ADVANCED SCIENCE AND PARTNERSHIPS FOR INTEGRATED RESOURCE DEVELOPMENT PROJECT

Digital Hydrogeologic Map of the Ararat Valley and Three-Dimensional Model of the Ararat Valley Groundwater Basin

September 2018

This publication was produced for review by the United States Agency for International Development. It was prepared by ME&A, Inc.

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Contract No. AID-OAA-I-14-00070/AID-111-TO-15-00001

Prepared for:
United States Agency for International Development
Armenia Mission
1 American Avenue
Yerevan 0082, Armenia

Prepared by:
ME&A, Inc.
4350 East-West Highway
Suite210
Bethesda, MD 20814
Tel:+13016524334
Fax: +1 240 630 8935
www.MEandAHQ.com

Armenian Branch of ME&A, Inc.
105/1 Teryan St., Suite 204,
Yerevan 0009
Republic of Armenia
Tel. +374 10 514 315
Fax: +374 10 514 317
Email: aspired@engl.com

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LIST OF ACRONYMS

3D	Three-dimensional
AHGW	ArcHydro Groundwater
ASPIRED	Advanced Science and Partnerships for Integrated Resource Development
CEWP	Clean Energy and Water Project
DEM	Digital Elevation Model
DSS	Decision Support System
EMIC	Environmental Monitoring and Information Center
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GMS	Groundwater Modeling System
GOA	Government of Armenia
HGUID	Hydrogeologic unit identifiers
MEINR	Ministry of Energy Infrastructures and Natural Resources
MNP	Ministry of Nature Protection
RGF	Republican Geologic Fund
TIN	Triangulated irregular network
WRMA	Water Resources Management Agency
USAID	United States Agency for International Development
USGS	United States Geological Survey

INTRODUCTION

The Advanced Science and Partnerships for Integrated Resource Development (ASPIRED) Project of the United States Agency for International Development (USAID) supports sustainable water resource management and sustainable practices of water users in the Ararat Valley through the use of science, technology, innovation and partnership initiatives. The ultimate goal is to reduce extraction of groundwater resources to the sustainable levels. The ASPIRED Project is implemented by ME&A, Inc. and its subcontractor, Computer Assisted Development, Inc. (CADI).

To support the Government of Armenia (GOA) in developing and implementing more stringent data driven policy for sustainable management of groundwater resources in the Ararat Valley, the ASPIRED Project works on establishing a comprehensive and reliable data system and developing decision support tools for the Ararat Valley.

In 2018, the ASPIRED Project began developing a comprehensive Ararat Valley groundwater basin model, using the ArcHydro Groundwater (AHGW) tools, Groundwater Modeling System (GMS), and MODFLOW advanced applications for groundwater modeling. This task is implemented in collaboration with and guidance from AQUAVEO, a U.S.-based company that provides solutions for modeling and visualizing groundwater and, surface-water hydrology and hydraulics. The work is based on the conceptual model for the Ararat Valley groundwater modeling, which was prepared by the ASPIRED team in June 2018. Using the inventory data that describes baseline conditions in the Ararat Valley for 2016, the ASPIRED team developed the three-dimensional (3D) model of the Ararat Valley structure. The 3D model is the first stage of creating the comprehensive groundwater flow model of the Ararat Valley basin to determine the values of groundwater inflow, groundwater outflow, and groundwater accumulation in the Ararat groundwater basin under conditions of groundwater use. The input data for calculating the volume of the groundwater reserve, the rates of groundwater recharge, and sustainable groundwater extraction rate in the Ararat Valley as of year 2016. Calculations for these three rates will be completed in fall 2019.

The ASPIRED Project also began developing a digital hydrogeologic map of the Ararat Valley, based on the digitizing hard-copy maps and geo-spatial datasets accumulated or produced by the ASPIRED Project. The project team is also incorporating into the digital map the findings of the scientific investigations report on the Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, prepared by the U.S. Geological Survey (USGS) in 2017. The ASPIRED team plans to enhance the preliminary version of the hydrogeologic map presented in this report, based on stakeholders' feedback on the initial outcomes, as well as based on the results of the groundwater flow model of the Ararat Valley to be completed in fall 2019.

This report presents the three-dimensional model of the Ararat Valley groundwater basin and preliminary version of the digital hydrogeological map. The report describes the conceptual model for the Ararat groundwater basin modeling, as well as the datasets and data sources used for the modeling process. This report is prepared for review by representatives from USAID and key stakeholders – Ministry of Nature Protection (MNP) of Armenia, its Water Resources Management Agency (WRMA), the Environmental Monitoring and Information Center (EMIC) state non-commercial organization, and other agencies.

1. BACKGROUND INFORMATION

The Ararat Valley is an inter-mountain depression of the Armenian Highlands. The Ararat Valley groundwater basin is a natural groundwater storage area, where the water enters from the surrounding Ararat and Aragats mountains and from the Geghama and Haykakan Par mountain ridges (Figure 1).

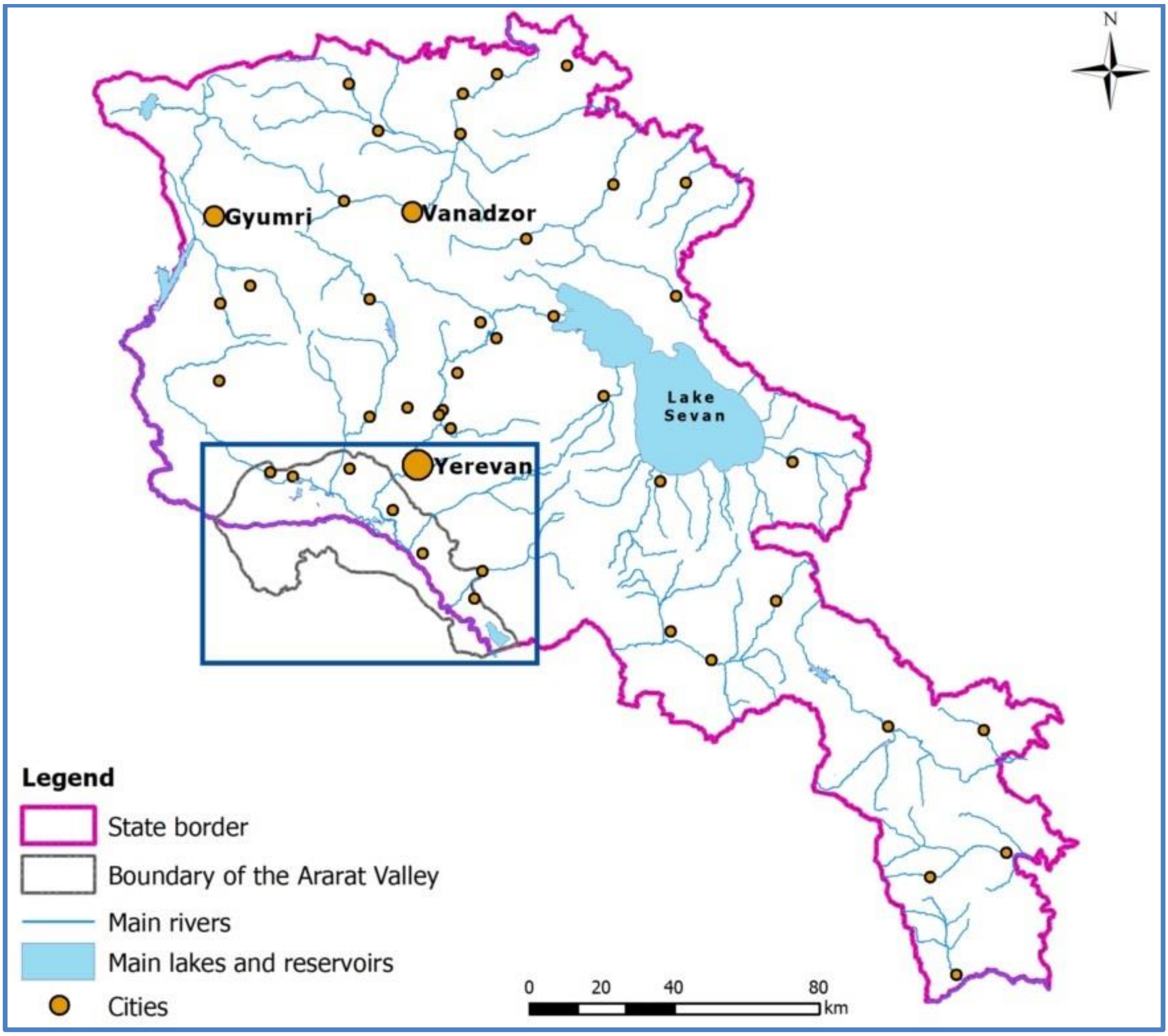


Figure 1: Location of the Ararat Valley ***(Source: ASPIRED Project)***

By its geomorphology, the Ararat Valley represents an inter-mountain depression associated with the valley of the Araks River and its tributaries - the Akhuryan, Metsamor (Sevjur), Qasakh, Hrazdan, Azat, Vedi Rivers in the territory of Armenia, and Kars River basin and the area of Igdir Province in the Turkish territory (Figure 2).

