerto Rico, and the Virgin Islands, with 57 located in the conterminous U.S. (USGS 2003). The areas mapped as PAs (USGS 2003) only include those areas where the PAs outcrop at the surface or subcrop beneath surficial deposits. However, many of the PAs are present at depth and underlie other PAs or underlie areas mapped as other rocks. The areas where the PAs are “buried” beneath other PAs or other rocks are not shown on the USGS PA map. The USGS PA map identifies an additional aquifer system, glacial deposit aquifers, and maps those as an overprint indicating that they can overlie either PAs or other rocks. In contrast to Heath, the USGS PA map does not identify stream-valley aquifers (Sargent et al. 2008).

The USGS PA map has been used as a framework for assessing groundwater resources and for understanding groundwater systems. For example, USGS assessments of groundwater availability (Reilly et al. 2008) and groundwater quality (Rowe et al. 2013; DeSimone et al. 2014) have been organized on the basis of PAs. Examples of process-based research conducted in the context of PAs include studies of redox (McMahon and Chapelle 2008), vulnerability to nitrate contamination (Gurdak and Qi 2012), recharge (McMahon et al. 2011), groundwater sustainability (Scanlon et al. 2012), and groundwater level response to climate variability (Kuss and Gurdak 2014).

Heath’s groundwater regions and the USGS PA map have both been used to develop and (or) evaluate classification systems that characterize surface-groundwater interaction. Wolock et al. (2004), building upon concepts developed by Winter (2001), identified 20 Hydrologic Landscape Regions (HLRs) in the U.S. Bedrock permeability was one of the variables considered in the statistical analysis (Wolock et al. 2004). Seven permeability classes, based on the USGS PA map, were recognized: six corresponding to the six lithologic categories and a seventh to other rocks. Glacial deposits were not included in the analysis. Santhi et al. (2008) subsequently evaluated the relationship between base flow indices and the HLRs, and used Heath’s (1984) groundwater regions as a framework for discussing results. Dahl et al. (2007) explicitly incorporated Heath’s (1982) classification criteria into a typology for characterizing groundwater-surface water interaction in Denmark.

The purpose of this paper is to subdivide, within the conterminous U.S., other rocks as identified on the USGS PA map (Figure 1A) into logically mapped subareas. It is important to subdivide these areas because other rocks account for about 40% of the conterminous U.S., and because about 3% of groundwater pumping in the U.S. is from other rocks (Maupin and Barber 2005). Also, stream base flow is not limited to areas mapped as PAs. Toward that end, regional-scale SHRs are identified as the basic subdivision of areas previously identified as other rocks.

From the perspective of a two-dimensional map, SHRs are complementary to Principal Aquifers. SHRs are only mapped in areas identified as other rocks on the USGS PA map, and they are not mapped in areas that are identified as PAs on the USGS PA map (Figure 1A). SHRs can include locally productive aquifers or can consist entirely of low permeability rocks or deposits. With the addition of SHRs, all areas of the conterminous U.S. belong to an internally-consistent mapped feature—either a PA or an SHR—thus providing a comprehensive, national-scale hydrogeologic framework. The newly defined framework is at a finer spatial scale than Heath’s groundwater regions. The framework of PAs and SHRs can be used to assess groundwater resources, to understand groundwater systems, and to

Figure 1. Maps of the conterminous U.S. showing: (A) Principal Aquifers, categorized by lithology, and other rocks; and (B) Principal Aquifers, areas where other rocks are and are not underlain by Principal Aquifers, and areas where glacial deposits overlie either Principal Aquifers or other rocks (as indicated by extent of Laurentide ice sheet).
help characterize the interaction of groundwater with surface water.

