United States Environmental Protection Agency

EPA/600/R-16/063 | May 2016 | Research at EPA
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Office of Research and Development
National Health and Environmental Effects Research Laboratory

EPA/600/R-16/063
May 2016

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by

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Student Services Contract #EP-15-W-000041

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Abstract

Researchers at the U.S. Environmental Protection Agency's Western Ecology Division have been developing hydrologic landscape maps for selected U.S. states in an effort to create a method to identify the intrinsic watershed attributes of landscapes in regions with little data. Each hydrologic landscape unit is assigned a categorical value from five key indices of macro-scale hydrologic behavior, including annual climate, climate seasonality, aquifer permeability, terrain, and soil permeability. The aquifer permeability index requires creation of a from-scratch dataset for each state. The permeability index for the Pacific Southwest (California, Nevada, and Arizona) expands and modifies the permeability index for the Pacific Northwest (Oregon, Washington, and Idaho), which preceded it. The permeability index was created by assigning geologic map units to one of 18 categories with presumed similar values of permeability to create a hydrolithologic map. The hydrolithologies were then further categorized into permeability index classifications of high, low, unknown and surface water. Unconsolidated, carbonate, volcanic, and undifferentiated units are classified more conservatively to better address uncertainty in source data. High vs. low permeability classifications are assigned qualitatively but follow a threshold guideline of 8.5x10-2 m/day hydraulic conductivity. Estimates of permeability from surface lithology is the current best practice for broad-scale assessment of groundwater flow characteristics in regions with little data, but assumptions are broad and may not be met due to lithologic variability with depth and intra-category variation in primary and secondary porosity. The permeability maps for each state were completed at the resolution of the best-available geologic map and should not be used to perform analysis on specific units or at scales finer than the primary dataset.

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Acronyms and Abbreviations

HL	Hydrologic Landscape
HLU	Hydrologic Landscape Unit
FHLU	Fundamental Hydrologic Landscape
PNW	Pacific Northwest
Ma	Mega-annum

Acknowledgments

Thanks to Keith Halford, Greg Pohll, Roy Haggerty, and Michael Campana for thoughtful comments. The information in this document has been funded entirely by the U.S. Environmental Protection Agency, in part through Student Services Contract #EP-15-W-000041. This report has been subjected to Agency review and has been approved for publication. The views expressed in this report are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

1. Introduction

1.1 Hydrologic Landscapes

Researchers at the U.S. Environmental Protection Agency's Western Ecology Division have been developing hydrologic landscape (HL) maps for selected U.S. states in an effort to develop a method to identify the intrinsic watershed attributes of landscapes in regions with little data. Beginning in Oregon (Wigington et al. 2013, Patil et al. 2014, Leibowitz et al. 2014) before expanding to the Pacific Northwest (Comeleo et al. 2014, Leibowitz et al. 2016), a series of classification indices were developed that, when assigned to geographic regions termed hydrologic landscape assessment units (HLUs), provide insight into the basic, macro-scale hydrologic functions of the landscape at multiple scales.

For a detailed discussion of the theoretical framework behind the hydrologic landscape indices, the reader is referred to previous project publications (Wigington et al. 2013, Patil et al. 2014, Leibowitz et al. 2014, Comeleo et al. 2014, Leibowitz et al. 2016). In brief, the hydrologic landscape indices were based on the hydrologic landscape concept of Winter (2001), who defined the fundamental hydrologic landscape unit (FHLU) as an area composed of an upland connected to a lowland by a slope, which functions as the 'basic building block of all hydrologic landscapes. FHLUs with similar characteristics, at single or nested scales, should exhibit similar patterns of hydrologic behavior.' This concept recognizes the central importance of geomorphology in defining watershed function (e.g., Grant 1997, Tague and Grant 2004, Jefferson et al. 2006). As such, the FHLU can guide hypotheses of hydrologic behavior across a broad range of questions by providing a way to 'objectively conceptualize…the movement of groundwater, surface water, and atmospheric water in different types of terrain' (Winter 2001). Since publication, Winter's (2001) concept has been widely applied to a variety of hydrologic and ecosystem research (e.g., Wolock et al. 2004, Tague and Grant 2004, Yadav et al. 2007, Kennard et al. 2010, Sawicz et al. 2011).

When developing the HL map for Oregon, Wigington et al. (2013) adapted the approach of Wolock et al. (2004), who delineated a 20-region national hydrologic landscape map using cluster analysis of five principal components based on variables indicative of climate, geology, terrain, and soil characteristics. Wigington et al. (2013) used similar characteristics to define hydrologic landscape regions, but selected five indices *a priori* to infer hydrologic function in a given region. These five indices consisted of 1) annual climate, 2) climate seasonality, 3) aquifer permeability, 4) terrain, and 5) soil permeability. Values for each index were assigned to classes and each hydrologic landscape assessment unit was assigned an index class for each category. These values were then evaluated against a cluster analysis of various hydrograph properties of 30 streams in Oregon and determined to provide a reasonable depiction of hydrologic behavior. Subsequent analytical work used the hydrologic landscape classifications to evaluate the predictive capabilities of a simple lumped hydrologic model of streamflow (Patil et al. 2014) and to assess the climate change vulnerability of streamflow in Oregon (Leibowitz et al. 2014).

Following the analysis of hydrologic landscapes in Oregon, the project was expanded to consider the Pacific Northwest (PNW), consisting of the states of Oregon, Washington, and

Idaho. This both provided the opportunity to improve several of the indices used for hydrologic landscape classification and required the creation of multiple datasets to feed into the classification scheme. Detailed discussion of the creation and/or modification of regional-scale climate, seasonality, terrain, soil permeability, and aquifer permeability for the PNW, as well as subsequent analysis, is given in Leibowitz et al. (2016) and Comeleo et al. (2014).

With completion of the PNW, the third and current project phase is creation of a hydrologic landscape map for the Pacific Southwest (herein defined as California, Nevada, and Arizona). This hydrologic landscape map is under preparation and will be discussed in future publications. This report details the creation of the aquifer permeability index for the Pacific Southwest HL map.

1.2 Aquifer Permeability Index

Wigington et al. (2013) stated that the inclusion of an aquifer permeability index provided "reasonable information on the relative importance of shallow subsurface vs. deep groundwater flows and the possible loss or gain of water through groundwater export or import." The aquifer permeability index attempts to provide a proxy for two metrics: the nature of groundwater flow paths (i.e., shallow vs. deep, aquifer vs. confining unit) and the timing of response (i.e., flashy vs. non-flashy). In areas of low permeability, it is expected that flow paths are shallow, and stream discharge is closely correlated to precipitation events with little lag. In areas of high permeability, aquifer storage is expected to be significant, flow paths are deep, and significant baseflow mediates stream discharge (cf. Grant 1997, Tague and Grant 2004, Tromp-Van Meerveld et al. 2007).

