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Creation of a Digital Aquifer Permeability Map for the Pacific Northwest

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Abstract

Hydrologic classification systems can provide a basis for broadscale assessments of the hydrologic functions of landscapes and watersheds and their responses to stressors such as climate change. One of the greatest challenges to this effort is obtaining consistent aquifer permeability information across states and regions. Here we review the rationale and approach for creating digital hydrolithology and aquifer permeability maps for the Pacific Northwest. The maps were created using existing digital state geologic maps and accompanying descriptions of lithologies. The aquifer permeability map allows the identification of areas where shallow subsurface vs. deep groundwater flows and the loss or gain of water through groundwater export or import may be important. This approach provides a consistent method for creating digital statewide representations of aquifer permeability across the United States which can be used in evaluating regional hydrologic vulnerability due to climate change.

Introduction

There is a growing need for hydrologic classification systems that can provide a basis for broadscale assessments of the hydrologic functions of landscapes and watersheds and their responses to stressors such as climate change. We developed a hydrologic landscape (HL) classification approach (Wigington et al., 2013), based on concepts from Winter (2001), that described major factors of climate-watershed systems that control the hydrologic characteristics of watersheds in Oregon. Major components of the classification included indices calculated from statewide maps of annual climate, climate seasonality, aquifer permeability, terrain, and soil permeability. We have used bias-corrected and statistically downscaled (BCSD) climate simulations drawn from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) to examine streamflow vulnerability associated with possible changes in Oregon HLs induced by projected climate change (Leibowitz et al., 2014). Currently, we are extending the Wigington et al. (2013) hydrologic landscape classification and climate change evaluation approach (Leibowitz et al., 2014) to the entire three-state Pacific Northwest (PNW) region (Oregon, Washington, and Idaho). One of the greatest challenges to this effort is obtaining consistent aquifer permeability information across the entire PNW region. In this document, we review the rationale and approach for creating a digital hydrolithologic map for the PNW (Figure 1). This was then used to create a digital aquifer permeability map for the PNW (Figure 2) for use in evaluating regional hydrologic vulnerability due to climate change.

Aquifers have traditionally been considered to be saturated geologic units capable of transmitting sufficient amounts of water under ordinary hydraulic gradients to support water production wells. In recent years hydrologists have recognized the need for a broader definition that acknowledged the importance of low-flow geologic formations to aquatic ecosystems. For example, Payne and Woessner (2010) noted the importance of aquifers with varying flow rates on streams and proposed a classification of aquifer flow systems that ranged from high flow to low flow, where low flow aquifers may serve as important sources of discharge to small streams and wetlands. In this report, we have adopted the aquifer definition by Winter et al. (1998) which states that aquifers are the permeable materials (e.g., soil, rock) through which groundwater flows.

Oregon Digital Aquifer Permeability Map

The Oregon HL classification (Wigington et al., 2013) required a digital statewide aquifer permeability map that could be used in a Geographic Information System (GIS) to represent groundwater behavior. At the time, comprehensive information on aquifer depths and their spatial variability was not readily available in map form, especially for areas where groundwater was currently not important for drinking water storage and supply. We felt that aquifer permeability 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 (e.g., Tague and Grant, 2004).

The U.S. Geological Survey National Atlas map of principal aquifer groups (U.S. Geological Survey, 2001; Figure 3) was the only statewide digital aquifer map available for Oregon. We determined that the mapping units in the national principal aquifer map were too large compared to HL assessment units (5,660 assessment units in Oregon with an average area of 44 km^2) and important aquifer types in parts of the state were not represented (Tague and Grant, 2004). Since an acceptable digital GIS dataset of aquifer permeability was not available for Oregon, we created one from existing paper aquifer unit maps for eastern Oregon (Gonthier, 1985) and western Oregon (McFarland, 1983). Aquifer subunit descriptions and estimated hydraulic conductivity values (Gonthier, 1985 and McFarland, 1983) for 18 different aquifer subunits from the paper maps were mapped onto a digital state geologic map (Walker et al., 2003; Figure 4). We combined 18 aquifer subunits into 7 aquifer units based on similarities in lithology and hydraulic conductivity (Figure 5). Based on the distributions of hydraulic conductivity values in the state, we created three aquifer permeability classes (Table 1 and Figure 6): (1) low permeability (estimated hydraulic conductivity $\leq$1.5 m/day), (2) moderate permeability (estimated hydraulic conductivity >1.5 and $\leq$3.1 m/day), and (3) high permeability (estimated hydraulic conductivity >3.1 m/day). Hydraulic conductivity values were not used for quantitative characterization of groundwater flow, but simply as a guide to combine mapped geologic units into generalized high, moderate, and low geologic permeability classes.

For units with low aquifer permeability (L), downward movement of water will likely be restricted at the soil-bedrock interface and waters will move along the bedrock interface to stream networks (Tromp-van Meerveld et al., 2007) with limited movement of water to deep groundwater reservoirs. Conversely, units with high aquifer permeability (H) typically will have water movement through deep groundwater flow paths (Tague and Grant, 2004). Mapped units with moderate (M) aquifer permeability would be expected to have movement of water to deep groundwater that is intermediate between high and low aquifer permeability units.

Expanding the Aquifer Permeability Map to Washington and Idaho

Using the HL approach to evaluate regional hydrologic vulnerability due to climate change requires a consistent method for creating digital state aquifer permeability maps, when none exist, from digital state geologic maps. Here we use a system for the classification of geologic units in state geologic maps into hydrolithologic categories based on a modification that we have made to the Gleeson North American classification system (Gleeson et al., 2011).

Gleeson et al. (2011) used representative permeabilities of hydrolithologies to map the distribution of near-surface (on the order of 100 m depth) permeability. This approach has great potential to allow the estimation of aquifer permeability in locations without statewide aquifer permeability data. Based on our experience with the Oregon aquifer permeability characteristics (Wigington et al., 2013), however, we recognized that the Gleeson et al. (2011) approach did not adequately describe all of the aquifer characteristics in Oregon. We modified the nine-category Gleeson North American classification system (Figures 7 and 8) by subdividing the volcanic category into four categories: older and younger volcanics, and older and younger basalts. In Oregon, volcanic rocks can range from high permeability (younger volcanics) to low permeability (older volcanics). Permeability in basalt formations can be highly variable but is generally considered to be high. Permeability is high in young, relatively unaltered volcanic material erupted from Pleistocene to Holocene-age volcanoes (Conlon, et al., 2005) due to vertical fractures and cracks. These vertical fractures can fill with fine-grained materials in older deposits resulting in lower permeability. Basalts are distinct from other volcanic rocks in terms of the characteristics which govern the mobility of lava flow. Basalts contain the least amount of silica, erupt at the highest temperature, and have the lowest viscosity, allowing basalt lava to move down gentle slopes easily. Basalts are hydrogeologically unique due to their low vertical conductivity combined with distinct flow tops, bottoms and interflow zones that have high horizontal conductivity.