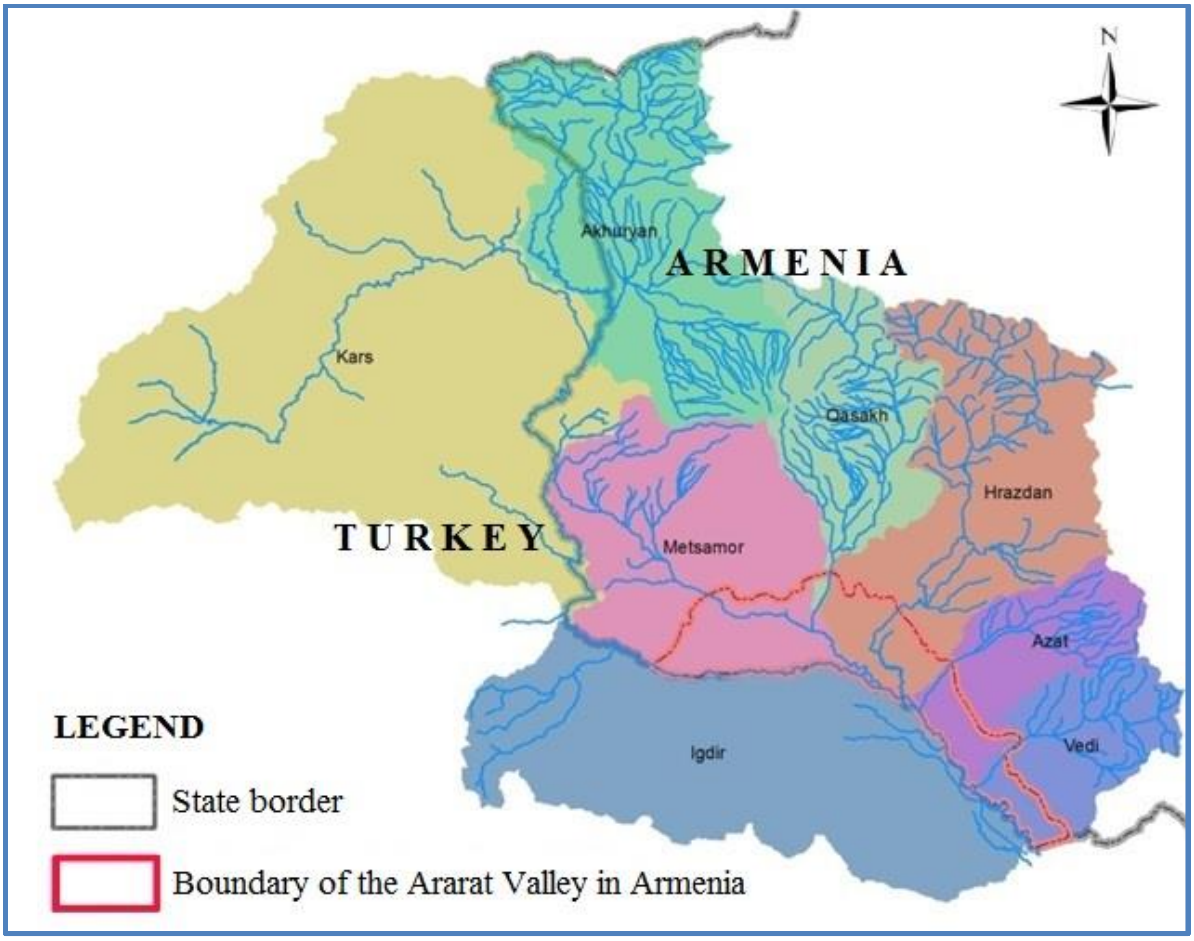


Figure 2: Ararat Valley catchment area *(Source: ASPIRED Project)*

The rivers' ancient buried valleys that are covered by the volcanic lava and subsurface deposits of modern drainage networks (rivers) serve as the routes through which water enters the Ararat groundwater basin. From a hydrogeologic perspective, the Ararat Valley groundwater basin is a closed inter-mountain artesian basin with groundwater recharge, storage and discharge areas.

The groundwater resources of the Ararat Valley are developed from precipitation, condensation, discharge of deep artesian inflows, and partially from surface flows within the Araks catchment basin with an area of 31,500 km^2, including 14,900 km^2 of Armenian territory and 16,600 km^2 of Turkish territory [8].

The study area for the ASPIRED Project is the part of the Ararat Valley within the boundaries of the Republic of Armenia. This is due to a limited data on the part of the groundwater basin on the territory of Turkey.

In Armenia, the Ararat Valley is located in the middle stream of Araks River and extends in the north-west and south-east direction for about 100 km with a width ranging from 10 to 25 km. The valley is located at elevations ranging from 800 m to 930 m above sea level and occupies an area of about 1,177 km^2. Figure 3 below presents the elevation contour map of the Ararat Valley.