The original hydrologic landscape map used existing paper maps of aquifers in Oregon (McFarland 1983, Gonthier 1984) to guide the creation of a digital, three-class aquifer permeability index map[1] (Wigington et al. 2013, Comeleo et al. 2014). Using the digital geologic map of Oregon (Walker et al. 2003) as a base, each polygon was assigned to an 'aquifer group' on the basis of the mapped aquifer boundaries and/or lithology. These groups were then assigned an estimated hydraulic conductivity value based on those tabulated in McFarland (1983) and Gonthier (1984) and grouped into high (>3.1 m/day hydraulic conductivity), medium (>1.5, and ≤3.1 m/day hydraulic conductivity), or low (<1.5 m/day hydraulic conductivity) permeability classes.

In contrast to Oregon, no statewide aquifer maps existed for Washington, Idaho, or the greater

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[1] 'Permeability' is used colloquially here and in other hydrologic landscape publications to imply the ability of water to move through the ground. Strictly, *intrinsic permeability* (K_i) is the ability of a porous medium to transmit a fluid. K_i is a function of a) the porosity of the medium and b) the connectivity of that porosity. K_i is typically reported in units of length squared per time (e.g., m^2/day). It should not be confused with *hydraulic conductivity* (K), which is a proportionality constant for flow through porous media and reported in units of length per time (e.g., m/day). K is a function of both the permeability of the media and of the fluid itself, related to K_i as $K = K_i \rho g/\nu$, where ρ is the density of the fluid, g is gravitational acceleration, and ν is the dynamic viscosity of the fluid. This distinction is critical to accurate calculations but may be lost colloquially, where 'permeability' is frequently used to mean hydraulic conductivity. Because of its more intuitive units, we formally report our values as hydraulic conductivity throughout this work. We retain references to 'permeability' as a general term in keeping with previous hydrologic landscape publications and to enhance interdisciplinary readability.

Northwest at the time of the HL project's expansion to the Pacific Northwest. The best (and possibly only) national-scale aquifer map of the United States is the 2003 Principal Aquifers of the United States, a compilation of a decades-long characterization and mapping effort by the U.S. Geological Survey which culminated in the Ground Water Atlas of the United States (Miller 1999 and associated publications). However, it is inapplicable to the HL classifications as it was produced for a scale of 1:5,000,000 (mean polygon size >75,000 km^2), three orders of magnitude greater than the desired scale for HL mapping. Additionally, the Principal Aquifers Map was designed to map the principal aquifers in a region and thus frequently maps deep aquifers like the Ogallala rather than the unconfined alluvial aquifer above.

In the absence of an available aquifer map, Comeleo et al. (2014) developed a digital permeability index map for the Pacific Northwest using data from a national map produced by Gleeson et al. (2011). Gleeson et al. (2011) classified previously-compiled national lithologic maps (Dürr et al. 2005, Jansen et al. 2010, Moosdorf et al. 2010) into nine hydrolithologic categories, each of which was assigned a mean hydraulic conductivity based on values derived from calibrated groundwater models. Their hydrolithologic categories included 1) coarse-grained unconsolidated, 2) fine-grained unconsolidated, 3) unconsolidated [undifferentiated], 4) coarse-grained siliciclastic sedimentary, 5) fine-grained siliciclastic sedimentary, 6) siliciclastic sedimentary [undifferentiated], 7) carbonate, 8) crystalline, and 9) volcanic.

Comeleo et al. (2014) assigned each polygon from state-produced digital geologic maps of Oregon, Washington, and Nevada to one of the categories defined by Gleeson et al. (2011), with the exception of the ninth class, volcanic rocks. While a necessary simplification at the continental scale, the lumping of all volcanic rocks obscures well-known differences in hydrologic behavior between volcanic types in the Pacific Northwest, where older volcanics are essentially impermeable and basalts and young volcanics host major aquifers and high-volume springs (McFarland 1983, Ingebritsen et al. 1992, Lindholdm 1996, Tague and Grant 2004, Saar and Manga 2004, Conlon et al. 2005, Jefferson et al. 2006, Kahle et al. 2011, Tague et al. 2013). To more accurately reflect these differences, Comeleo et al. (2014) expanded the Gleeson et al. (2011) classification system to include older volcanics, younger volcanics, older basalts, and younger basalts, producing a 12-class hydrolithologic map of the Pacific Northwest. Estimated permeability values for the expanded classes were calculated using values from calibrated groundwater models, after Gleeson et al. (2011).

To produce the aquifer permeability index map that is used in the HL map of the Pacific Northwest, Comeleo et al. (2014) simplified the three-class system employed by Wigington et al. (2013) in Oregon to a two-class system. Using a hydraulic conductivity threshold of 8.5×10^{-3} m/day, each hydrolithologic unit was assigned to a high or low permeability class. As calculated by Gleeson et al. (2011), this value is the cutoff between fine-grained unconsolidated materials and undifferentiated unconsolidated materials, which the project team deemed an appropriate distinction for units likely to be permeable vs. impermeable (Leibowitz et al. 2016).

The aquifer permeability index for the Pacific Southwest is an outgrowth of the work of Gleeson et al. (2011) and Comeleo et al. (2014), but with important modifications. First, we further expand the Pacific Northwestern classification system from nine classes to 18. Second, we assign probable permeability values to each class according to the calculations made by

Gleeson et al. (2011) and Comeleo et al. (2014), but report them only to the order of magnitude. These changes were made in an effort to 1) allow a more accurate characterization of uncertainty and groupings made in geologic mapping, 2) reflect differences in geologic mapping approach across regions, and 3) reflect differences in regional geology in the Pacific Southwest.

There are two components to the ultimate product provided here, 1) a hydrolithologic map classified according to 18 possible values based on similar hydrogeologic characteristics (Plate 1, Table 1), and 2) the hydrolithologic map further classified into a binary high/low system designed for use in the hydrologic landscapes system (Plate 2). Our approach, discussion of the datasets and classification decisions, and a discussion of assumptions and limitations of this method are provided below.

2. Methods

Both the hydrolithologic units and permeability class designations were produced at the scale of, and using the polygons defined by, the best available digital geologic maps for a given state. The availability of geologic data varies greatly at the state level; in Arizona, the best available map is at a scale of 1:1,000,000 while in California it is 1:750,000 and in Nevada it is 1:250,000. When determining the appropriate scale to complete the hydrolithologic unit maps, we used the best available data at the state level rather than apply an arbitrary set scale to the Pacific Southwest region, which would have resulted in a map at a similar resolution to the existing dataset produced by Gleeson et al. (2011). As a result, the hydrolithologic units were mapped at disparate scales across state lines, but take advantage of finely mapped data where it is available.