Starting with Oregon, descriptions of lithologies accompanying the state geologic map were used to classify geologic units into 12 hydrolithologic categories (Figure 9). High permeability young volcanics and basalts were defined as upper (late) Miocene (5 Ma) to mid-Miocene (11 Ma). Mid-Miocene and older basalts were also classified as high permeability. Low permeability older volcanics were defined as older than mid-Miocene. We used combined hydrolithologic categories (sedimentary and unconsolidated) when there was insufficient grain size information to classify as either fine-grained or coarse-grained. These combined categories have permeability values intermediate between the fine-grained and coarse-grained permeability values. We visually inspected and compared digital and paper maps of the aquifer groups derived from the published Oregon aquifer unit maps (McFarland, 1983; Gonthier, 1985) versus the hydrolithologic categories. We noted approximately 20 areas with discrepancies, evaluated them for inconsistencies or disagreements in interpreting descriptions of local-scale lithologies, and reconciled differences in the final map of hydrolithologic categories.

Once we were satisfied with the characteristics of the Oregon hydrolithologic category map (Figure 9), we applied this approach to the Washington (WA DNR, 2005) and Idaho (Johnson and Raines, 1995) state geology maps to produce the three state hydrolithology map (Figure 1). We note that the Washington state geologic map was produced with a much smaller minimum mapping unit than the Oregon and Idaho maps, which were produced at similar resolutions. In Idaho and Washington, statewide digital aquifer permeability maps were not available for evaluating our hydrolithologic category maps. Instead, we compared our maps with the U.S. principal aquifers map (Figure 3) and the nine-category Gleeson North American hydrolithologic map (Figure 7) obtained from the author. We noted differences in approximately 38 map units in

Idaho and 55 map units in Washington. These differences were evaluated and reconciled in the Idaho and Washington hydrolithologic category maps. In Idaho, the majority of differences between non-volcanic classes in the Gleeson classification versus our classification were due to differences in grain size determination for unconsolidated and sedimentary rocks. In Washington, the majority of differences were due to inconsistent classification of metaigneous, metasedimentary, and metavolcanic rocks. In our classification, all intrusive (plutonic) igneous rocks as well as all metamorphic, metaigneous, metasedimentary, and metavolcanic rocks were classified as low permeability crystalline rocks. Finally, we defined High and Low permeability classes based on similarities in lithology and hydraulic conductivity values from Table 2 in order to produce the PNW aquifer permeability map (Figure 2).

Data Limitations and Assumptions

There is significant difficulty in generalizing site specific hydrogeologic information to create statewide maps of aquifer permeability. Vertical and horizontal heterogeneity and large areas lacking site-specific permeability data can lend error and uncertainty to broad-scale categorizations. However, regional-scale research and planning often requires the development of statewide representations of aquifers. Several assumptions were made during the production of the Pacific Northwest aquifer permeability map (Figure 2) and, depending on how the map is used, certain limitations may apply.

The permeability map assumes that 1) each hydolithologic category has the same permeability within the region (Table 2); 2) there is a relationship between mapped geologic units and the assigned hydrolithologic category; and 3) state geologic maps are an accurate and consistent representation of subsurface and surficial geology. Though we used estimated hydraulic conductivity values mainly as a guide to assign each hydrolithologic category into a high or low permeability class, we note that these values are only valid if the geologic material is saturated and that unsaturated permeabilities can be much lower.

Conclusion

Development of the Wigington et al. (2013) HL maps beyond Oregon requires digital representations of annual climate, climate seasonality, aquifer permeability, terrain, and soil permeability. Since annual climate, climate seasonality, terrain, and soil permeability can be derived from nationally available datasets (Wigington et al., 2013), the main bottleneck in expanding HL mapping into other states has been the lack of digital statewide aquifer permeability maps. Statewide maps showing the approximate extent of major aquifer units are available for Oregon (McFarland, 1983; Gonthier, 1985), but most states do not have such maps. The modification of the Gleeson et al. (2011) approach allows us to develop digital aquifer permeability maps from lithologic descriptions using state geology maps. This provides us with a consistent method for creating digital statewide representations of aquifer perrmeability across the United States. These generalized aquifer permeability maps allow us to identify areas where shallow subsurface vs. deep groundwater flows and the loss or gain of water through groundwater export or import may be important.

Digital copies of the Pacific Northwest hydrolithologic category map and aquifer permeability map can be obtained by contacting R. L. Comeleo (comeleo.randy@epa.gov)

Acknowledgements and Disclaimer

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Table 1. Oregon aquifer subunits, groups and permeability classes based on field measurements of hydraulic conductivity (K, m/d) values from Gonthier (1985) and McFarland (1983).

Aquifer Subunit **Hydraulic Conductivity Range and (Median)**	**Aquifer Group** **(Hydraulic Conductivity Estimate)**	**Permeability Class** **(Hydraulic Conductivity Estimate)**
West Cascade Volcanics 0.031 – 3.1 (0.31) Coast Range Rocks 0.0031 – 3.1 (0.24) Older Volcanics 0.0031 – 0.31	Older Volcanic (0.31)	Low (≤1.5)
Klamath Bedrock 0.031 – 3.1 (0.61) Igneous and Metamorphic <0.0031 – 0.31	Igneous and Metamorphic (0.61)	
Columbia River Basalt 0.031 – 9.1 (1.5) Basalt 0.31 – 3.1	Basalt (1.5)	Moderate (>1.5 and ≤3.1)
Klamath Granitic Saprolite 1.5 – 6.1 (3.1)	Klamath Granitic Saprolite (3.1)	
Basin-fill and Alluvial 7.6 – 46	Basin-fill and Alluvial (15)	High (>3.1)
Sedimentary – Southeast (no data) Sedimentary – Wasco County 3.1 – 15 Sedimentary – Hermiston-Ordnance 91 – 305 Sedimentary – Grand Ronde Valley 3.1 – 31 Sedimentary – Northwest 6.1 – 12,192 (61) 9.1 – 27 (18) 0.031 – 91 (9.1) Sedimentary – West-Central 61 – 1829 (183) 11 – 24 (18) 3.1 – 31 (7.6) Sedimentary - Southwest 1.5 – 46 (6.1) 9.1 – 27 (18)	Sedimentary (18)	
High Cascade Volcanics North (no data) Central (no data) South 3.1 – 31 (23) Volcanic and Sedimentary 3.1 – 152	Volcanic and Sedimentary (23)	

Table 2. Hydrolithologic Categories based on literature values of estimated hydraulic conductivity (K, m/d). Hydraulic conductivity estimates for most categories are the geometric mean of permeability values from studies compiled by Gleeson et al. (2011). Hydraulic conductivity estimates for volcanic and basalt categories are from a subset of the regional scale hydrogeological studies compiled by Gleeson et al. (2011) where volcanic deposits were investigated. Estimated hydraulic conductivity values for volcanics and basalts were supplemented with additional values from studies of volcanics in the Pacific Northwest. Local-scale lithologies from Freeze and Cherry (1979) are shown for illustrative purposes only.