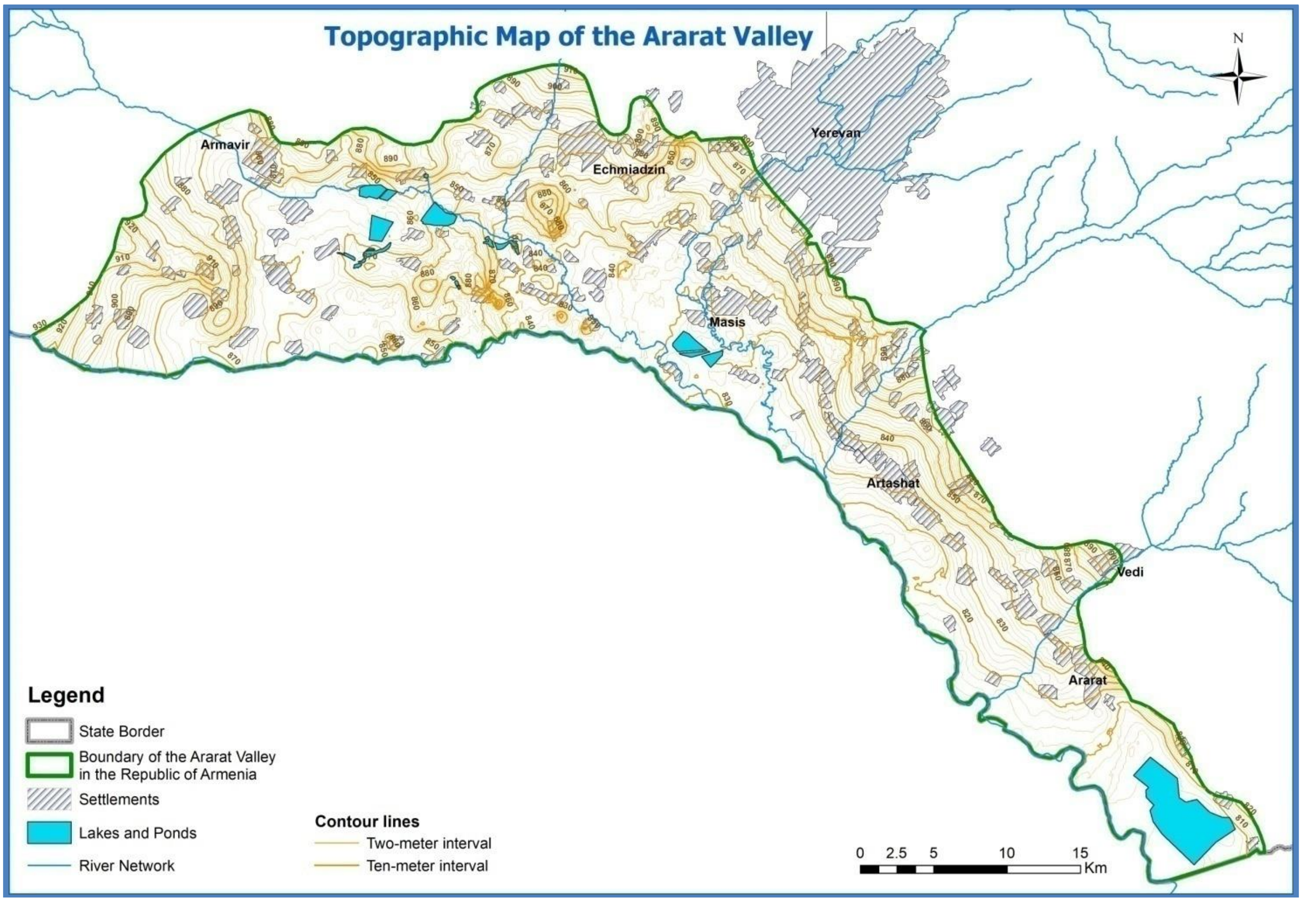


Figure 3: Topography of the Ararat Valley ***(Source: ASPIRED Project)***

To provide sufficient data on the baseline situation in the study area, the ASPIRED team conducted an inventory of groundwater wells, natural springs and fish farms of the Ararat Valley in 2016. Overall, the inventory covered 2807 wells, 14 groups of natural springs, and 235 fish farms. ASPIRED described the lithologic structure for all the 2807 wells, as well as developed a comprehensive database with data from field measurements and desk surveys.

The results of inventory served as main datasets for:

(1) Preparing the Hydrogeologic Framework of the Ararat Valley, in cooperation with USGS;
(2) Developing the digital hydrogeologic map of the Ararat Valley;
(3) Modeling the three-dimensional structure of the Ararat Valley groundwater basin; and
(4) Developing groundwater flow model of the Ararat Valley.

2. CONCEPTUAL MODEL OF THE ARARAT VALLEY GROUNDWATER BASIN

The main objective of the Ararat Valley groundwater basin modeling is **to provide the GOA with a decision-support tool** for (a) formulation of a data-driven policy for effective management of the Ararat Valley groundwater resources; (b) development of a long-term strategy on planning, conservation and management of the groundwater resources in the Valley; and (c) improvement of control mechanisms over the use of groundwater in the Ararat Valley.

As a starting point of modeling the Ararat Valley groundwater basin, a conceptual model was prepared, using materials of the stratigraphic and groundwater modeling course provided by AQUAVEO to the ASPIRED personnel and representatives of the WRMA, EMIC, and academia in January 2018. The conceptual model schematically presents the input data requirements, calculations, and expected outcomes of the groundwater flow modeling (Figure 4). The ASPIRED team presented the conceptual model and discussed it with EMIC representatives in June 2018. The ASPIRED Project received the hydrogeologists' concurrence on the proposed approach and methodology.

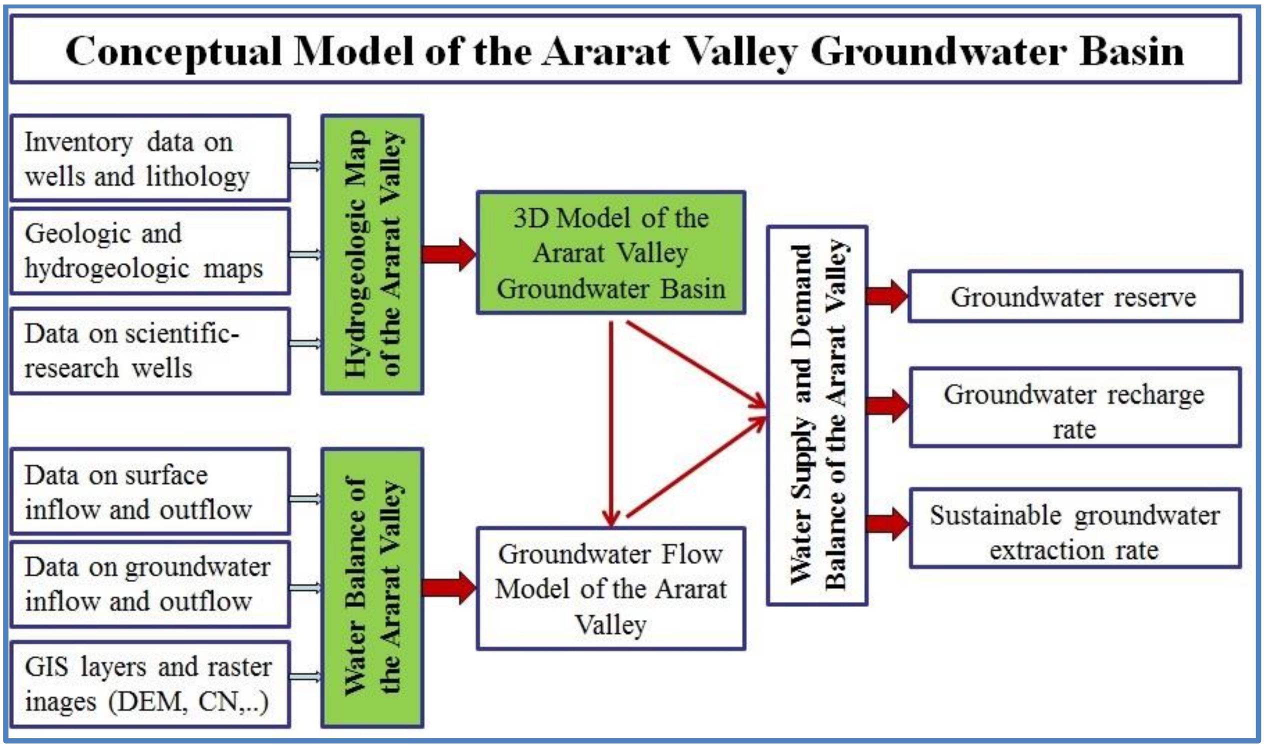


Figure 4: Schematics of the Ararat Valley groundwater basin conceptual model ***(Source: ASPIRED Project)***

The ASPIRED team implemented the green-highlighted components of the conceptual model in 2017-2018. The water balance of the Ararat Valley is presented in the ASPIRED Project's report on Methodology and Calculated Values of Natural Flow and Water Balance of the Ararat Valley (September 2018). This report presents the hydrogeologic map of the Ararat Valley and 3D model of the Ararat Valley groundwater basin.

The **ArcGIS** is the main environment for technical implementation of the Ararat Valley groundwater basin conceptual model. The following tools under ArcGIS are used for groundwater modeling by ASPIRED:

- **Decision Support System** – an open-source extension to ArcGIS developed by the USAID/Armenia Clean Energy and Water Program (CEWP) in 2012-2015 and further enhanced by the ASPIRED Project in 2017-2018. The DSS includes a Hydrological Model to calculate the water balance components. In 2017-2018, ASPIRED customized and calibrated the DSS for the Ararat Valley to calculate the water balance.

- **Arc Hydro Tools** – an extension to ArcGIS developed by Environmental Systems Research Institute (ESRI) that includes general data model for framework and temporal modeling of the surface water hydrology.

- **3D Analyst Tools** - an extension to ArcGIS developed by ESRI to create, run, and analyze the 3-dimentional models under the ArcGIS environment.