Table 1: Hydrostratigraphic Units and Permeability Classes as defined for the Pacific Southwest (California, Arizona, and Nevada), expanding on the work of Comeleo et al. (2014) and after Gleeson et al. (2011). H = high, L = low, U = unknown, Ma = mega-annum

Hydrolithologic unit	Perm-eability class	Mean hydraulic conductivity (m/day; a=Gleeson et al. 2011, b=Comeleo et al. 2014)	Hydraulic conductivity range (m/day; Freeze and Cherry 1979)	Notes
Crystalline	L	6.7×10^{-3} (a)	1.0×10^{-7} – 1.0×10^{2} (as fractured and unfractured igneous rocks)	Plutonic and metamorphic, including sills, dikes, and near-surface plugs, chert, quartzite
Older volcanics	L	6.3×10^{-3} (b)		Generally pre-mid Miocene intermediate and felsic flows, pyroclastics, old tuffs. Generally mid-Miocene or older; in Nevada includes older than T3 (~ 17 Ma), in Arizona is 'mid-Miocene' or ~11 Ma. Presumed low-permeability.
Younger volcanics	H	1.9×10^{-1} (b)		Younger Miocene and Post-Tertiary volcanics (in Nevada, ~17 Ma; in Arizona, mid-Miocene or ~11 Ma). Includes unit Tba, a catchall for poorly characterized volcanics and basalt units, where local-scale maps did not distinguish better than Crafford (2007). According to Stewart (1980), Tba is 'mostly younger'. Presumed high permeability.
Older basalts	H	2.1×10^{-1} (b)	1.0×10^{-1}– 1.0×10^{4} (as permeable basalts)	In Nevada, older than T3 (~17 Ma). In Arizona mid-Miocene or ~11 Ma
Younger basalts	H	8.2×10^{2} (b)		In Nevada, younger than T3 (~17 Ma). In Arizona, younger than mid-Miocene (~11 Ma)
Other carbonate	L	1.3×10^{0} (a)	1.0×10^{-3}– 1.0×10^{0}	Carbonate isolated from known karstic aquifers; may be karstic but insufficient data to determine. In general in Nevada, includes any carbonate younger than Permian upper carbonate aquifer unit (as designated by Sweetkind et al. 2011). Also includes interbedded carbonate and siliciclastic units which probably have lower hydraulic conductivity values.
Carbonate in known karstic province	H		1.0×10^{0} – 1.0×10^{4}	In Nevada, includes units mapped as Lower and Upper Carbonate Aquifer Units (Sweetkind et al. 2011), pre-Mesozoic.
Coarse-grained sedimentary	H	2.7×10^{-1} (a)	1.0×10^{-4} – 1.0×10^{0}	Sandstone, conglomerate, breccia, known fractured quartzite
Fine-grained sedimentary	L	2.7×10^{-5} (a)	1.0×10^{-7} – 1.0×10^{-3}	Shale, mudstone, claystone, sinter and other hot spring deposits. In Nevada, includes Ts (tuffaceous sedimentary) units

Table 1 continued

Hydrolithologic unit	**Perm-eability class**	**Mean hydraulic conductivity (m/day; a=Gleeson et al. 2011, b=Comeleo et al. 2014)**	**Hydraulic conductivity range (m/day; Freeze and Cherry 1979)**	**Notes**
Undifferentiated indurated	Case-by-Case	5.3x10^{-4} (as sedimentary) (a)	-	Undifferentiated sedimentary, undifferentiated sedimentary with igneous. Often consists of interbedded shales and sandstone undifferentiated at mapped scale or of units defined broadly as terranes by Crafford (2007). Attempted to assign to H/L permeability class on case-by-case basis rather than U, but retained undifferentiated indurated in hydrolithologic classification to reflect uncertainty in designation.
Fine-grained unconsolidated	L	8.5x10-^{3} (a)	1.0x10^{-3} – 1.0x10^{1}	Playa deposits, known fine-grained floodplain deposits, loess, lakebed deposits
Till	L		1.0x10^{-6} – 1.0x10^{0}	Glacial units; generally rare throughout Pacific Southwest.
Coarse-grained unconsolidated	H	1.1x10^{1} (a)	silty sand: 1.0x10^{-2} – 1.0x10^{3} clean sand: 1.0x10^{1} – 1.0x10^{4} gravel: 1.0x10^{2} – 1.0x10^{5}	Dune deposits, known well-sorted sands, gravels
Older alluvium (except CA)	H			Younger and older alluvium differentiated on both Nevada and Arizona geologic maps; presumed lower permeability than younger alluvium as may be moderately cemented.
Younger alluvium (except CA)	H			Presumed high permeability; includes active stream channels. Note that California did not differentiate between older and younger alluvium "Younger alluvium" is thus the default for that state and there is no 'older alluvium.'
Undifferentiated unconsolidated	H	1.0x10^{-1} (a)		Mostly used in Arizona and California where units are too coarse to designate and do not fit alluvial well
Poorly sorted unconsolidated	H			Known colluvium, landslide
Undifferentiated	U	-	-	Mostly breccia where no further knowledge known; in Nevada Crafford (2007) assigns both Jurassic breccias and some young landslide deposits to breccias.
Water	W	-	-	Waterbodies as designated on original geologic maps

For the states of Arizona and California, we used the Preliminary Integrated Geologic Map Database for the United States, Western States v. 1.2 (Ludington et al. 2005 and references therein), a USGS effort to produce a unified digital geologic map of the United States from the 1:250,000 to 1:1,000,000 scale. These maps are based on the best available maps produced at the state level, but with uniform attributes and supplemental map unit, lithologic unit, and age-attribute tables that unify and supplement the data available in the original state-produced maps. Metadata available from the USGS website detail the individual references used to identify each unit, including reports and maps available at a more detailed scale. For Nevada, we used a newer, higher resolution state map (Crafford 2007) as the base for hydrolithologic classification.

Different philosophies have informed the production of statewide geologic maps and these differences maintain legacies in the updated maps. For example, units in California were defined by age rather than lithology in the earliest statewide effort at geologic mapping. This approach, despite wide recognition of its limitations, has held through the most recent update to the state map (Saucedo et al. 2000) and many lithologically distinct units may thus be mapped only as, for example, “Silurian-Ordovician” with no reference to actual lithology. Ludington et al. (2005) subdivided many units according to location and lithology to account for heterogeneities in a large and geologically complex state, but difficulties remain in characterizing certain age-defined units within the state of California. Similarly, in Arizona the best available geologic map is at a scale of 1:1,000,000 (Richard et al. 2000), which results in the lumping of many hydrologically-distinct units into a single grouped lithology, like “Jurassic sandstone and shales.” The scale of our map in Arizona is thus comparable to that of Gleeson et al. (2011), but we grouped many geologic units more conservatively into undifferentiated hydrolithologic categories. Finally, while the geologic map of Nevada is completed at a fine scale, Crafford (2007) favored assignments to often outdated terrane and formation names when grouping units, which did not always result in a clearly defined lithology.