Regional-scale Hydrolithologic Category **Local-scale Lithologies**	**Hydraulic Conductivity Estimate (K, m/d)**	**Aquifer Permeability Class**
Fine-Grained Sedimentary	2.7E-5	
Shale		
Sedimentary	5.3E-4	
Older Volcanic[1]	6.3E-3	
Crystalline	6.7E-3	Low
Fractured igneous and metamorphic rock		
Unfractured igneous and metamorphic rock		
Fine-grained Unconsolidated	8.5E-3	
Unweathered marine clay		
Glacial till		
Silt, loess		
Unconsolidated	8.5E-2	
Coarse-grained Sedimentary	2.7E-1	
Sandstone		
Younger Volcanic[2]	2.9E-1	
Carbonate	1.3	
Karst limestone		
Limestone and dolomite		High
Coarse-grained Unconsolidated	10.7	
Silty sand		
Clean sand		
Gravel		
Older Basalt[3]	21	
Younger Basalt[4]	816	

[1]Includes mid-Miocene and older volcanics. Hydraulic conductivity estimate is geometric mean value from Willamette Basin Basement Confining Unit, Table 1, Conlon, et al., 2005, Belcher, 2010 (Nevada), and Pool and Dickenson, 2007 (Arizona).

[2]Includes late Miocene and younger volcanics. Hydraulic conductivity estimate is geometric mean value from Willamette Basin High Cascades Unit, Table 1, Conlon, et al., 2005 and Sanford, et al., 2004 (New Mexico).

[3]Includes Columbia River Basalt Group and other Miocene basalts as described in Generalized Geologic Map of the Snake River Basin, Whitehead, 1992. Hydraulic conductivity estimate is median value for basalt units from Table 3, Kahle et al., 2011 (Columbia Plateau Regional Aquifer System).

[4]Chiefly basalt of the Snake River Group as described in Generalized Geologic Map of the Snake River Basin, Whitehead, 1992. Hydraulic conductivity estimate from Table 1, Lindholm, 1996 (Snake River Plain Regional Aquifer System).

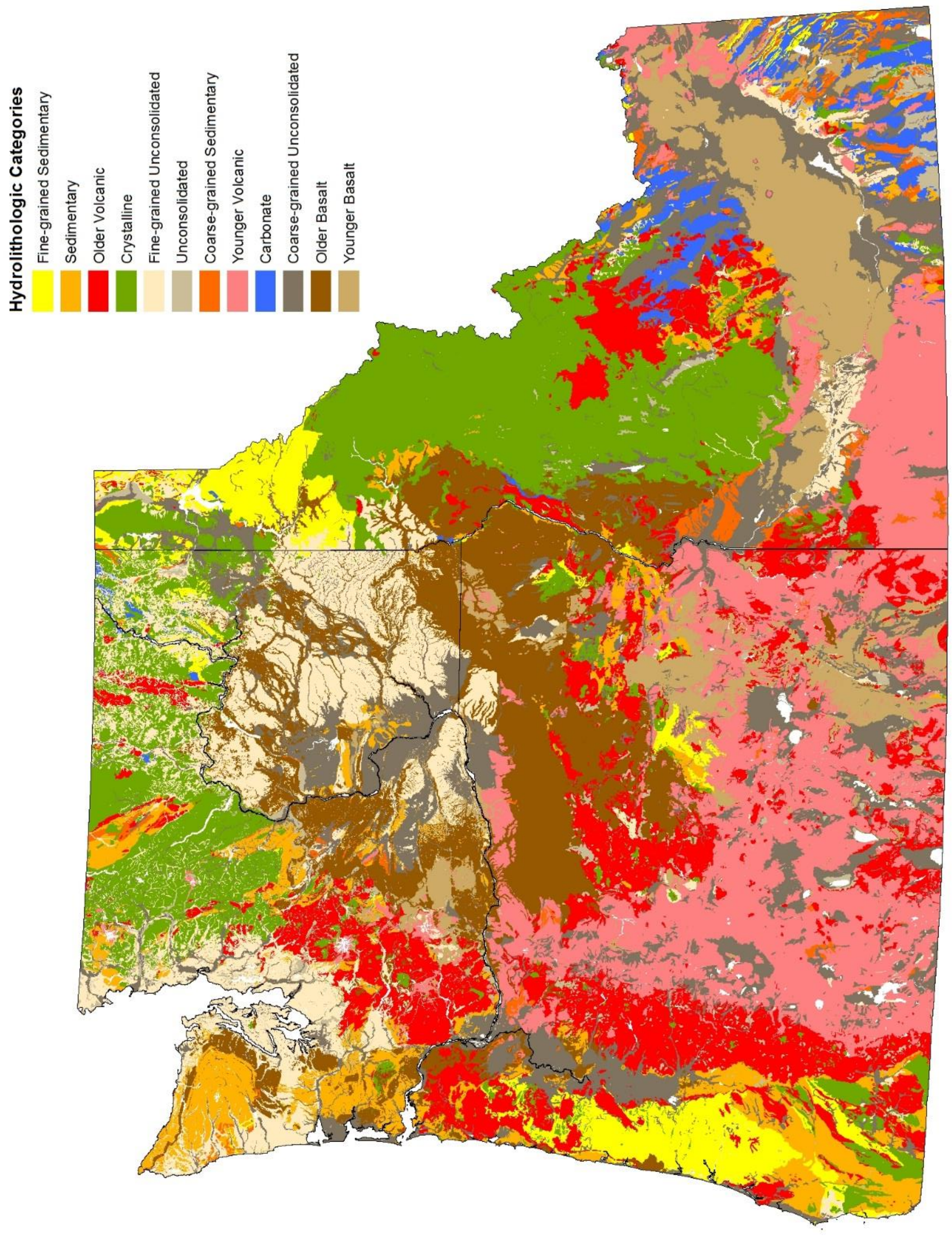

Figure 1. Hydrolithologic categories in the Pacific Northwest. Descriptions of local-scale lithologies were used to classify geologic units in state geologic maps from Oregon, Washington, and Idaho.