- **Arc Hydro Groundwater (AHGW) Tools** – an extension to ArcGIS developed by AQUAVEO that is a general data framework for groundwater modeling. The AHGW Tools include three main components: Groundwater Analyst, Subsurface Analyst, and MODFLOW Analyst. The AHGW is a geodatabase design tool for representing groundwater datasets within ArcGIS. The data model helps to archive, display, and analyze multidimensional groundwater data, as well as has several components to represent different types of datasets, including representations of aquifers and wells/boreholes, 3D hydrogeologic models, temporal information, and data from simulation models. The AHGW Tools are also used to import, edit, and manage groundwater data stored in an AHGW geodatabase.

- **MODFLOW Data Model –** a geodatabase design tool for storing MODFLOW simulations, developed by AQUAVEO and works tightly with MODFLOW Analyst tools under the GMS.

3. DIGITAL HYDROGEOLOGIC MAP OF THE ARARAT VALLEY

The main purpose of compiling the digital hydrogeologic map of the Ararat Valley is to develop a comprehensive data system for informed decision-making on Ararat Valley groundwater basin. The preliminary version of the hydrogeological map includes the following digitized components:

- Geological formations and tectonic structures of the Ararat Valley;
- Morphological structure of the Ararat Valley;
- Pressure boundaries between flowing and non-flowing wells;
- Main hydrogeologic units of the Ararat Valley groundwater basin; and
- Maps of the potentiometric surfaces of the Ararat Valley aquifers.

The data sources for the development of the above-mentioned digitized components include:

- Historic hard-copy maps and reports on geologic formations and hydrogeologic structures accumulated in the Republican Geologic Fund (RGF) of the Ministry of Energy Infrastructures and Natural Resources (MEINR) of Armenia;
- Datasets and maps of the Assessment Study of Groundwater Resources of the Ararat Valley prepared within the framework of CEWP in 2013-2014;
- Datasets on inventory of the groundwater wells in Ararat Valley including their lithologic structures, conducted by the by Hydrogeologic Monitoring Center State Non-Commercial Organization of the MNP of Armenia in the framework of the ASPIRED Project in 2016; and
- Datasets on Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin, which the ASPIRED team compiled in cooperation with USGS in 2017.

The ASPIRED Project incorporated all the mentioned digitized components and geo-spatial datasets into a single GIS-based geodatabase on the Ararat Valley. All the GIS thematic layers were constructed using the WGS-1984 geographic coordinate system, with UTM Zone-38N geographic projection.

The sections below provide descriptions of the main components of the preliminary version of the digitized hydrogeologic map of the Ararat Valley. ASPIRED plans to further enhance the hydrogeologic map, based on stakeholders' feedback on the initial outcomes presented in this report, as well as based on the results of the groundwater flow model of the Ararat Valley to be completed in 2019.

3.1. Geologic Formations

The geologic structure of the Ararat Valley was formed as a result of depressions and the eruption of the Upper and Lower Quaternary basaltic lavas. It involves limnic-fluvial and effusive water bearing formations with thicknesses up to 500 meters. Beneath those formations is a folded water-resistant formation which has Paleozoic and Mezocainosoic sandstone, clay, and carbonate rocks. The Ararat Valley is currently filled with alluvial, proluvial, and lacustrine sediments. The Ararat Valley groundwater basin contains inter-bedded geologic material consisting of dense clays, gravels, sands, volcanic basalts, and andesite deposits [1, 4, 8].

The ASPIRED team developed the geologic map of the Ararat Valley by digitizing the hard-copy map of the scale of 1:100,000 presented in the Report on the reassessment of the operational reserves of underground fresh water in the Ararat Artesian Basin of the Armenian SSR, RFG Report# 01532, 1983 [7]. The digitized GIS map, including the fault zones is presented in Figure 5.

3.2. Morphologic structure

The Ararat Valley has a complex tectonic and hydrogeologic structure. The valley represents a superimposed inter-mountain trough of the Araks River's tectonic zone, divided by the subsequent folding process into the following five morphological sub-divisions (structures of second order) from west to east:

1. Hoktemberyan depression;
2. Sovetashen uplift;
3. Artashat depression;
4. Khor Virap uplift; and
5. Arazdayan depression.

These five morphologic structures that are presented in the Figure 6 differ in their geological composition, thickness of water bearing rocks, number of aquifers and impermeable layers, and their hydraulic properties [8].

3.3. Pressure boundaries

Analysis of pressure boundaries (boundary between flowing and non-flowing wells) was conducted by USGS in the Hydrogeologic Framework of the Ararat Basin [10]. Spatial analysis was performed using GIS software for digitizing the pressure boundaries for 1984. The ASPIRED team analyzed the water level data from the 2007 and 2016 field inventories to generate a raster grid of the hydraulic heads in both years using GIS software. The 2016 raster grid was then subtracted from the 2007 raster grid to determine the change in hydraulic head between 2007 and 2016. The largest decreases (more than 2 m) in hydraulic head between 2007 and 2016 fell outside the 2016 pressure boundary. Within the pressure boundary, changes in hydraulic head generally were minimal or indicated slight increases (Figure 6).