Methodology

SHRs were identified in two phases (Figure 2). In the first phase, Other Rock Regions (ORRs) were defined as regions underlain by geologic units of comparable age, lithology, and geologic or physiographic setting. ORRs were an intermediate product. In the second phase, ORRs were evaluated relative to the presence of PAs that may underlie the ORRs and (or) glacial deposits that may overly the ORRs. The presence or absence of stream-valley aquifers overlying an SHR was not considered, which is consistent with the identification of PAs. Identification and mapping of ORRs and SHRs was facilitated using digital databases and geographic information system tools.

In the first phase, areas identified as other rocks on the PA map (USGS 2003) were intersected with geologic units from the Geologic Map of North America (Reed et al. 2005; Garrity and Soller 2009). Polygons and segments of polygons from the Geologic Map that were located within the area of other rocks were retained; polygons and segments of polygons from the Geologic Map that were located in areas of PAs were eliminated. The intersection resulted in 310 geologic units distributed across 14,000 polygons within the conterminous U.S.; segments of polygons from the Geologic Map were taken as polygons at this stage. The area of the average polygon was about 230 km². Each polygon was evaluated from a hydrogeologic perspective and compared to neighboring polygons for the purposes of defining ORRs. ORRs were not assembled through the development of an algorithm or script, but rather through inspection.

Polygons were assembled into ORRs primarily on the basis of age and lithology, which are the primary descriptors of geologic units (Garrity and Soller 2009). Divisions of geologic age were as small as periods and as large as eras, largely reflecting the precision associated with the geologic units. Three lithologic classes were recognized: sedimentary (clastic or carbonate), crystalline (plutonic or metamorphic), or volcanic (Tertiary or Quaternary). Rocks of Archean and Proterozoic age were classified as crystalline. Lithologic categorization was based primarily on the relatively coarse-resolution Geologic Map of North America (Garrity and Soller 2009), but also on the relatively fine-resolution State Geologic Map Compilation (Horton et al. 2017). The Geologic Map of North America was given priority because it provides consistency across state boundaries, whereas the state-scale geologic maps do not. However, the Geologic Map of North America in some cases does not provide sufficient lithologic information, and therefore the state-scale geologic maps needed to be used. For example, the Geologic Map of North America does not distinguish between sedimentary and metasedimentary rocks. In some situations, geologic units of disparate age and lithology were assigned to ORRs that would otherwise consist of geologic units of similar age and lithology; in those cases, the disparate geologic units were relatively small and contiguous with the larger ORR.

Assemblage of polygons into ORRs also depended on the location of the polygons within geologic provinces, and other geologic or physiographic features. Four geologic provinces were recognized (Reed and Bush 2007): Cordilleran Mountain System, Central Interior, Coastal Plain, and Appalachian-Ouachita Mountain Systems. Additional geologic features included sedimentary basins and other structures (Frezon and Finn 1988; Coleman and Cahan 2012). Physiographic regions were identified from Fenneman and Johnson (1946). The boundaries of the provinces, sedimentary basins and other structures, and physiographic regions are generalized and were used only as a guide for assembling polygons into ORRs. A total of 66 ORRs were identified, with an average size of about 48,000 km².

In the second phase, the presence of PAs that might be buried beneath ORRs was taken into account (Figure 1B). The presence of PAs beneath ORRs was taken into account (Figure 1B). The presence of PAs beneath ORRs was taken into account (Figure 1B). The presence of PAs beneath ORRs was taken into account (Figure 1B). The presence of PAs beneath ORRs was taken into account (Figure 1B). The presence of PAs beneath ORRs was taken into account (Figure 1B).
Great Plains—Lower Cretaceous and Paleozoic—were not utilized because those PAs contain saline water at depth (Whitehead 1996).

Also in the second phase, the presence of glacial deposits that might overlie ORRs was considered (Figure 1B). The extent of glacial deposits was taken as the southernmost extent of the Laurentide ice sheet (Arnold et al. 2008) because most of the surficial deposits within that area are mapped as glacial sediments (Soller et al. 2009; Soller and Reheis 2004). The area within the extent of the Cordilleran ice sheet was excluded because most of the surficial deposits within that area are mapped as residual materials and other non-glacial sediments.