In all states, hydrolithologic unit designations were first assigned based on the lithology of the geologic map without considering any further criteria. When the lithology was unclear from the state map, we consulted state and county maps, adjacent units, and Google Earth to guide our assignment to a hydrolithologic category. These assignments were then checked generally against the geologic history of the region, the Ground Water Atlas of the United States (Planert and Williams 1994; Robson and Banta 1995), and any groundwater modeling in the area or of similar units and adjusted accordingly. Our hydrolithologic units do not explicitly include the influence of structure or any consideration of the thickness of the geologic unit exposed at the surface. Likewise, while we use “younger” and “older” designations to suggest the likelihood of secondary decreases in permeability, secondary permeability is not explicitly addressed and may cause significant variations from the permeability estimated herein.

3. Hydostratigraphic Units: expansion from Comeleo et al. 2014

3.1 Unconsolidated Units

In recognition of state-to-state differences and in an effort to preserve the information available in the geologic maps, we expanded the unconsolidated categories of Comeleo et al. (2014) to allow some age and uncertainty distinctions. Comeleo et al. (2014), after Gleeson et al. (2011), includes categories for 1) coarse-grained unconsolidated, 2) fine-grained unconsolidated, and 3) unconsolidated [undifferentiated]. We also include 1) poorly-sorted unconsolidated, which includes known colluvium and landslide deposits, 2) till, which, though minor in the Pacific Southwest, typically has very low permeability (Freeze and Cherry 1979), and categories for 3) older alluvium, and 4) younger alluvium. Not all states designate a younger vs. older alluvium and, in practice, the alluvial categories can be lumped with our unconsolidated (undifferentiated) units when designating a permeability classification.

However, older alluvium has a greater likelihood of greater compaction and/or cementation, thus decreasing its permeability relative to younger alluvium. We retain the distinction to allow for potential broader future use of the hydrolithologic map in states where the distinction was originally made in geologic mapping. The California geologic map (Ludington et al. 2005) did not distinguish between younger and older alluvium; all known alluvium in California is thus coded as younger alluvium and no age distinction is implied.

Additionally, the geologic map of California is somewhat unusual in having a strongly skewed polygon area distribution; while the state is mapped at a scale of 1:750,000 (average polygon size 34 km^2), several unconsolidated units are very large (maximum 55,120 km^2). We assigned these units to the category "undifferentiated unconsolidated", to reflect the greater uncertainty in their designations and the fact "that at the county scale these units show features like playas and other fine-grained units. As a result, the Great Valley and valleys in the Basin and Range province of California contain a large volume of undifferentiated unconsolidated sediments. We also followed this strategy in Arizona, where similar uncertainty in the Basin and Range provinces precluded assignment to a known alluvial (and thus coarse-grained) category.

3.2 Carbonate Units

The hydrogeology of carbonate rocks is the most variable of any broad rock group, with more than 60 processes and controls influencing porosity and permeability (Brahana et al. 1988). Carbonates may operate on one extreme as nearly impermeable confining layers, and at the other extreme as aquifers so permeable they are governed by the hydraulics of open channel flow. As a result, generalizations about the permeability of carbonates are nearly impossible and aquifer characterization requires extensive data. Recognizing this lack of data, Gleeson et al. (2011) characterized all carbonate units as a single category and calculated a mean permeability of 1.3 m/day; however, as discussed above, the estimated permeability of carbonate units both showed a dependence on scale and had outliers in the spread of permeability values, indicating that the single grouping was an inappropriate metric. Because carbonates are not common in the Pacific Northwest, Comeleo et al. (2014) did not attempt to further categorize them and applied the Gleeson et al. (2011) values to the limited exposures present.

In contrast with the PNW, carbonate units form much of the bedrock exposures across the Basin and Range of Nevada and Arizona and are known to host large aquifers (Prudic et al. 1995, Sweetkind et al. 2011). We thus desired to provide a better characterization of carbonate units and separated them into two categories: 1) carbonates in known karstic provinces and 2) other carbonates. In general, carbonate units older than the Eocene were assigned to the high-permeability karstic category, reflecting the potential for a longer history to allow for greater dissolution and in keeping with known aquifer units in Nevada. Younger carbonate units (e.g., lacustrine carbonates in Nevada) were assigned to the "other carbonate" category. This unit, while considered to be lower permeability in our permeability classes, is actually an effort to quantify uncertainty in karst development and reflects an absence rather than presence of knowledge.

3.3 Volcanic Units

Similar to carbonate units, the permeability of volcanic units can vary by up to 13 orders of magnitude (Davis 1969). Development of primary and secondary permeability is dependent on composition, cooling history, age, climate, and thickness. Broadly speaking, basalts and other lava flows tend to host productive aquifers due to both primary permeability in the flow tops and because the layered nature of multiple flows allows for significant groundwater movement along the interflow areas (Wood and Fernandez 1988). However, older volcanics tend to become more impermeable as a result of clay formation from weathering, compaction, and mineral deposition, and mid-Cenozoic and older volcanic rocks are often impermeable (Davis 1969). As discussed above, Comeleo et al. (2014) broke out the Gleeson et al. (2011) original volcanic unit into older vs. younger and basaltic vs. volcanic (i.e., non-basaltic) categories to better match known behaviors in the Pacific Northwest. They set a younger vs. older boundary based on observed behaviors in the Oregon Cascades between volcanics with a natural break at about 11 mega-annum (Ma) (Ingebritsen et al. 1992).

Using these groupings as precedent, when building hydrologic permeability maps of the Pacific Southwest, we retain "older" vs. "younger" and "basalt" vs. "non-basalt volcanic" designations, but redefine them according to the geologic history of the given region. We retain it for two reasons: 1) geologic maps tend to be built with an emphasis on geologic provenance and age, rather than textural differences, and our groupings are thus somewhat dictated by pre-assumed age similarities, and 2) in the absence of extensive site-specific knowledge required to properly characterize many volcanic units, age represents a best guess at permeability. However, when using the hydrolithologic maps, it should be remembered that this designation is actually an imperfect shorthand for "generally impermeable" vs. "generally permeable."

In Arizona, non-basalt volcanic units are grouped similarly to the Pacific Northwest, with an age break defined as 'middle Miocene,' generally accepted to be around 10-12 Ma. This is based on the categorization employed by the geologic map, which breaks its volcanic groupings at the middle Miocene.

In Nevada, much of the surface geology is dominated by Cenozoic volcanism (Stewart 1980; Crafford 2007). Volcanism began about 43 Ma and continued until about 17 Ma, becoming more silicic and voluminous into the Miocene and depositing thick units of ash-fall tuffs across the state. At about 17 Ma, volcanism abruptly became mafic and/or bimodal, depositing basalt and thick ashflow units in a thick band across the northern and southwestern portions of the state. Volcanism peaked about 11 Ma and waned until about 6 Ma. Volcanic activity has been scattered and chiefly mafic since the late upper Miocene, including some activity into the Pleistocene-Holocene.