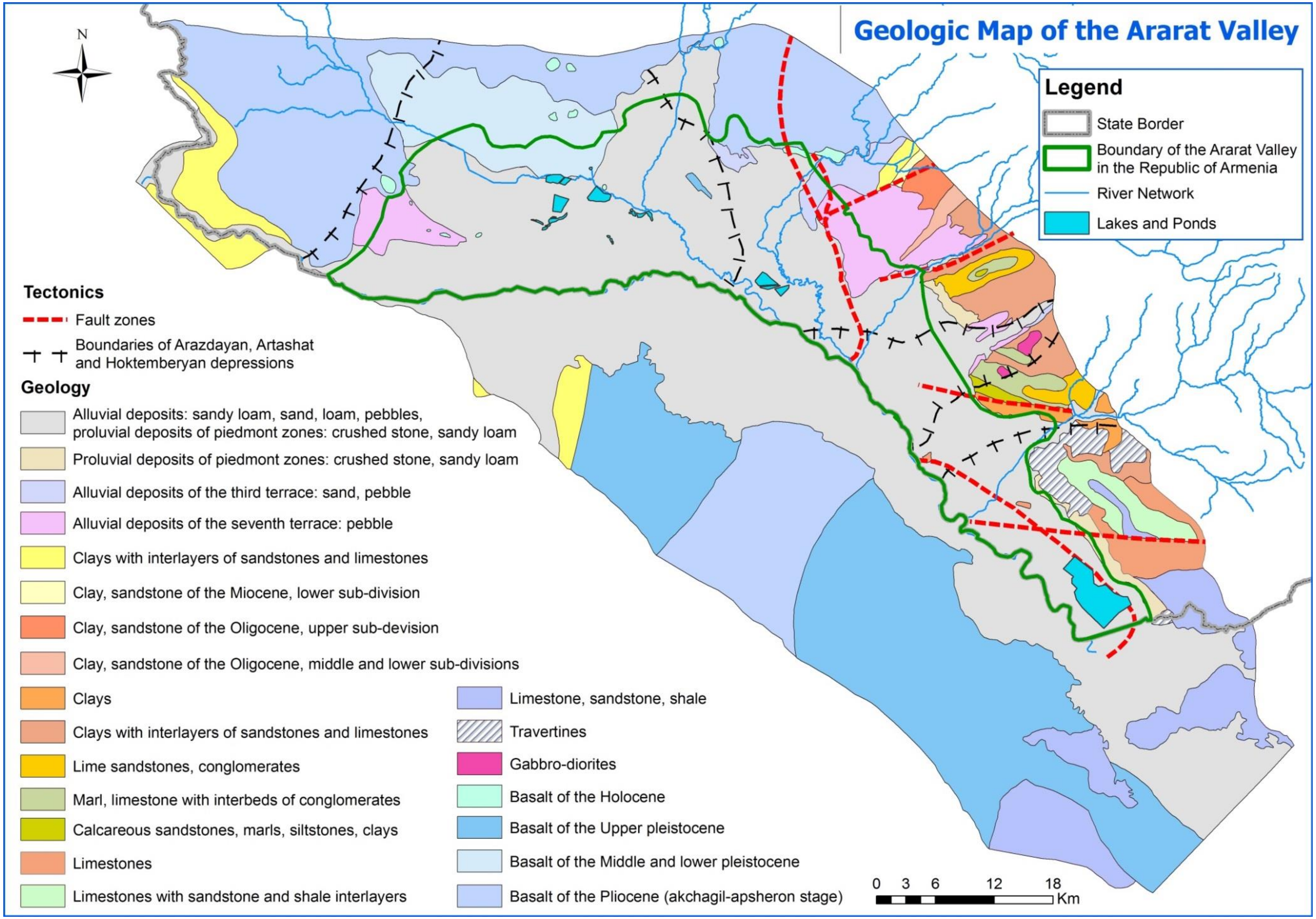


Figure 5: Geologic Map of the Ararat Valley ***(Source: ASPIRED Project)***

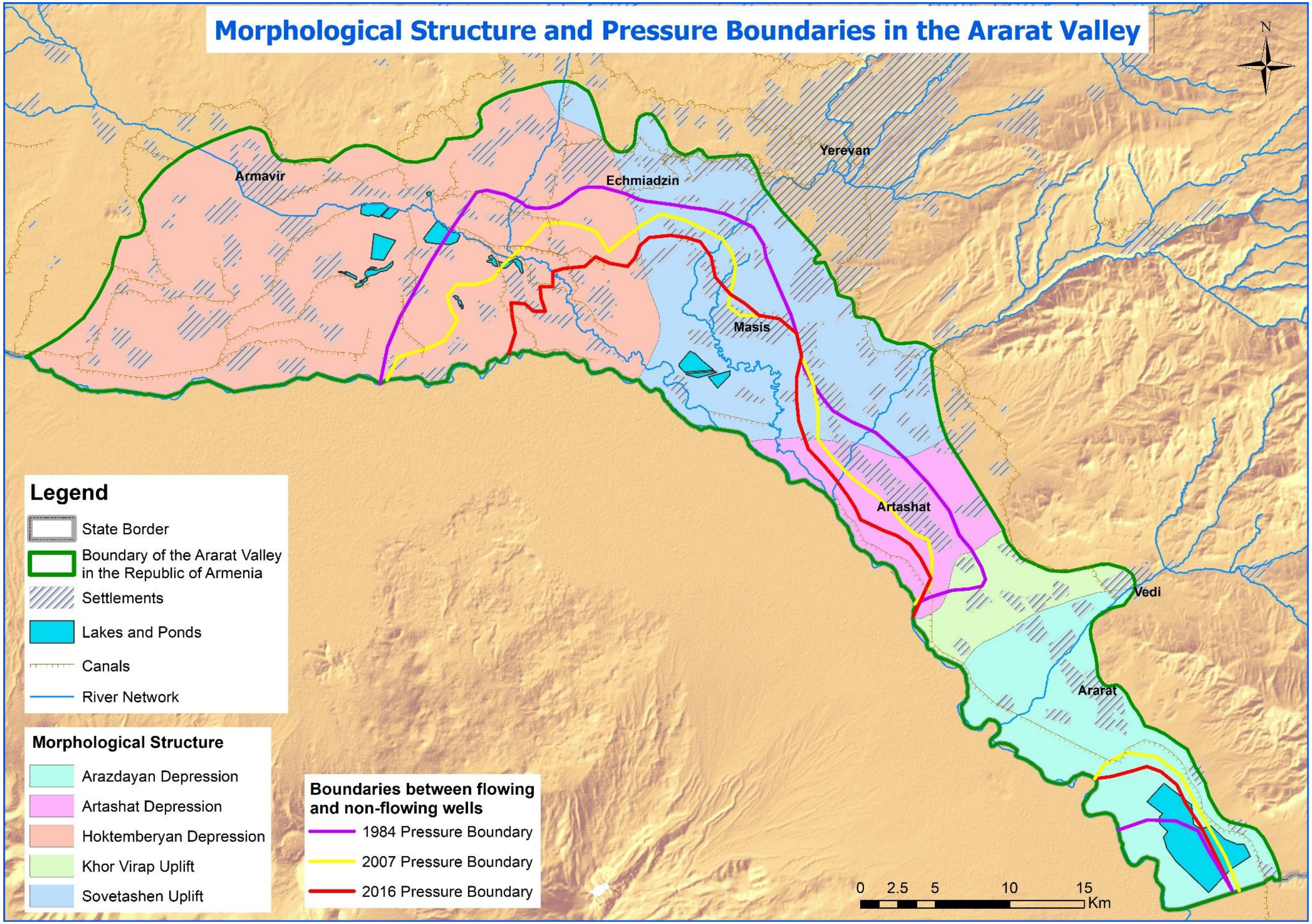


Figure 6: Morphological structure and pressure boundaries in the Ararat Valley ***(Source: USGS, ASPIRED Project)***

According to datasets from the 2016 well inventory, the non-flowing aquifer conditions were on the edges of the Ararat Valley groundwater basin where the basin depth becomes shallower. The flowing artesian wells, a central part of the study area, were the primary source of water that sustained the development and growth of the aquaculture industry for the purposes of raising mainly trout and sturgeon. The artesian conditions, generally high water quality, and cool water temperatures enabled aquaculture industries to thrive; however, the flowing wells reduced the artesian pressure in the aquifer. As a result, many wells that were flowing have ceased to flow [10].

Analysis shows that the pressure boundary shrank between 1984 and 2016, indicating that a large area has been affected by groundwater depletion. The area within the Ararat Valley with flowing wells (within the pressure boundary) decreased from approximately 42,298 ha in 1984 to 32,107 ha in 2007 and further to 22,366 ha in 2016. This is about a 50-percent reduction in area between 1984 and 2016.

3.4. Main Hydrogeologic Units of the Ararat Valley Groundwater Basin

The main hydrogeologic units of the Ararat Valley groundwater basin are described in the Hydrogeologic Framework of the Ararat Basin that was developed by the USGS in cooperation with the ASPIRED Project [10]. USGS and the ASPIRED team used lithologic logs of about 2,800 wells from the 2016 inventory database and the generalized lithologic descriptions of main hydrologic structures provided in the Assessment Study of Groundwater Resources of the Ararat Valley [8, 9]. Based on the lithology of about 2,800 wells, the ASPIRED team and USGS identified 24 unique lithologic layers and determined the water-bearing potential for each of the 24 unique lithologic layers, using interpretation of lithologic descriptions (Table 1).

Table 1. Description of the lithologic layers of the Ararat Valley groundwater basin

#	*Lithologic description*	*Thickness (meters)*			*Water bearing potential*
		Maximum	*Minimum*	*Mean*	
1.	Basalt with volcanic slag and sand	82	1	23.7	High
2.	Boulder pebble deposits with clay filling	88.7	1.8	22.9	Moderate
3.	Boulder pebble deposits with coarse – grained sand filling	93.2	4.5	29.1	High
4.	Boulder pebble deposits with sand – clay filling	80	4	30.1	High
5.	Clay sand	8.8	7	7.9	Low
6.	Coarse – grained sand	49.7	6	40.1	High
7.	Dense basalt andesite dacite	61.6	0.5	21.5	Low
8.	Dense clay	60	0.5	8.7	Low
9.	Fine – grained silty sand	14.6	5.8	9.3	High
10.	Gravel	89.5	1	35.0	High
11.	Gravel pebble deposits with clay filling	74.3	10	26.7	Moderate
12.	Gravel pebble deposits with coarse – grained sand and boulder filling	109.8	4	31.2	High

#	Lithologic description	Thickness (meters)			Water bearing potential
		Maximum	Minimum	Mean	
13.	Gravel pebble deposits with sand – clay filling	89	6	39.3	Moderate
14.	Gravel sand	89.5	4	38.7	Low
15.	Gypsiferous salt bearing clay with inter-bedded siltstone and marl and sandstone	2	2	2.0	Low
16.	Highly fractured basalt	147.8	0.2	35.6	Moderate
17.	Loam	56	0.3	5.3	Low
18.	Loam sandy loam	39.2	3	19.2	Low
19.	Poorly cemented sandstone	11	6	7.4	High
20.	Sandy clay with inter-bedded sand pebbles and gravel	73	1	12.3	Moderate
21.	Sandy loam	70	0.4	10.9	Moderate
22.	Slangs and fragments of volcanic rocks and pumice sand	75	8	24.0	High
23.	Slightly fractured porous basalt	110	2	33.1	High
24.	Volcanic tuff	15	8	11.3	Low

Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, USGS, 2017

Top elevations of the wells were corrected with the LandSAT 30-m digital elevation model (DEM), available through the USGS Earth Explorer website (https://earthexplorer.usgs.gov). Hydrogeologic unit thicknesses and the top and bottom elevations were then adjusted using the corrected well top elevations. The final corrected lithologic elevations were used to group the lithologic descriptions into larger units, as demonstrated on Figure 7 below. As a result, the 24 unique lithologic layers were consolidated into nine hydrogeologic units based on lithology and water-bearing potentials, using the lithologic logs of the groundwater wells [10].