Each ORR was then evaluated with respect to the presence or absence of underlying PAs and (or) overlying glacial deposits (Figure 2). If the relationships were consistent across the entire ORR, then the ORR was identified as an SHR. If the relationships were not consistent, then the ORR was subdivided so that the relationships were consistent; at this stage, previously identified polygons from Phase 1 were subdivided as needed. In some cases, subdivided ORRs were combined with other subdivided ORRs to form an SHR. A total of 69 SHRs were identified with an average area of 46,000 km².

Each of the SHRs was classified using three criteria: (1) presence or absence of underlying PAs or overlying glacial deposits, (2) primary lithology, and (3) geologic province. The first criterion is referred to as Type (Table 1). The classification of an SHR is based on the predominant characteristic across the SHR. Geodatabases containing information about the ORRs and SHRs are available (Belitz et al. 2018).

In the discussion section, we provide some information on community supply wells. The latitude and longitude for each well was obtained from Price and Maupin (2014). These data were intersected with SHR boundaries to obtain summaries.

### Discussion

If the USGS PA map (USGS 2003) were used to categorize wells or streams that are located in areas outside of PAs, then they would all be grouped into a single category: “other rocks.” In this paper, these areas were subdivided into 69 SHRs, thus providing a finer scale of resolution for assessing groundwater systems than was previously possible. In the discussion that follows, the locations of community supply wells in the conterminous U.S. are used to illustrate the utility of characterizing SHRs by type. The discussion also includes a summary of SHRs by lithology and geologic province, and presents some potential refinements and extensions that could be undertaken.

| Overlain by Glacial? | Underlain by PA? | SHR Type       |
|---------------------|-----------------|----------------|
| No                  | Yes             | Type NN        |
| Yes                 | Type YN         | Type YY        |

### Characterization of Wells in the Context of SHR Type

Water wells are one of the primary means by which groundwater resources can be characterized. And given the three dimensional nature of groundwater systems, it is important to know an SHR’s type (Table 1) because a well can extract water from the SHR, an underlying PA if present, the overlying glacial deposits if present, or some combination of the SHR, PA, and glacial deposits. If a well’s two-dimensional position, as indicated by its latitude and longitude, plots within the boundaries of an SHR classified as Type NN (Table 1), then it is likely that the well is tapping rocks within the SHR; wells plotting
Figure 3. Map showing the 69 Secondary Hydrogeologic Regions of the conterminous United States. Table A1 provides information for each of the 69 SHRs.
Table 2
Number and Size (Square Kilometers) of Secondary Hydrogeologic Regions Based on: Type, Primary Lithology, and Geologic Province

| Presence of PA Below or Glacial Deposits Above | Number | Area  |
|-----------------------------------------------|--------|-------|
| Type NN                                       | 44     | 1,810,000 |
| Type NY                                       | 12     | 860,000  |
| Type YN                                       | 9      | 200,000  |
| Type YY                                       | 4      | 310,000  |
| Primary Lithology                             |        |        |
| Sedimentary                                   | 42     | 2,000,000 |
| Crystalline                                   | 14     | 730,000  |
| Volcanic                                      | 9      | 190,000  |
| Mixed                                         | 4      | 280,000  |
| Geologic Province                             |        |        |
| Central Interior                              | 31     | 1,840,000 |
| Cordilleran                                   | 26     | 1,000,000 |
| Appalachian-Ouachita                          | 6      | 210,000  |
| Coastal Plain                                 | 6      | 100,000  |

Note(s): Area is rounded to the nearest 10,000 km². PA, principal aquifer. Explanation of type is provided in Table 1. The total area of the conterminous U.S. is about 8 million square kilometers.

near boundaries may require additional inspection. SHRs classified as Type NN account for about 23% of the total area of the conterminous U.S. (Table 2), and about 9% of the community supply wells are located in these areas (Figure 5). Information from these community supply wells, such as water quality data, could be used to characterize groundwater resources in SHRs classified as Type NN. In this paper, these areas have been subdivided into 44 SHRs (Table 3).