We initially separated younger non-basaltic volcanics and basalt from older at 6 Ma, in keeping with a shift from voluminous Cenozoic volcanism to isolated, typically basaltic and locally-sourced Quaternary volcanism (Stewart 1980). This break point fit both that previously employed in the Pacific Northwest (mid Miocene, ~11 Ma; Comeleo et al. 2014), and the interpreted geologic history of Nevada, which separates Quaternary volcanism from older, more altered units. However, this grouping assigned the well-studied, tuffaceous aquifers in the vicinity of the Nevada Test Site (Sweetkind et al. 2011; Zyvoloski et al. 2003) to an impermeable classification. We thus reclassified volcanic units that dated to about 16-17 Ma as "young." Although the older of these likely have reduced permeability, this grouping allows us to account for the limited data available when assigning permeability values.

Notable to the interpretation of non-basaltic volcanic units across the Pacific Southwest, tuffs are particularly difficult to designate without site-specific knowledge. The permeability of tuffs is typically extremely heterogeneous at both a local and regional scale and vary according to their age and degree of welding (Wood and Fernandez 1988). Unwelded and older tuffs tend to act as confining layers due to poor primary permeability or the development of zeolitic clays from weathering; younger welded tuffs, however, can form regionally-important aquifers as a result of extensive fracture networks. On most geology maps, the degrees of welding or weathering are not typically noted or are noted as 'ashflow and ashfall tuffs.' As a result, like carbonate and undifferentiated lithologies (e.g., unconsolidated), they are resistant to permeability classification based on lithology. In the absence of extensive local studies, which do not exist in many areas and are out of the scope of a mapping effort of this scale, distinguishing by age is our best effort to provide a first-order assessment of the potential reduction in permeability due to weathering-produced zeolitic clays. However, we acknowledge that many of these classifications could be in error.

Additionally, when interpreting the hydrolithologic map it is important to consider the high degree of anisotropy typical of basalts, which tend to have very high horizontal permeability but very low vertical permeability (e.g., in the Wanapum flow of the Columbia River Basalt Group, vertical anisotropy was estimated at 500:1; Kahle et al. 2011). As a result, while the horizontal permeabilities are very high, the basaltic plateaus tend to be groundwater discharge areas, with recharge occurring near the plateau margins (Whitehead 1994).

Finally, in California, the volcanic groupings were not consistent across the state; many units were undated and groupings encompassed a huge variety of volcanic units, not differentiating between tuffs, basalts, et cetera. We assigned volcanic units to a hydrolithologic classification on a case-by-case basis using dates from the literature where available or the context of geologic history provided by the map.

3.4 Undifferentiated Units

In general, undifferentiated units were created to indicate areas where data was insufficient to further classify a geologic unit into a definitive hydrolithologic unit. In particular, the "indurated, undifferentiated," class was created to reflect the coarse resolution geologic mapping of Arizona, where some units include both permeable and impermeable lithologies (e.g., unit JTr, which includes both rhyolite and sandstone or unit Js, which includes both sandstone and siltstone in confining layer-aquifer pairs).

3.5 Permeability classification

As discussed above, when developing the Oregon HL system, Comeleo et al. (2014) and Wigington et al. (2013) empirically designated three permeability classes to best represent the spread of values across the state of Oregon. However, these classifications were collapsed into a simpler high/low system with a hydraulic conductivity threshold value of 8.5×10^{-2} m/day when the system was expanded to the Pacific

Northwest (Leibowitz et al. 2016). Using the average hydraulic conductivity values calculated by Gleeson et al. (2011), with additional calculations for the expanded volcanic classifications, this binned most crystalline rock and fine-grained sediments as low permeability, and carbonates, younger extrusive igneous, and most unconsolidated units as high permeability.

Our assignment of hydrolithologic units to high vs. low permeability classes is consistent with that of Comeleo et al. (2014) and Leibowitz et al. (2016). However, we note that while the average permeability values calculated by Gleeson et al. (2011), with amendments by Comeleo et al. (2014), guided our assignment of hydrolithologic units to high vs. low permeability classes, the assignments were made qualitatively, not quantitatively. This does not invalidate the previous determination of an appropriate threshold value, which we still believe is appropriate (as discussed further in Section 4), but is meant to address concerns that an average permeability value for a single hydrolithologic unit, particularly one derived from calibrated groundwater models, is an over-interpretation of available data.

4. Discussion: Assumptions and Limitations

4.1 Hydrostratigraphy

Interpretation of hydrologic parameters from the porosity and permeability of a given lithology has been the subject of nearly a century's effort (e.g., Meinzer, 1923, 1927, 1942, Toth 1962, 1963; Maxey 1964; Davis 1969; Bear 1972; Freeze and Cherry 1979, Todd 1983; Heath 1984). However, while geology and hydrogeology are integrally related, the nature of that relationship is unpredictable and the data required to estimate that relationship typically unavailable. While we believe the maps developed herein are based on the best available data and in keeping with efforts to address permeability at the regional and global scale (e.g., Gleeson et al. 2011; Maxwell et al. 2015), several important caveats highlight the need both for better field data and better approaches to determining permeability.

As Gleeson et al. (2011) note, assigning permeability values on the basis of mapped surface geology requires three key assumptions: 1) that "each hydrolithology has a representative, scale-independent, regional-scale permeability", 2) "hydrolithologies can be paired with lithologies" and 3) "lithology maps represent the geology of the shallow subsurface accurately and consistently."

Gleeson et al. (2011) statistically show that their regional-scale, model-derived permeability values appear to be reasonable representations of global permeability. Their calculated average permeabilities fall mostly within the commonly accepted ranges of local-scale permeability as grouped by lithology (e.g., Freeze and Cherry 1979). Additionally, the calculated permeabilities pass statistical tests for log-normality, as is generally accepted for the distribution of permeability in a given geologic unit (Davis 1969, Freeze and Cherry 1979), and most of the geometric mean permeabilities plotted against the length of unit modeled do not show systematic trends, indicating independence from scaling effects. However, not all the groupings meet their statistical criteria for scale independence and normality. As Gleeson et al. (2011) note, the permeability values for carbonates fail normality tests and show a dependency on scale. Additionally, the broad "unconsolidated" [undifferentiated] grouping fails all normality tests, suggesting that it does not represent a real, physically-based permeability category (an unsurprising result from an undifferentiated unit).

Implicit in Gleeson and colleagues' (2011) assumption of the existence of representative, scale-independent permeability values is the argument that they can be accurately determined using calibrated groundwater models. While groundwater models undoubtedly provide a powerful tool to understand hydrologic behavior in a regional (and increasingly global) setting, the direct relationship between calibrated model parameters and lithologically-constrained permeability bears further investigation.