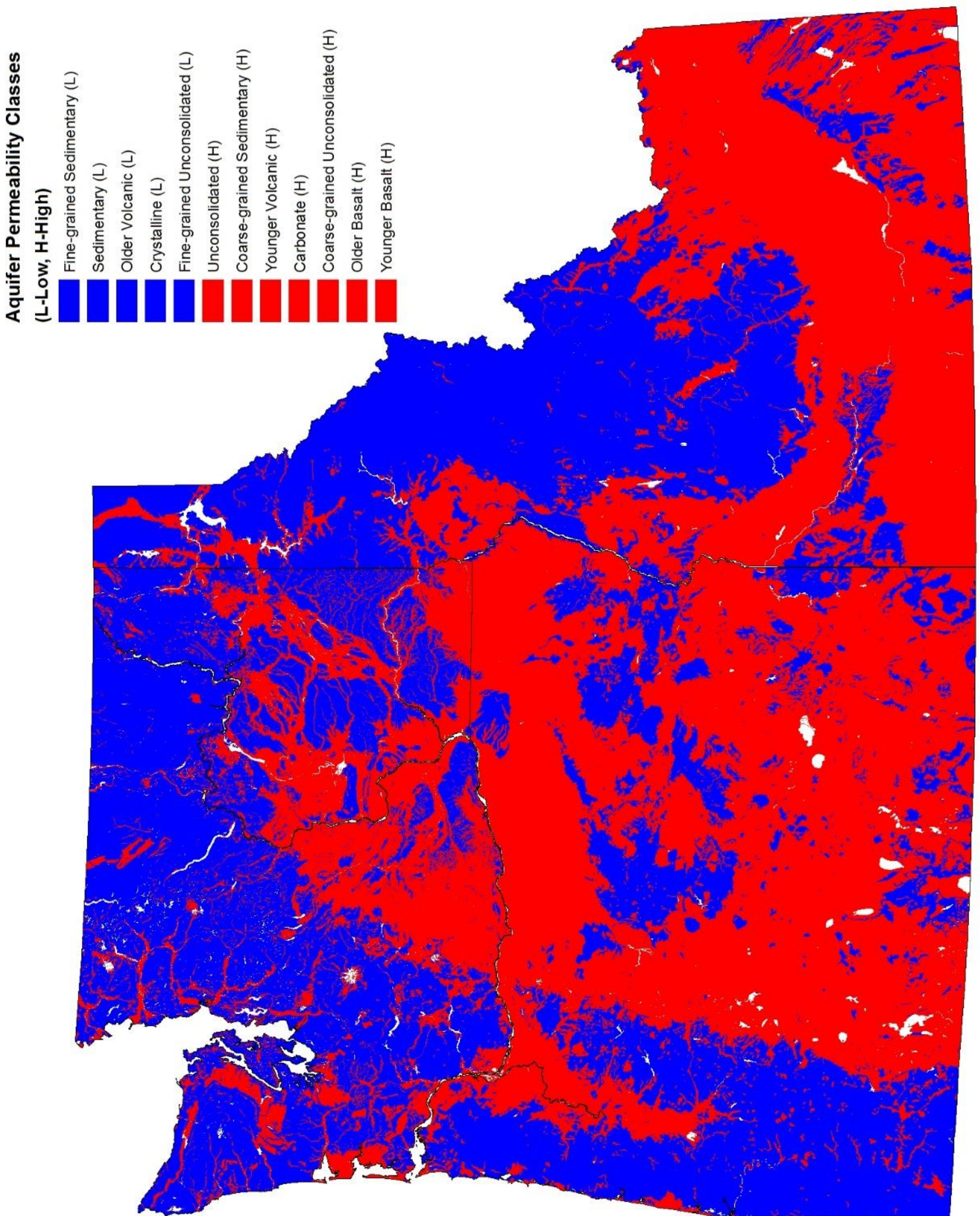

Figure 2. Aquifer permeability classes in the Pacific Northwest. High and Low permeability classes based on similarities in lithology and estimated hydraulic conductivity values found in Table 2.