If a well’s two-dimensional position plots within the boundaries of an SHR that is underlain by a PA and (or) overlain by glacial deposits, then the well might or might not tap rocks within the SHR. Additional inspection of the vertical position of the well screen or open interval would be needed. Comparable difficulties can also arise when categorizing wells that plot within the boundaries of a PA because PAs can also be overlain by glacial deposits and (or) underlain by other PAs. In the absence of information about which geologic units are tapped by a well, one could still categorize the well based upon its plotting position. In this paper, there are 26 SHRs identified as Type NY, YN, or YY, and they account for about 18% of the total area (Table 2) and about 20% of the community supply wells in the conterminous U.S. (Figure 5).

SHRs Summarized by Lithology and Geologic Province
The lithology of an SHR is important because it provides an indication of the nature of the porosity and permeability of the rocks that comprise it, and because it can affect water quality. This is particularly important for SHRs that are Type NN; in these areas, one can generally expect wells to tap the volume of rock identified as an SHR. By definition, SHRs are not PAs, and are generally comprised of low permeability rocks or deposits.

Forty-two of the 69 SHRs are comprised of sedimentary rocks (Table 3, Figure 4B), and these SHRs might include sandstones of limited spatial extent, or they might include carbonate rocks. Carbonates can be highly porous and permeable, particularly if the rocks have been exposed to secondary dissolution. In other cases, however, the porosity and permeability of carbonates can be quite low (Belitz and Bredehoeft 1988). As noted by Miller (2000),
are represented. In the Appalachian-Ouachita Mountain System, all of the SHRs are classified as Type NN and all four lithologic classes are represented. In the Cordilleran Mountain System, all of the SHRs are sedimentary and all four Types are represented. (Table 3). In the Central Interior, three-quarters of the SHRs comprised of mixed lithology could be subdivided on the basis of lithology.

Porosity and permeability within these SHRs can be quite variable, and minor aquifers might or might not be present. SHRs comprised of mixed lithology could be subdivided on the basis of lithology.

Geologic provinces provide a context for assessing and understanding groundwater in areas mapped as SHRs (Table 3). In the Central Interior, three-quarters of the SHRs are sedimentary and all four Types are represented. In the Cordilleran Mountain System, all of the SHRs are classified as Type NN and all four lithologic classes are represented. In the Appalachian-Ouachita Mountain System, none of the SHRs are underlain by a PA and only two of the four lithologic classes are represented. In the Coastal Plain, all of the SHRs are sedimentary, and five of the six are underlain by a PA. The five SHRs classified as YN (Table 1) in the Coastal Plain can be characterized as confining layers and wells located in these SHRs are likely to extract water from an underlying PA.

**Possible Refinements and Extensions of the Current Work**

The identification of SHRs is an important step in obtaining an improved understanding of the hydrogeologic framework of the conterminous U.S. Additional work can be pursued to develop a more refined understanding of that framework. Also, the newly developed framework can be used for purposes beyond characterization of groundwater accessed by wells.

The boundaries of the PAs as defined by the USGS (2003) are relatively generalized. The precision of the PA boundaries could be increased if one were to use the boundaries of geologic units as identified in the Geologic Map of North America (Garrity and Soller 2009). The criteria for identifying the PAs are defined in the Groundwater Atlas (Miller 2000), and those criteria could be used to identify the appropriate geologic units that correspond to the PAs. Alternatively, one could use the higher-resolution State Geologic Map Compilation (Horton et al. 2017), but substantial effort would be required to resolve differences that may occur across state lines. The existing boundaries of PAs were respected in this paper in order to maintain consistency with previous work (USGS 2003).