As discussed by Seaber (1988), geologic mapping typically considers the solid characteristics of the lithology in question, while hydrogeology is interested in the void space within it. Hydrogeologic designations based on lithology must thus consider a number of other parameters, most of which are difficult to measure and vary on multiple scales: the degree of primary permeability, secondary weathering and/or fracturing, anisotropy, heterogeneity, faulting, and others. As Davis (1969) notes, "the influence of rock type on gross permeability of rocks is not as large as one might expect….Truly large differences in well yields between areas having different rock types are usually due to differences in the histories of weathering and/or of fracturing of the rock rather than to lithologic differences. As an example, rocks in a thrust sheet may be more than 100 times more permeable than similar rocks in an adjacent autochthonous mass, yet in another region the two rock types may have nearly identical permeabilities." Thus, while groundwater models may be calibrated and verified to provide reasonable representations of hydrologic behavior in their region of interest, the permeability in question is most likely an integration of many factors influencing regional permeability and is not directly correlated to the primary porosity or permeability of the lithologies in question.

Additionally, groundwater models are frequently revised with the addition of new data, resulting in radically different parameter estimations. For example, K. Halford (personal communication) notes that models from the Death Valley Regional Flow System (Belcher 2004) and Yucca Mountain (Zyvoloski et al. 2003) provided 20% of the regional hydraulic conductivity estimates calculated by Gleeson et al. (2011), but a subsequent internal review by the USGS has determined these estimates to be demonstrably wrong. The Death Valley Regional Flow System and Yucca Mountain regions are characterized by voluminous tuff deposits, which, as discussed in Section 3.3., are notoriously difficult to characterize (Wood and Fernandez 1988). The permeability of tuffs are typically heterogeneous at both a local and regional scale and vary according to their age and degree of welding, requiring extensive field characterization to assess. As a result, tuffs do not fit well into a classification scheme based on lithology and decades-long, multi-agency efforts, such as those undertaken by the Death Valley Regional Flow System and Yucca Mountain projects, and estimates of their permeability may result in flawed efforts.

We implicitly consider the importance of secondary influences on permeability in several ways: first, the distinction between older and younger units of similar lithology assumes a general reduction in primary permeability with age as a result of secondary mineralization or cementation. In contrast, age tends to increase the permeability of carbonate units due to dissolution, often leading to distinctive landforms and prominent springs. For this reason, we classified carbonate units in known karstic provinces, which tend to have extremely high permeability, separately from 'other' carbonates, where data were not available or no karstic characteristics were identified and permeability was thus considered low. However, our system does not explicitly consider the influence of structure on permeability, which is too difficult to determine in the absence of better data. As a result, low-yield, fractured-rock aquifers are probably missed by our permeability designations and our permeability estimates in many crystalline environments are likely to be underestimates.

Finally, the assumption that a two-dimensional geologic map can accurately represent the parameters of a three-dimensional aquifer is inherently problematic. The hydrostratigraphic and permeability index maps are based on the use of lithology as an imperfect proxy for permeability. However, in the context of the HL classification, permeability is itself an imperfect proxy for aquifer storage. The simplified high vs. low classification provides a first-order conceptual model for defining regions where the hydrographic response to climate is mediated by significant groundwater storage vs. flashy systems with shallow flow and little storage (Tague and Grant 2004, Tague and Grant 2009, Safeeq et al. 2013). As such, a better metric than permeability would be transmissivity, which is the hydraulic conductivity multiplied by the thickness of the aquifer. Transmissivity is thus a measure of horizontal flow per unit width under a unit aquifer hydraulic gradient, as opposed to strictly the capacity of the matrix to transmit water. However, its estimation requires either 1) a knowledge of aquifer thickness in addition to hydraulic conductivity, or 2) data derived from aquifer tests.

These data can be derived from extensive drilling, geologic characterization, aquifer pump tests, and modeling, but cannot be reliably estimated in the absence of abundant field data. An extensive metadata analysis might be able to compile reasonable estimates of aquifer transmissivity for our multi-state region, but the results would be heavily skewed toward populated, generally wet areas where human populations are large and groundwater is abundant enough for beneficial use. An investigation of this scale would be of great importance to the hydrogeologic community but is beyond the scope of this project. Indeed, the problem of the third dimension and the large-scale mapping of groundwater parameters is considered a 'grand challenge of hydrology' that is the subject of much active research (Gleeson and Cardiff 2013, Maxwell et al. 2015).

4.2 Aquifer permeability classes: high vs. low

As discussed in Sections 1.2 and 3.5, the classification of estimated aquifer permeability values into bins has evolved through the HL project. For the PNW, a threshold hydraulic conductivity value of 8.5×10^{-3} m/day was selected to demarcate high vs. low. This value is approximately consistent with criteria developed by Payne and Woessner (2010) to separate low flow from limited or no flow aquifers. As part of a groundwater classification tool that they developed to guide hydrologic assessments (similar in spirit to the HL project), Payne and Woessner (2010) collected over 20,000 individual well records and aquifer property descriptions from the western United States and grouped them into quartiles according to hydraulic conductivity, transmissivity, specific yield, and specific capacity, then empirically evaluated groupings against previously published values for aquifer productivity (e.g., Bear 1979, Heath 1984) to develop "flow potential" classes. These aquifer flow potential classes, as applied to surface water-groundwater connectivity, are given in Table 2.

Table 2: Flow potential classes and aquifer flow narrative description test as defined by Payne and Woessner (2010). By considering Codes A, B, and C to consist of high flow potential and Code L to consist of low flow potential, these bins are consistent with the classification value applied by Leibowitz et al. (2016)

Code	Flow Class Potential	K (m/day)	Aquifer Flow Narrative Description Test
A	High flow	$>7.6\times10^{1}$	May provide significant groundwater discharge to large streams and rivers
B	Intermediate flow	$>8.0\times10^{-1}$ – 7.6×10^{1}	May provide significant groundwater discharge to small and moderate size streams and rivers
C	Low flow	1.0×10^{-2} - 8.0×10^{-1}	Limited groundwater discharge potential except for small streams and wetlands
L_f	Limited or no flow	$<1.0\times10^{-2}$	Generally not used for any type of water supply and provide little or no groundwater discharge to surface water.

Payne and Woessner (2010) emphasize that these aquifer flow potential classes are partitioned narratively, not numerically. Similarly, we emphasize again that our flow classes are defined qualitatively and that numerical values of estimated permeability have been used as guides only. However, Payne and Woessner's (2010) qualitative descriptions are guided by a statistical analysis of 20,000 well tests and aquifer property descriptions, and we thus credit their accompanying values as evidence of physically-meaningful breaks.