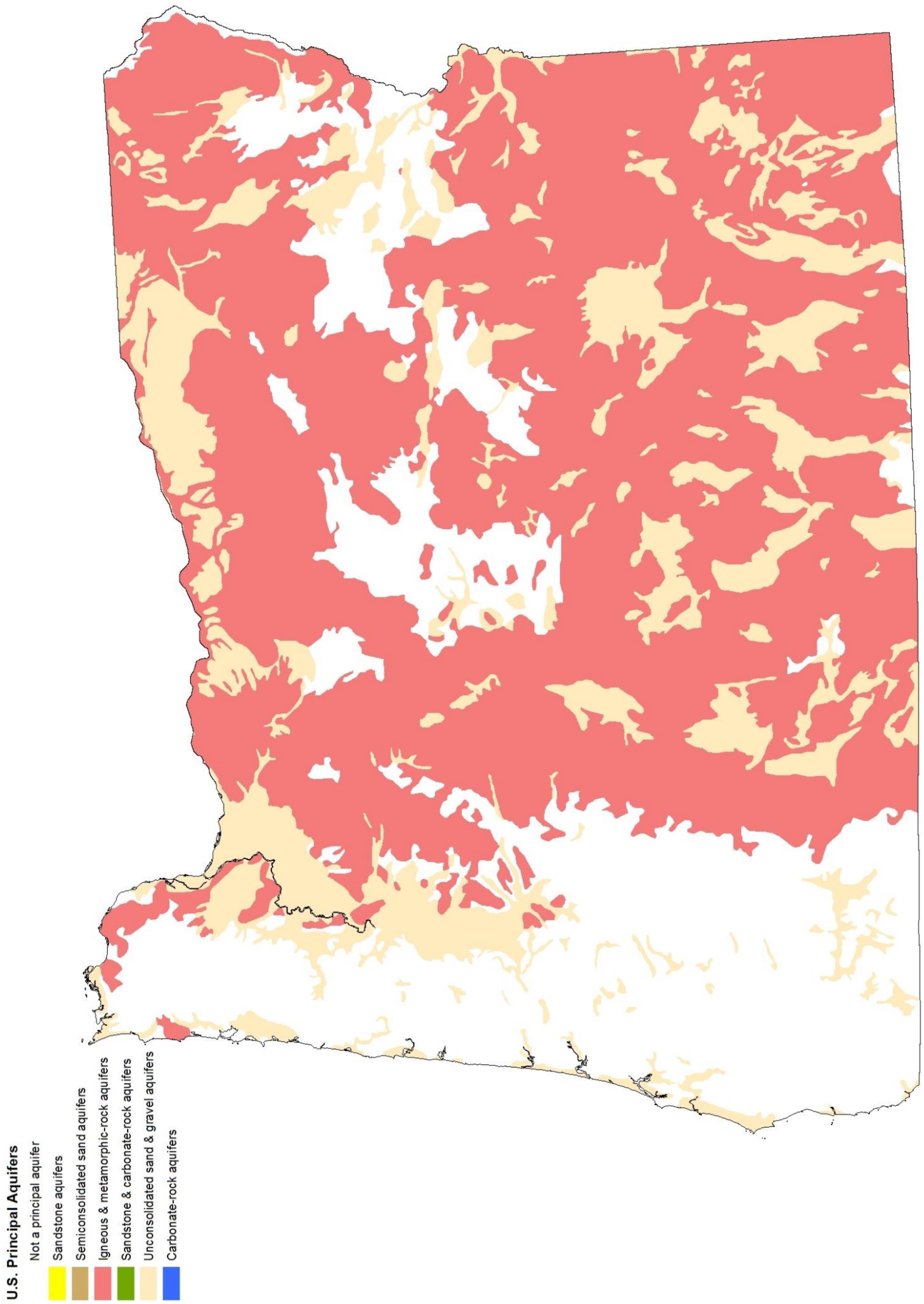

Figure 3. U.S. Geological Survey National Atlas map of principal aquifer groups in Oregon (U.S. Geological Survey, 2001).

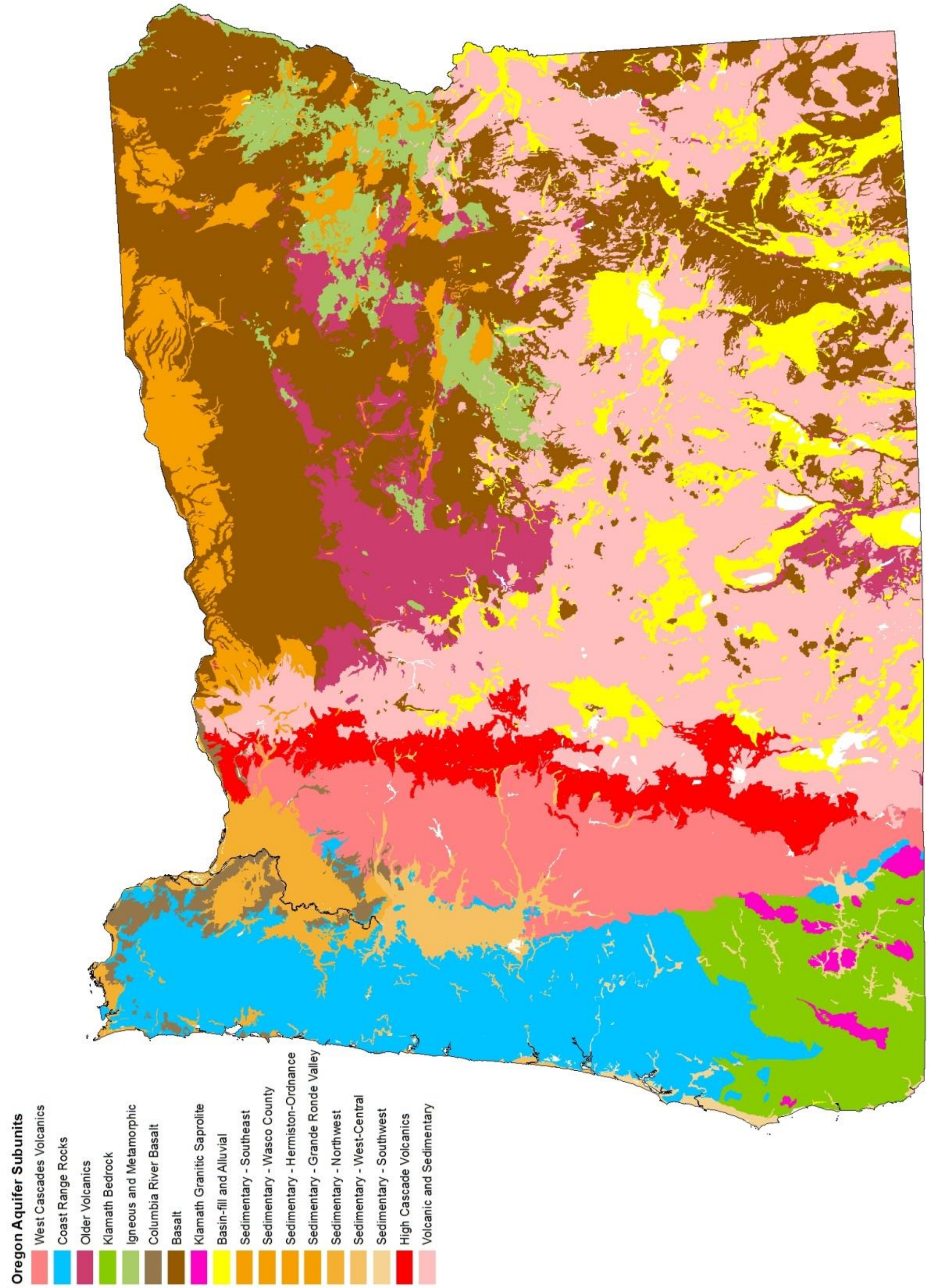

Figure 4. Oregon aquifer subunits from Gonthier (1985) and McFarland (1983) mapped onto a digital state geologic map (Walker et al., 2003).