The presence or absence of overlying glacial deposits was used to help classify SHRs (Table 1, Figure 4A). In this paper, the extent of glacial deposits was taken as the southernmost extent of Laurentide glaciation (Arnold et al. 2008). The depositional setting, thickness, and texture of deposits within the glaciated extent were not considered in the classification of the SHRs; these characteristics could be considered when evaluating groundwater resources in those SHRs overlain by glacial deposits. Identification of the vertical position of the well screen or open interval would be a critical part of such assessments.

Stream-valley aquifers are not recognized as a PA (Miller 2000), nor do the SHRs account for the presence or absence of overlying stream-valley aquifers. However, stream-valley aquifers can be important sources of water supply (Sargent et al. 2008), particularly in the unglaciated Central Interior subprovince. Although stream-valley aquifers have been generally mapped along major rivers and tributaries (Heath 1984; Miller 2000), they have not been mapped along smaller tributaries. In some cases, stream-valley aquifers can extend across the boundaries of several PAs and (or) SHRs. The State Geologic Map Compilation (Horton et al. 2017) does provide a basis for a relatively comprehensive identification of stream-valley aquifers, but it is beyond the scope of this paper to undertake that effort. In some assessments of PAs, stream-valley aquifers were not separated from the larger PA. For example, assessment of groundwater quality in the High Plains PA included sedimentary rocks in areas mapped as other rocks can include shale, siltstone, evaporate deposits, silt, and clay. In some areas, sedimentary rocks can be fractured.

Fourteen of the 69 SHRS are comprised of crystalline rocks (Table 3, Figure 4B). If a well taps crystalline rocks, then the groundwater is generally expected to be transmitted through fractures; in many cases, storage occurs in the overlying sediments. Eight of the 14 crystalline SHRs are of Type NN, with seven located in the Cordilleran geologic province. The remaining six crystalline SHRs are Type NY, and are located either in the glaciated Central Interior subprovince or in the Appalachian part of the Appalachian-Ouachita geologic province.

The remaining 13 SHRS are comprised of volcanic rocks or are classified as mixed, in which case there is no predominant lithologic class (Table 3, Figure 4B). All of the volcanic and mixed SHRs are Type NN, and 11 of the 13 are located in the Cordilleran geologic province. Porosity and permeability within these SHRs can be quite variable, and minor aquifers might or might not be present. SHRs comprised of mixed lithology could be subdivided on the basis of lithology.
well located within stream-valley aquifers (Gurdak et al. 2009); in that study the stream-valley aquifers were considered to be in hydrologic connection with the High Plains PA (Gutentag et al. 1984). Assessments of groundwater in SHRs that include overlying stream-valley aquifers could implicitly incorporate those aquifers as has been done with PAs or additional work could be done to identify stream-valley aquifers as appropriate.

The approach for identifying SHRs presented in this paper could be extended to areas of the U.S. that are outside of the conterminous states. Hawaii is underlain by a single PA (USGS 2003), and therefore no SHRs need be identified. Two PAs are identified in Puerto Rico, one in the Virgin Islands, and areas identified as other rocks in both territories are recognized as a minor aquifer (Miller et al. 1999); the minor aquifer could be defined as an SHR or it could be further subdivided. A single PA, consisting of unconsolidated deposits, is recognized in Alaska (USGS 2003). Areas of other rocks in Alaska include a wide range of lithologies, geologic ages, geologic and physiographic settings, and permafrost zones (Miller et al. 1999), and additional work would be required to identify SHRs.

The SHRs identified in this paper could be used to update previous work that identified Hydrologic Landscape Regions (HLRs) and assessed stream base flow in the context of HLRs (Wolock et al. 2004; Santhi et al. 2008). Those studies recognized six lithologic classes in the 60% of the conterminous U.S. that are mapped as PAs, and one lithologic class corresponding to other rocks which comprise the remaining 40%. Following the logic of the previous work and given the lithologies identified in the present work, four lithologic classes (Figure 4B)—crystalline, mixed, sedimentary, or volcanic—could be recognized in areas mapped as other rocks rather than just one. In addition, the previous work did not account for glacial deposits; future work could recognize glacial deposits and represent them using one or more lithologic classes. It is beyond the scope of this paper to re-evaluate HLRs or to relate stream base flow to bedrock permeability.