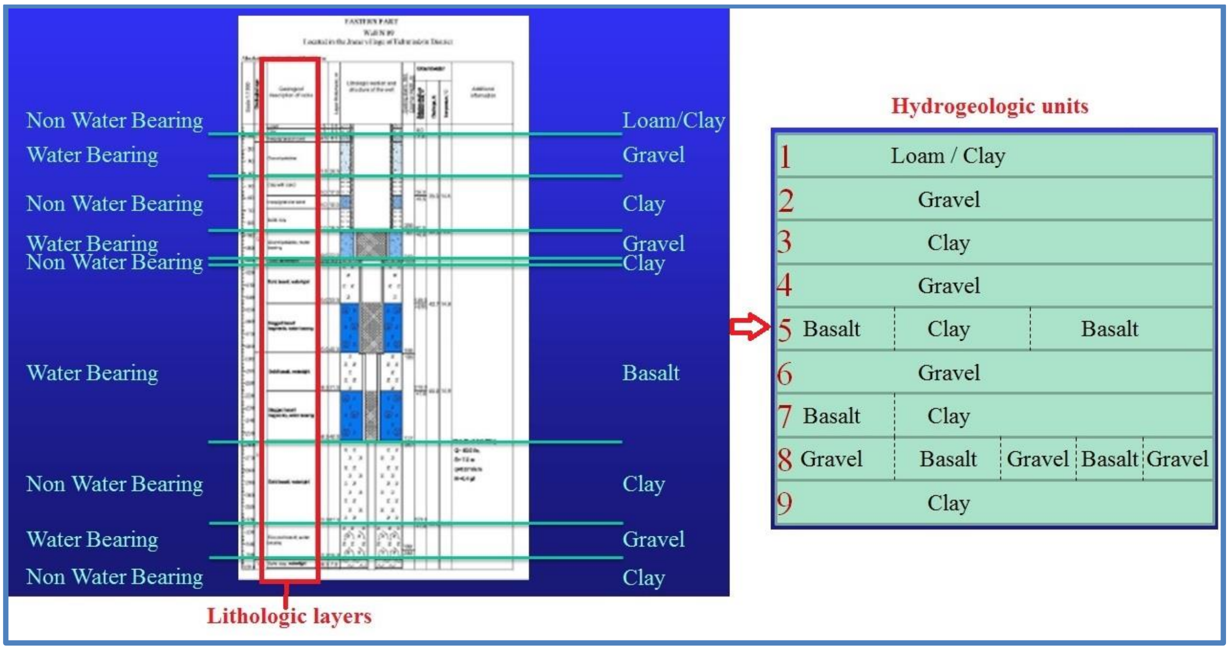


Figure 7: Grouping the lithologic layers into the hydrogeologic units *(Source: USGS webinar training materials)*

Below is detailed description of the nine hydrogeologic units of the Ararat Valley groundwater basin [10]:

Hydrogeologic Unit 1: The uppermost hydrogeologic unit (Unit 1) consists primarily of loam, dense clay, and sandy loam. The unit is characterized mostly by loam, which makes up about 66% of the geologic unit. Sandy loam and a dense clay layer make up the other 25% (12% and 13%, respectively). The remaining geologic material includes boulder pebble deposits with clay filling (1%), loam sandy loam (1%), and sand and fragments of volcanic rocks and pumice sand (7%). Lithologic logs from 2,300 wells were used to define Unit 1, and spatially these wells covered most of the Ararat Valley groundwater basin. Unit 1 had the third highest number of wells drilled into the unit when compared to all other unit descriptions and lithologic logs. Unit 1 was the thinnest when compared to the other 8 units, with a mean thickness of 8 m.

Hydrogeologic Unit 2: The uppermost water-bearing unit, Unit 2, consists primarily of boulder pebble deposits with coarse-grained sand filling, gravel pebble deposits with coarse-grained sand and boulder filling, and gravels. About 42% of the hydrogeologic unit is boulder pebble deposits. Gravel pebble deposits with coarse-grained sand and boulder filling and gravels make up the other 38% (28% and 10%, respectively). The remaining geologic material includes basalt with volcanic slag and sand (1%), boulder pebble deposits with clay filling (3%), boulder pebble deposits with sand-clay filling (7%), dense basalt andesite dacite (1%), gravel pebble deposits with clay filling (1%), gravel pebble deposits with sand-clay filling (1%), gravel sand (3%), sandy loam (1%), and slags and fragments of volcanic rocks and pumice sand (2%). Lithologic logs from 2,483 wells were used to define Unit 2. Spatially, the wells covered most of the Ararat Valley groundwater basin, with the higher density of wells in the south-central part of the basin. Compared to the other eight units, Unit 2 had the greatest number of wells drilled into the unit, was the thickest unit with a mean thickness of 32 m and was the thinnest measured water-bearing unit.

Hydrogeologic Unit 3: Unit 3 underlies unit 2 and is a non-water-bearing unit (confining layer). It consists of dense clay, sandy clay with inter-bedded sand pebbles and gravel, and dense basalt andesite dacite. The unit was characterized mostly by dense clays that constitute about 69% of the geologic unit. Sandy clay with inter-bedded sand pebbles and gravel and dense basalt andesite dacite make up the other 18% (11% and 7%, respectively). The remaining geologic material includes boulder pebble deposits with clay filling (1%), clay sand (1%), gravel pebble deposits with clay filling (1%), gravel pebble deposits with sand-clay filling (1%), highly fractured basalt (1%), loam (1%), loam sandy loam

(4%), sandy loam (2%), and volcanic tuff (3%). Lithologic logs from 2,242 wells were used to define Unit 3 and spatially these wells covered most of the basin, with a higher density of wells in the south-central part of the basin. Unit 3 ranked fourth in the total number of wells drilled into the unit.

Hydrogeologic Unit 4: Unit 4 underlies Unit 3 and is the second water-bearing unit. Unit 4 consists primarily of gravel pebble deposits with coarse-grained sand and boulder filling, boulder pebble deposits with coarse-grained sand filling, and gravel. The unit is characterized mostly by gravel pebble deposits with coarse-grained sand and boulder filling, which make up about 35% of the geologic unit. Boulder pebble deposits with coarse-grained sand filling and gravel make up the other 41% (34% and 7%, respectively). The remaining geologic material includes basalt with volcanic slag and sand (3%), boulder pebble deposits with clay filling (1%), boulder pebble deposits with sand-clay filling (2%), gravel pebble deposits with sand-clay filling (2%), gravel sand (3%), highly fractured basalt (9%), sandy clay with inter-bedded sand pebbles and gravel (1%), slags and fragments of volcanic rocks and pumice sand (3%), and slightly fractured porous basalt (1%). Lithologic logs from 2,348 wells were used to define Unit 4 and spatially these wells covered most of the basin with a higher density of wells in the south-central part of the basin. Unit 4 had the second largest number of wells drilled into the unit. The thickest part of the unit, based on the interpolated values, was in the central and eastern sub-regions of the basin.