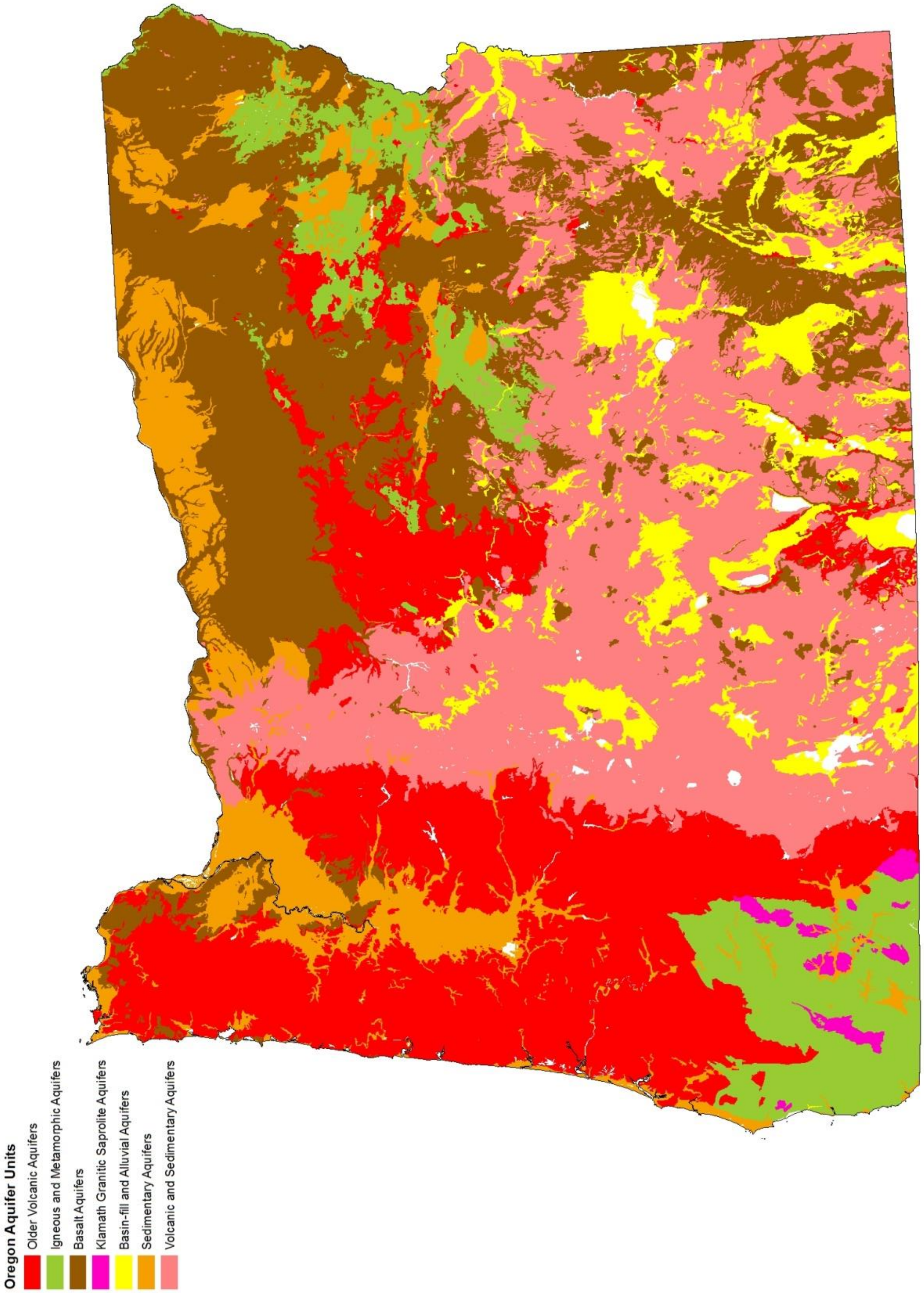

Figure 5. Oregon aquifer units created by combining 18 aquifer subunits (Figure 4) based on similarities in lithology and hydraulic conductivity obtained from Gonthier (1985) and McFarland (1983).