Summary

Classification of groundwater regions is important because it provides a foundation and context for a wide range of studies. The USGS has classified the Nation’s groundwater, recognizing 57 Principal Aquifers in the conterminous U.S. (Miller 2000; USGS 2003). The USGS PA map identifies PAs only where they outcrop at the surface or subcrop beneath surficial deposits. Areas outside of the Principal Aquifers were simply identified as “not a principal aquifer” (Miller 2000) or as “other” (USGS 2003). For the purposes of discussion, areas
outside of PAs are defined here as “other rocks.” It is important to subdivide areas of other rocks into smaller regions for several reasons: they account for 40% of the conterminous U.S.; 29% of the nation’s community supply wells are located in these areas; and, stream base flow is not limited to areas mapped as PAs.

In this paper, areas mapped as other rocks were subdivided into 69 SHRs (Figure 3). SHRs typically consist of low permeability rocks or deposits, but can include locally productive aquifers. The basic building block for identifying SHRs were geologic units as identified on the Geologic Map of North America (Garrity and Soller 2009), with supplementary information obtained from the State Geologic Map Compilation (Horton et al. 2017), to insure that SHRs consist of rocks of comparable age and lithology. SHRs also were assembled using additional analog and digital maps to insure that the geologic units within an SHR are of comparable geologic or physiographic setting (Fenneman and Johnson 1946; Frezon and Finn 1988; Reed and Bush 2007; Coleman and Cahan 2012). In addition, SHRs were assembled so that they have a consistent relationship with respect to the presence or absence of underlying PAs and (or) overlying glacial deposits.

For the purposes of discussion and context, each SHR was classified using three criteria: (1) presence or absence of underlying PAs and (or) overlying glacial deposits, (2) primary lithology, and (3) geologic province and subprovince. The relationship between an SHR and underlying PAs or overlying glacial deposits is important because it provides some indication of whether a supply well is extracting water from rocks within the SHR. The lithology of an SHR provides an indication of the nature of the porosity and permeability of the rocks that comprise it, and can affect the quality of groundwater within it. Classification by geologic province and subprovince provides context for assessment and understanding.

The newly developed SHR map is a complement to the PA map previously published by the USGS (USGS 2003). SHRs are identified in areas where the PAs were not, and are not identified where the PAs were. The two maps, taken together, provide a national-scale hydrogeologic framework for conducting a wide range of groundwater studies and research. Additional work can be done to refine and extend that framework.

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Authors’ Note

The author(s) does not have any conflicts of interest to report.

Appendix A

Table A1 provides characteristics of each of the 69 Secondary Hydrogeologic Regions (SHRs): area, lithologic class, and type. A lower-case “x” in the first position of an SHR name indicates an SHR that consists of rocks that are comparable or identical to an adjacent principal aquifer (PA); the text following the “x” is the name of the associated PA (Miller 2000). The SHRs with a lowercase “x” could be considered to be a part of the adjacent PA. Several of the SHRs include a suffix; Table A2 provides a description of the abbreviations used in the suffix.

Table A1: Characteristics of Secondary Hydrogeologic Regions (SHRs)