Our analysis is concerned with hydrologic behavior in the context of climate adaptability and groundwater-surface water interactions. We thus consider the break between low flow and limited or no flow to be the most meaningful and retain that value as a guide in making our assignments of hydrolithologic units to a high vs. low permeability class. However, studies with different interests, such as potential contaminant movement or beneficial aquifer use, may choose to define the high/low class breaks differently. We hope that by providing the hydrolithologic map, in addition to the aquifer permeability class and HL map, these datasets may be put to a broader use within the scientific community.

4.3 Scale

Both the hydrolithologic unit and aquifer permeability index maps were produced at the scale of the base geologic map used in a given state, but the classifications should be considered an interpretation of the most likely average permeability as determined from the lithologic unit description, other available maps and reports, and any groundwater models available in a given region. The maps were designed for application to NHDPlusV2 -derived HLUs (McKay et al. 2012, Leibowitz et al. 2016) averaging approximately 60 km^2. The qualitative estimates of hydrolithologic characteristics and permeability should be applied only at a regional scale and not considered representative of conditions at a local one, as this may lead to inaccurate assessments that cannot be resolved within the scope of our investigation.

For example, the characterization of Death Valley varies across state lines and much of the California side is categorized as high permeability, despite prominent playa conditions and core data measuring low permeability (K. Halford, USGS, personal communication). The geologic map of Nevada (Crafford 2007) maps playa sediments specifically; we were thus able to assign playa areas in Nevada to a low permeability classification. However, the source map from California does not make this distinction and the region surrounding Death Valley (and other valley fill sequences in the California Basin and Range province) is grouped into a broad Quaternary Alluvium unit. This is reflected in our categorization of this area as "undifferentiated unconsolidated" (as opposed to another category like "older alluvium"; these units were in fact one of the drivers to expand the classification system over that of Comeleo et al. 2014). Because most undifferentiated unconsolidated units in the mapped areas consist of valley fill sequences, which are typically coarse-grained, unconsolidated units that host groundwater, and the relative area of fine-grained playa sediments included in these mapped geologic units is small, we made the decision to assign undifferentiated unconsolidated hydrolithologic units to a high permeability classification.

Flint et al. (2013) make a similar categorization decision, but it would ultimately improve our map to be able to segregate California playas into their own classifications. Unfortunately, doing so would require us to hand-digitize the existing better-scale geologic maps of California, which are not currently available in digital form. The time required for that endeavor puts it beyond the scope of the HL project.

5. Conclusions

The aquifer permeability map is an intrinsic dataset required for the creation of the greater hydrologic landscapes map and was designed specifically for that purpose. While developed using a semi-quantitative approach, the hydrolithologic units that were assigned and the aquifer permeability classifications should be considered qualitative. They represent a conceptual model of the potential importance of groundwater in a given hydrologic landscape assessment unit and can, in consideration with other aspects of the watershed, serve as a foundation to develop conceptual understanding of the groundwater interactions in a given hydrologic unit.

We believe this dataset, while qualitative and undoubtedly of a first-order approximation, fills an important data gap in providing a regional-scale map of permeability that does not, to our knowledge, currently exist. With appropriate caveats and an understanding of the methodology behind its creation, the aquifer permeability map presented here can be used as a stand-alone dataset, in particular to guide input values for regional-scale groundwater modeling.

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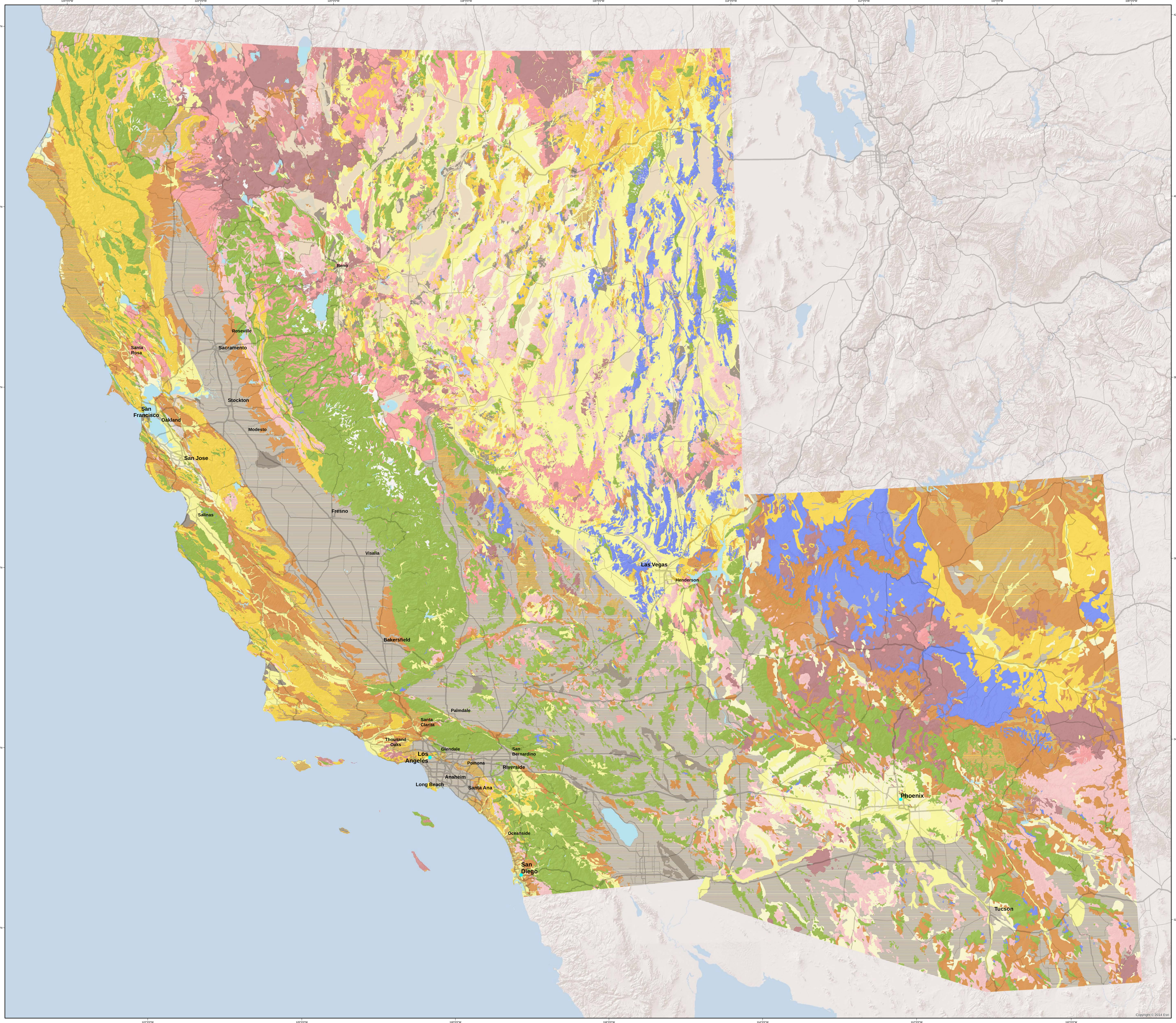
Pacific Southwest Hydrolithologic Categories