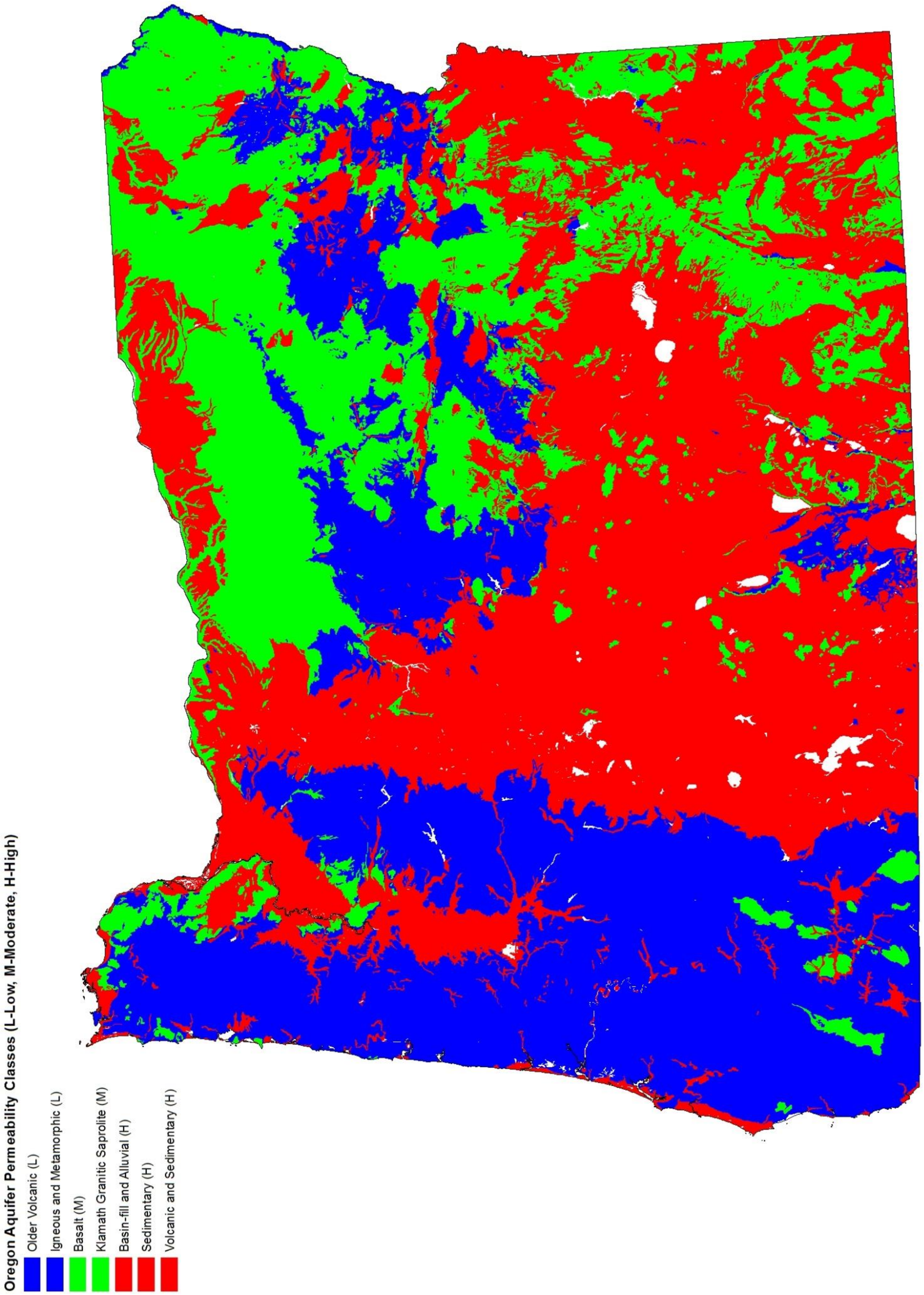

Figure 6. Oregon aquifer permeability classes based on hydraulic conductivity values obtained from Gonthier (1985) and McFarland (1983) in the seven unit aquifer map (Figure 5).

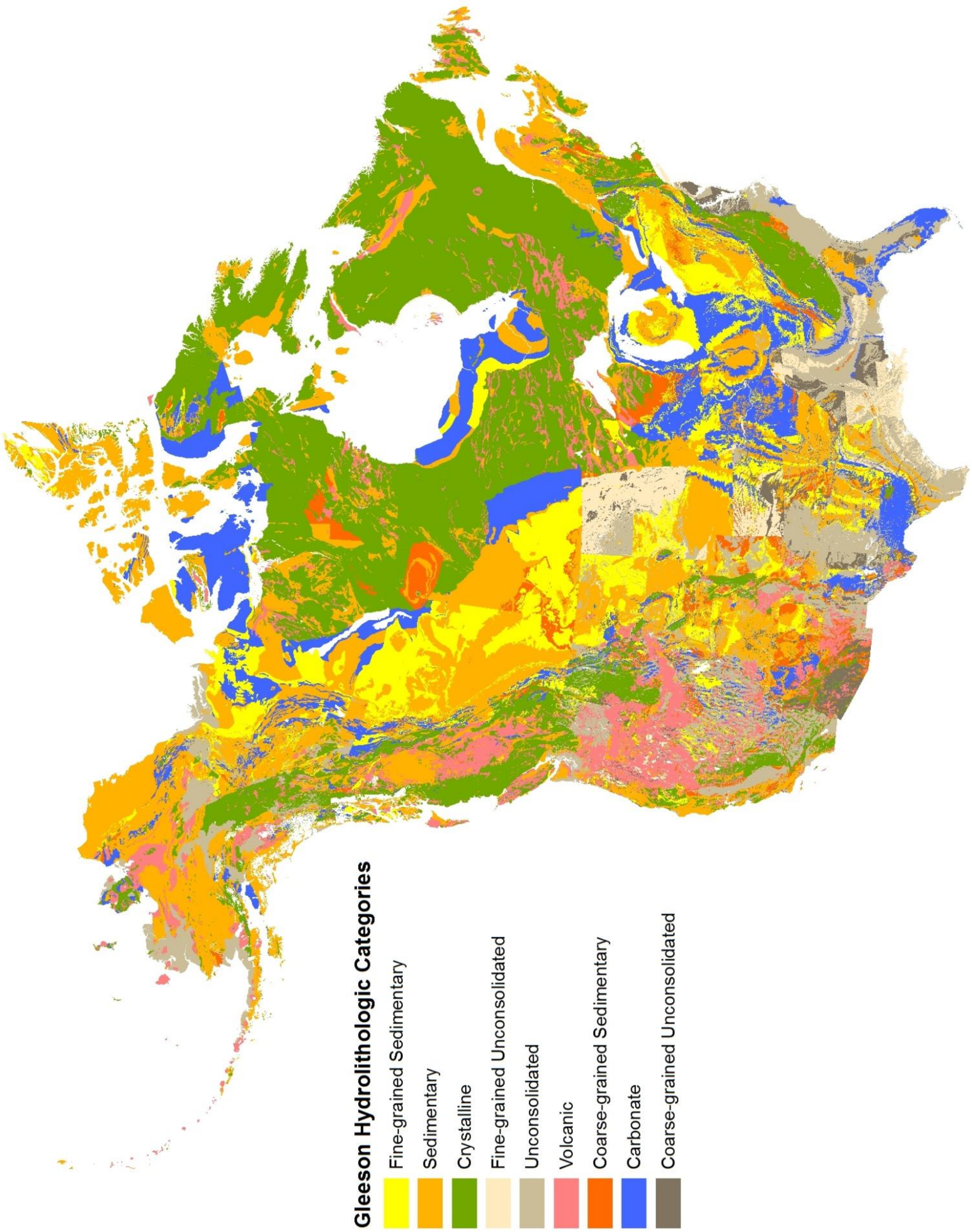

Figure 7. Gleeson et al. (2011) North American hydrolithologic categories in a 1-kilometer cell size North American raster map.