| SHR Description                      | Area  | Lithologic Class | Type |
|--------------------------------------|-------|------------------|------|
| Cordilleran, Western                 |       |                  |      |
| WA OR Coast Ranges—S                 | 22,113| Sedimentary      | NN   |
| WA OR Coast Ranges—V                 | 15,214| Volcanic          | NN   |
| xPugetSound                          | 55    | Sedimentary      | NN   |
| Northern Cascade Mountains           | 38,354| Crystalline       | NN   |
| Middle Cascade Mountains             | 14,060| Volcanic          | NN   |
| Middle & Southern Cascade Mtns       | 14,881| Volcanic          | NN   |
| Klamath Mountains                    | 31,922| Crystalline       | NN   |
| Coast Ranges                         | 64,749| Sedimentary       | NN   |
| Sierra Nevada                        | 64,533| Crystalline       | NN   |
| Southern CA Mtns                     | 24,997| Mixed             | NN   |
| Cordilleran, Intermountain           |       |                  |      |
| Pacific NW Volcanics                 | 46,165| Volcanic          | NN   |
| Blue Mountains                       | 9182  | Mixed             | NN   |
| Basin and Range Highlands           | 232,826| Mixed             | NN   |
| Grand Canyon                         | 45,684| Sedimentary       | NN   |
| xColorado Plateau                    | 2612  | Sedimentary       | NN   |
| Rio Grande Highlands                 | 30,269| Volcanic          | NN   |
| Cordilleran, Rocky Mountains         |       |                  |      |
| Northern Rocky Mtns—X                | 134,612| Crystalline       | NN   |
| Northern Rocky Mtns—S                | 36,159| Sedimentary       | NN   |
| Northern Rocky Mtns—V                | 22,332| Volcanic          | NN   |
| Northern Rocky Mtns—Q                | 4489  | Sedimentary       | NN   |
| Middle Rocky Mtns—X                  | 19,373| Crystalline       | NN   |
| Middle Rocky Mtns—S                  | 62,604| Sedimentary       | NN   |
| Middle Rocky Mtns—V                  | 13,850| Volcanic          | NN   |
| Southern Rocky Mtns—X                | 45,402| Crystalline       | NN   |
| Southern Rocky Mtns—S                | 21,650| Sedimentary       | NN   |
| Southern Rocky Mtns—V                | 19,815| Volcanic          | NN   |
| Central Interior, unglaciated        |       |                  |      |
| Black Hills-X                        | 2061  | Crystalline       | NN   |
| Black Hills-S                        | 2583  | Sedimentary       | YN   |
| Front Range                          | 4337  | Sedimentary       | NN   |
| Upper Cretaceous, unglaciated        | 189,739| Sedimentary       | NN   |
| Raton Basin                          | 60,664| Sedimentary       | NN   |
| Eastern New Mexico                   | 85,391| Sedimentary       | NN   |
| Interior Permian                     | 168,054| Sedimentary      | NN   |
| Interior Pennsylvanian               | 68,586| Sedimentary       | NN   |
| OK Permian—Pennsylvania              | 3939  | Sedimentary       | NN   |
| Ozarks Paleozoic                     | 470,74| Sedimentary       | YN   |
Table A1

| SHR              | Area          | Lithologic Class | Type  |
|------------------|---------------|------------------|-------|
| Ozarks-X         | 693           | Crystalline      | NN    |
| Arches-unglaciated | 69,242       | Sedimentary      | NN    |
| Texas-Triassic   | 12,177        | Sedimentary      | NN    |
| Texas-Cretaceous | 2586          | Sedimentary      | NN    |
| Texas-Pennsylvanian | 15,235     | Sedimentary      | NN    |
| West TX—S        | 19,503        | Sedimentary      | NN    |
| West TX—I        | 11,640        | Volcanic         | NN    |
| Llano Uplift     | 8086          | Mixed            | NN    |
| Edwards-Trinity KT | 65,046       | Sedimentary      | YN    |

The number in the first column corresponds to the numbers on the Map of SHR (Figure 3). Area is reported in square kilometers. Type refers to the presence of a Principal Aquifer beneath (first letter) or glacial deposits above an SHR (second letter). Y, yes, present. and N, no, not present. Mtns, Mountains.

Table A2

| Abbreviation | Description |
|--------------|-------------|
| K            | Cretaceous  |
| PZ           | Paleozoic   |
| Q            | Quaternary  |
| S            | Sedimentary |
| T            | Tertiary    |
| V            | Volcanic    |
| X            | Crystalline |

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