Hydrolithologic Categories

Crystalline	Younger Volcanic	Coarse-Grained Unconsolidated	Sedimentary, Undifferentiated
Older Volcanic	Older Basalt	Poorly-Sorted Unconsolidated	Undifferentiated
Other Carbonate	Younger Basalt	Unconsolidated, Undifferentiated	Water
Fine-Grained Sedimentary	Karstic Carbonate	Older Alluvium	
Fine-Grained Unconsolidated	Coarse-Grained Sedimentary	Younger Alluvium	
Till			

Lakes and Rivers

Roads

N

SCALE 1:1,500,000

0 37.5 75 150 225 300

Kilometers

Universal Transverse Mercator Projection, Zone 11 N

Map Production Date - November 2014

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LIMITATIONS ON USE: This map is not intended to be used or displayed at any scale larger than 1:1,500,000

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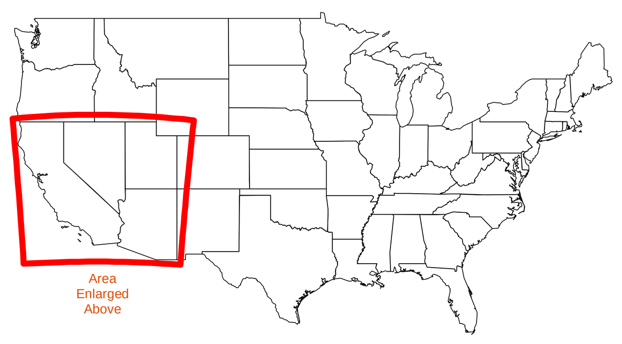
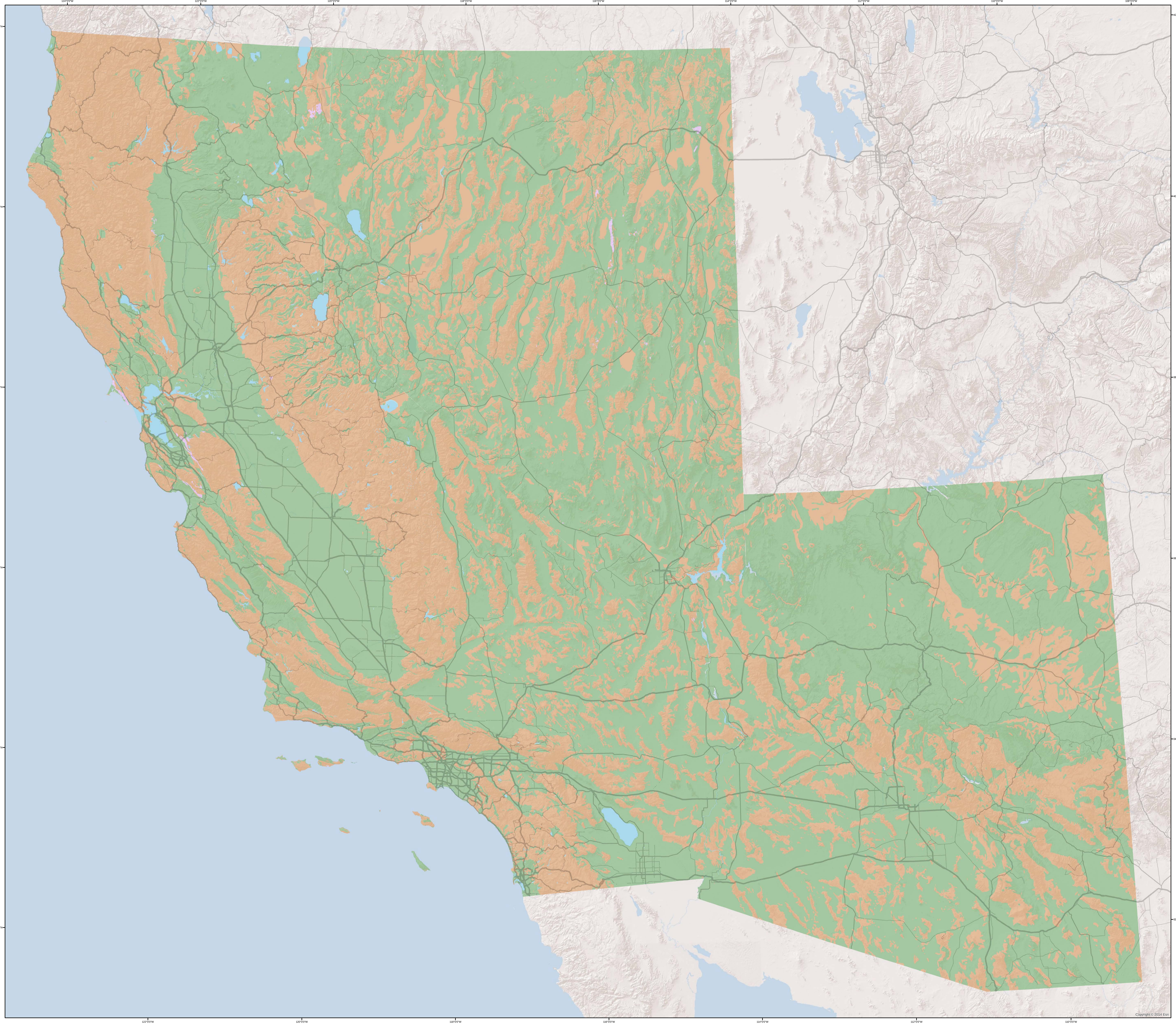


Pacific Southwest Aquifer Permeability Index



Hydrolithologic Categories

- High
- Low
- Unknown
- Water
- Lakes and Rivers
- Roads

N

SCALE 1:1,500,000

0 1,250 2,500 5,000 7,500 10,000
Kilometers

Universal Transverse Mercator Projection, Zone 11 N

Map Production Date - November 2014

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MAP PRODUCTION AND ANALYSIS: L.E. Stratton

MAP DATA: Ludington, S., Moring, B.C., Miller, R.J., Stone, P.A., Bookstrom, A.A., Bedford, D.R., Evans, J.G., Haxel, G.A., Nutt, C.J., Flyn, K.S. and M.J. Hopkins, 2007. Preliminary integrated geologic map databases for the United States. Western States: California, Nevada, Arizona, Washington, Oregon, Idaho, and Utah. United States Geologic Survey Open-File Report 2005-1305. Version 1.3. [CA and AZ]

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LIMITATIONS ON USE: This map is not intended to be used or displayed at any scale larger than 1:1,500,000

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