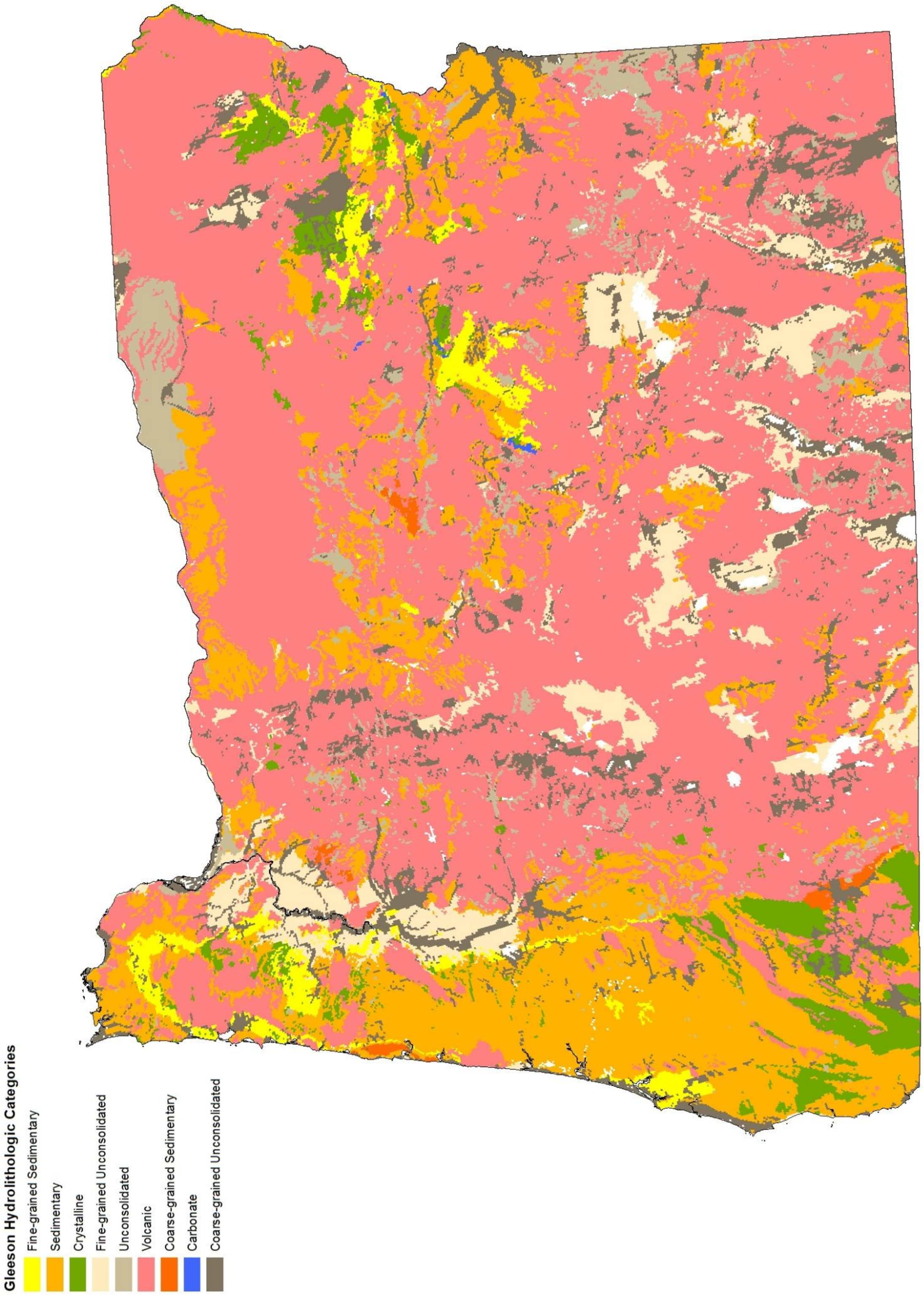

Figure 8. Gleeson et al. (2011) hydrolithologic categories in Oregon extracted from a 1-kilometer cell size North American raster map.

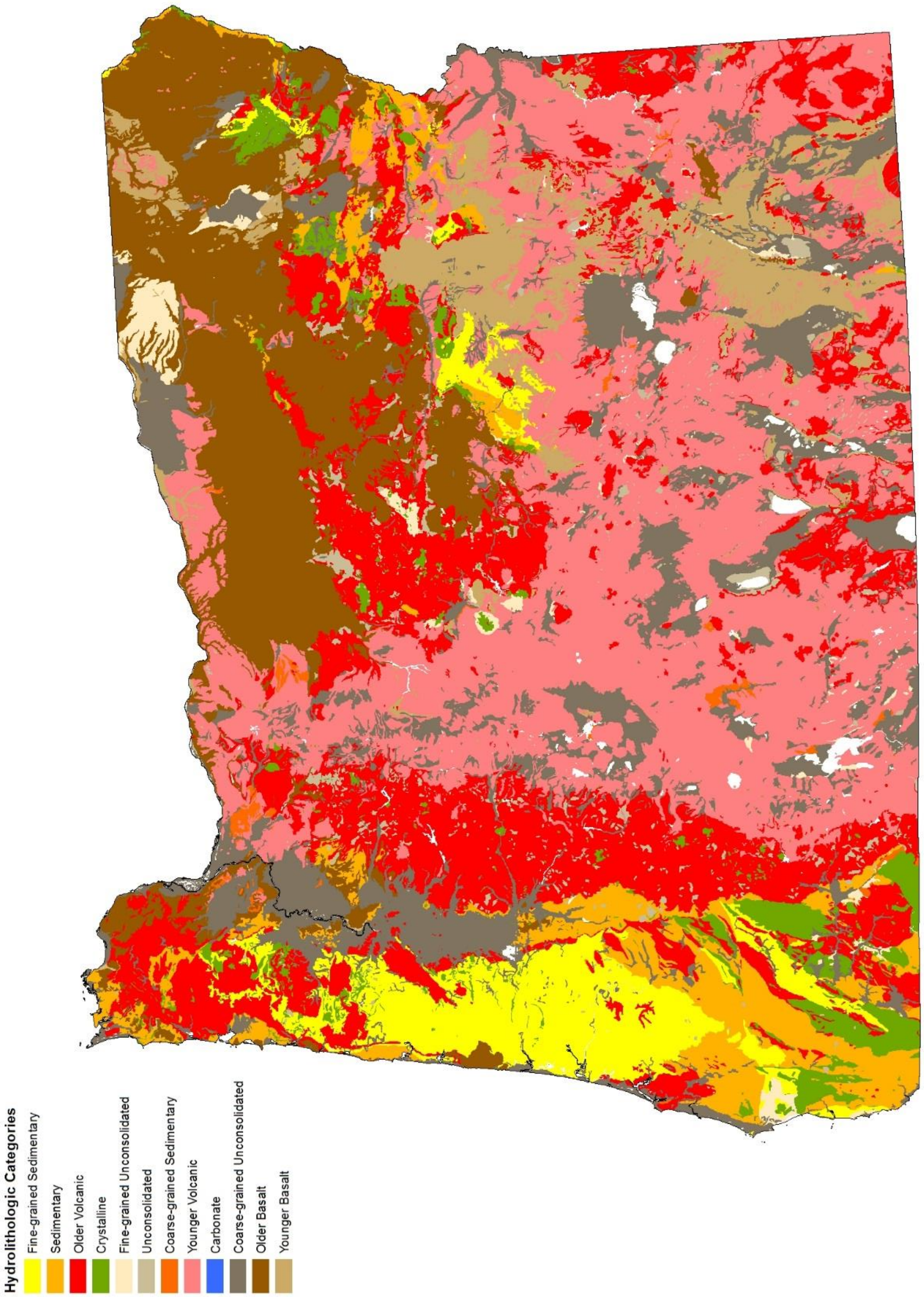

Figure 9. Hydrolithologic categories in Oregon. Descriptions of local-scale lithologies were used to classify geologic units in the Oregon state geologic map (Walker et al., 2003).