Hydrogeologic Unit 5: Underlying Unit 4, Unit 5 is a non-water-bearing unit (confining layer), consisting primarily of dense clay, dense basalt andesite dacite, and sandy clay with inter-bedded sand pebbles and gravel. The unit is characterized by dense clay, which makes up about 68% of the geologic unit. Dense basalt andesite dacite and sandy clay with inter-bedded sand pebbles and gravel make up the other 23% (12% and 11%, respectively). The remaining geologic material includes clay sand (1%), sandy loam (4%), and volcanic tuff (3%). Lithologic logs from 1,462 wells were used to define Unit 5. The western part of the Ararat Valley groundwater basin had few lithologic logs available to define the geologic unit. The south-central and eastern sub-regions of the basin have a higher density of wells than the western sub-region. Unit 5 ranked fifth in the total number of wells drilled into the unit in the Ararat Valley. The mean thickness of the unit was 9m (the second thinnest unit). The thickest part of this unit, based on the interpolated values, was in the central sub-region of the basin.

Hydrogeologic Unit 6: Underlying unit 5, Unit 6 is the third water-bearing unit that consists primarily of highly fractured basalt, gravel pebble deposits with coarse-grained sand and boulder filling, and boulder pebble deposits with coarse-grained sand filling. The unit is characterized mostly by highly fractured basalt, which makes up about 43% of the geologic unit. Gravel pebble deposits with coarse-grained sand and boulder filling and boulder pebble deposits with coarse-grained sand filling make up the other 21% (12% and 9%, respectively). The remaining geologic material includes basalt with volcanic slag and sand (5%), boulder pebble deposits with sand-clay filling (7%), fine-grained silty sand (6%), gravel (9%), gravel pebble deposits with sand-clay filling (1%), gravel sand (1%), poorly cemented sandstone (1%), slugs and fragments of volcanic rocks and pumice sand (1%), and slightly fractured porous basalt (6%). Lithologic logs from 1,378 wells were used to define Unit 6. There were few lithologic logs in the southwestern part of the Ararat Valley groundwater basin available to define the geologic unit. More wells were available in the southern part of the central sub-region and in the eastern sub-region of the basin. Unit 6 ranked sixth in the total number of wells drilled into the unit. The thickest part of the unit, based on the interpolated values, was in the south-central part of the central sub-region and northern part of the eastern sub-region.

Hydrogeologic Unit 7: Underlying Unit 6, Unit 7 is a non-water-bearing unit (confining layer) that consists primarily of dense basalt andesite dacite, dense clay, and sandy clay with inter-bedded sand pebbles and gravel. The unit is characterized mostly by dense basalt andesite dacite, which makes up about 48% of the geologic unit. Dense clay and sandy clay with inter-bedded sand pebbles and gravel made up the other 49% (37% and 12%, respectively). The remaining geologic material included gravel pebble deposits with sand-clay filling (1%) and loam (1%). Lithologic logs from 875 wells were used to define Unit 7. Although fewer wells were used to define this unit than to define Units 1 through 6, spatially the wells used to define Unit 7 covered most of the Ararat Valley groundwater basin. The central sub-region had the higher density of wells than the other sub-regions. Unit 7 ranked seventh in the total number of wells drilled into the unit. The mean thickness of the entire unit was 10 meters and the maximum measured thickness, determined from lithologic logs, was 60 meters. The thickest part of the unit, based on the interpolated values, was in the eastern sub-region of the basin. The maximum interpolated thickness of Unit 7 is greater than the measured thickness likely because it includes topographically high areas along the perimeter of the basin and because of the limited spatial distribution of available lithologic information.

Hydrogeologic Unit 8: Underlying Unit 7, Unit 8 is the fourth water-bearing unit that consists primarily of highly fractured basalt, slightly fractured porous basalt, and gravel pebble deposits with coarse-grained sand and boulder filling. The unit is characterized mostly by highly fractured basalt, which makes up about 68% of the geologic unit. Slightly fractured porous basalt and gravel pebble deposits with coarse-grained sand and boulder filling make up the other 19% (13% and 6%, respectively). The remaining geologic material included basalts with volcanic slag and sand (5%), boulder pebble deposits with coarse-grained sand filling (4%), and slags and fragments of volcanic rocks and pumice sand (4%). Lithologic logs from 832 wells were used to define unit 8. The western and eastern sub-regions of the Ararat Valley groundwater basin had few available lithologic logs. There were more logs available in the southern part of the central sub-region. Unit 8 ranked eighth in the total number of wells drilled into the unit. One potential reason for the lack of lithologic information for Unit 8 could be high drilling costs required to complete a well in unit 8 because of large depths. The thickest part of the unit was in the central sub-region of the basin.

Hydrogeologic Unit 9: Underlying Unit 8, Unit 9 is a non-water-bearing unit (confining layer) and the framework's deepest unit, consisting primarily of dense basalt andesite dacite, dense clay, and sandy clay with inter-bedded sand pebbles and gravel. The unit was characterized mostly by dense basalt andesite dacite, which makes up about 46% of the geologic unit. Dense clay and sandy clay with inter-bedded sand pebbles and gravel made up another 53%, 43%, and 10%, respectively. Lithologic logs from 166 wells were used to define Unit 9. Unit 9 had the least number of available wells. However, these wells spatially covered most of the Ararat Valley groundwater basin with the highest concentration of wells located in the basin's center. The thickest part of the unit, based on the interpolated values, was in the central sub-region.

Tables 2 and 3 below provide respectively the summary statistics and summary descriptions of the nine hydrogeologic units identified in the Ararat Valley groundwater basin. The raster images on Figure 8 show spatial distribution of the thicknesses of all nine hydrogeologic units [10].

Table 2. Summary statistics on the main hydrogeologic units

Unit ID	*Primary geological material*	*Number of wells drilled into the unit*	*Average unit thickness (meters)*	*Maximum measured thickness within unit (meters)*
1	Loam/clay	2,301	8	51
2	Gravel	2,483	32	89
3	Clay	2,242	14	62
4	Gravel	2,346	27	110
5	Dense basalt/clay	1,462	9	73
6	Gravel	1,378	17	148
7	Dense basalt/clay	875	10	60
8	Gravel/fractured basalt	832	23	119
9	Dense clay	166	22	68

Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, USGS, 2017

Table 3. Summary of the main hydrogeologic units of the Ararat Valley groundwater basin

Hydro-geologic unit ID	*General name*	*Lithology*	*Water-bearing potential*
1	Loam/clay	Loam, dense clay, sandy loam, sandy clay with inter-bedded sand pebbles and gravel, boulder pebble deposits with clay filling, loam sandy loam, clay sand, and boulder pebble deposits with sand-clay filling	Low
2	Gravel	Boulder pebble deposits with coarse-grained sand and boulder filling, gravel, boulder pebble deposits with sand-clay filling, gravel sand, boulder pebble deposits with clay filling, slags and fragments of volcanic rocks and pumice sand, sandy loam, gravel pebble deposits with sand-clay filling, dense basalt andesite dacite, basalt with volcanic slag and sand, gravel deposits with clay filling, coarse-grained sand, highly-fractured crushed basalt, and sandy clay with inter-bedded sand pebbles and gravel	High
3	Clay	Dense clay, sandy clay with inter-bedded sand pebbles and gravel, dense basalt andesite dacite, loam sandy loam, volcanic tuff, sandy loam, gravel pebble deposits with clay filling, gravel pebble deposits with sand-clay filling, loam, clay sand, boulder pebble deposits with clay filling, and highly-fractured crushed basalt	Low
4	Gravel	Gravel pebble deposits with coursing-grained sand and boulder filling, boulder pebble deposits with coursing-grained sand filling, highly-fractured crushed basalt, gravel, slags and fragments of volcanic rocks and pumice sand, basalt with volcanic slag and sand, gravel sand, gravel pebble deposits with sand-clay filling, boulder pebble deposits with sand-clay filling, slightly fractured basalt porous, boulder pebble deposits with clay filling, sandy clay with inter-bedded sand pebbles and gravel, course- grained sand, fine-grained silty sand, and gravel pebble deposits with clay filling	High
5	Dense basalt/clay	Dense clay, dense basalt andesite dacite, sandy clay with inter-bedded sand pebbles and gravel, sandy loam, volcanic tuff, clay sand, loam, and boulder pebble deposits with sand-clay filling	Low
6	Gravel	Highly-fractured crushed basalt, gravel pebble deposits with coarse-grained sand and boulder filling, boulder pebble deposits with coarse-grained sand filling, gravel, boulder pebble deposits with sand-clay filling, slightly fractured basalt porous, fine –grained silty sand, basalt with volcanic slag and sand, slags and fragments of volcanic rocks and pumice sand, gravel pebble deposits with sand-clay filling, gravel sand, poorly cemented sandstone , gravel pebble deposits with clay filling, and sandy clay with inter-bedded sand pebbles and gravel	High
7	Dense basalt/clay	Dense basalt andesite dacite, dense clay, sandy clay with inter-bedded sand pebbles and gravel, loam, gravel pebbles deposits with sand-clay filling, and gypsiferous salt bearing clay with inter-bedded siltstone marl and sandstone	Low
8	Gravel/fractured basalt	Highly fractured basalt crushed, slightly fractured basalt porous, gravel pebble deposits with coarse-grained sand and boulder filling, basalt with volcanic slag and sand, boulder pebble deposits with coarse- grained sand filling, slags and fragments of volcanic rocks and pumice sand, and coarse – grained sand	High
9	Dense clay	Dense basalt andesite dacite, dense clay, and sandy clay with inter-bedded sand pebbles and gravel	Low

Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, USGS, 2017

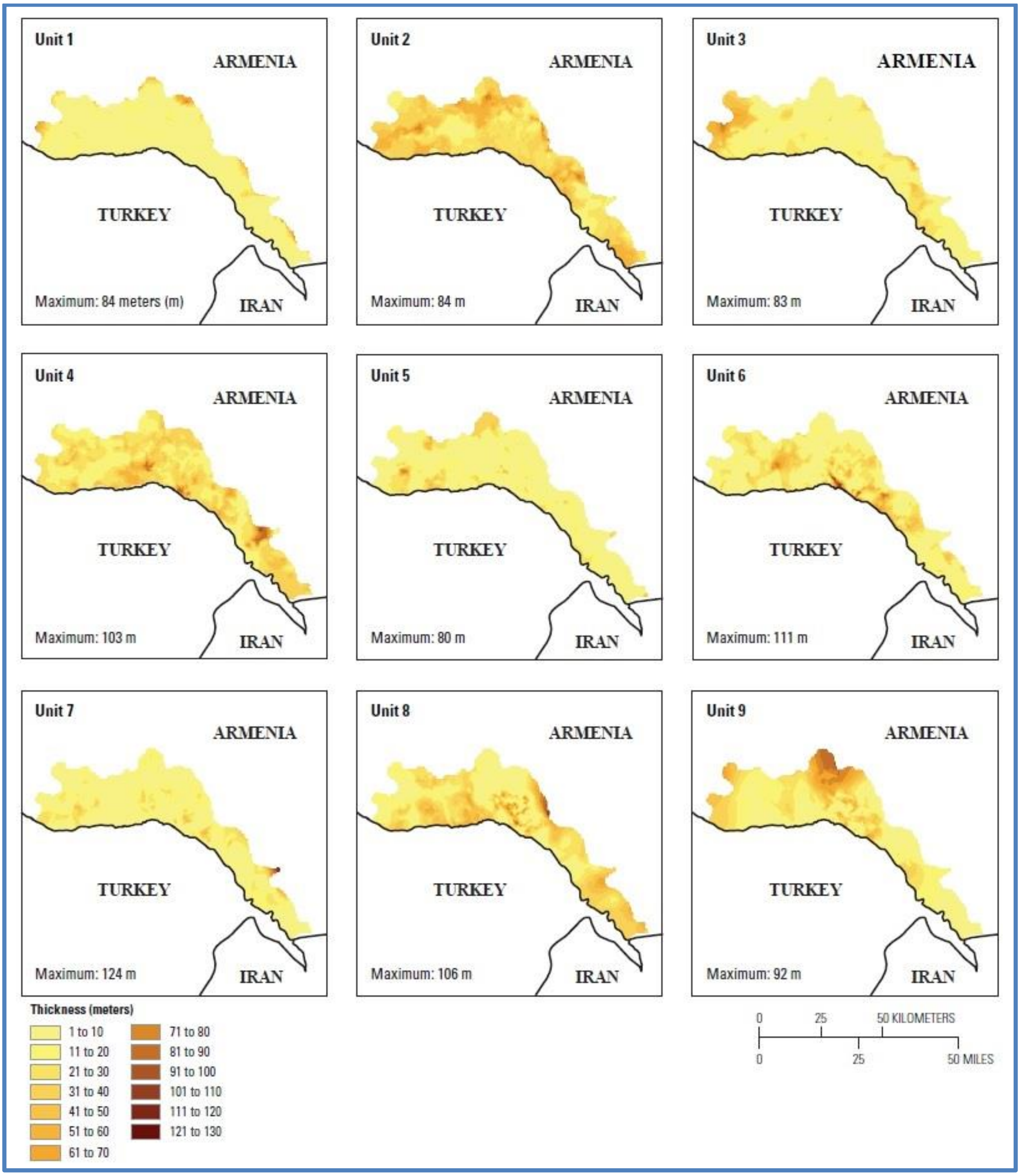


Figure 8: Thickness of all nine hydrogeologic units in the Ararat Valley groundwater basin ***(Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, USGS, 2017)***

3.5. Maps of the Potentiometric Surfaces

USGS used data collected during the 2016 well inventory to construct potentiometric surface maps of the four water-bearing units in the Ararat Valley groundwater basin, namely Units 2, 4, 6 and 8 [10]. Potentiometric surface maps were generated using GIS software for each of the four water-bearing hydrogeologic units (Figures 9-12). The potentiometric surface for Hydrogeologic Unit 2 had limited available water-level measurements because the 2016 well inventory focused on the confined and didn't contain data for the unconfined aquifer. The direction of groundwater flow in Hydrogeologic Units 2, 4, 6, and 8 was estimated based on flow paths drawn perpendicular to potentiometric contours.

Hydrogeologic Unit 2: Hydrogeologic Unit 2 is the shallowest aquifer and is considered a surface aquifer. For Hydrogeologic Unit 2, the estimated direction of groundwater flow is from the west to north in the western part of the study area (away from the Araks River) and from west to east and north to south (toward the Araks River) in the eastern part of the study area. The flow paths indicate that while the Araks River is a losing stream (discharging to groundwater) in the western part of the basin, it is a gaining stream (groundwater is discharging to the river) in the eastern part of the basin (Figure 9).

Hydrogeologic Unit 4: In Hydrogeologic Unit 4, the general direction of groundwater flow is from west to east and north to south (toward the Araks River); however, groundwater flow is northwesterly in the northwestern part of the study area (Figure 10).

Hydrogeologic Unit 6: Hydrogeologic Unit 6 has this same general pattern of groundwater flow (Figure 11) as Hydrogeologic Unit 4.

Hydrogeologic Unit 8: Hydrogeologic Unit 8 is the deepest of the aquifer units and it is confined in the study area. Groundwater-flow direction is from the south to north (away from the Araks River) in the western part of the study area (Figure 12).

After analyzing the potentiometric maps, USGS came to the following conclusions [10]:

- Groundwater flow is from west to east and north to south (toward the Araks River) elsewhere in the Ararat Valley groundwater basin.
- The large spacing between potentiometric contours in the center of the basin coincides with areas of heavy groundwater withdrawals and high well densities in Hydrogeologic Unit 8.
- The large spacing between potentiometric contours in Hydrogeologic Unit 8 in the center of the study area could indicate high transmissivity relative to areas with closer contour spacing.

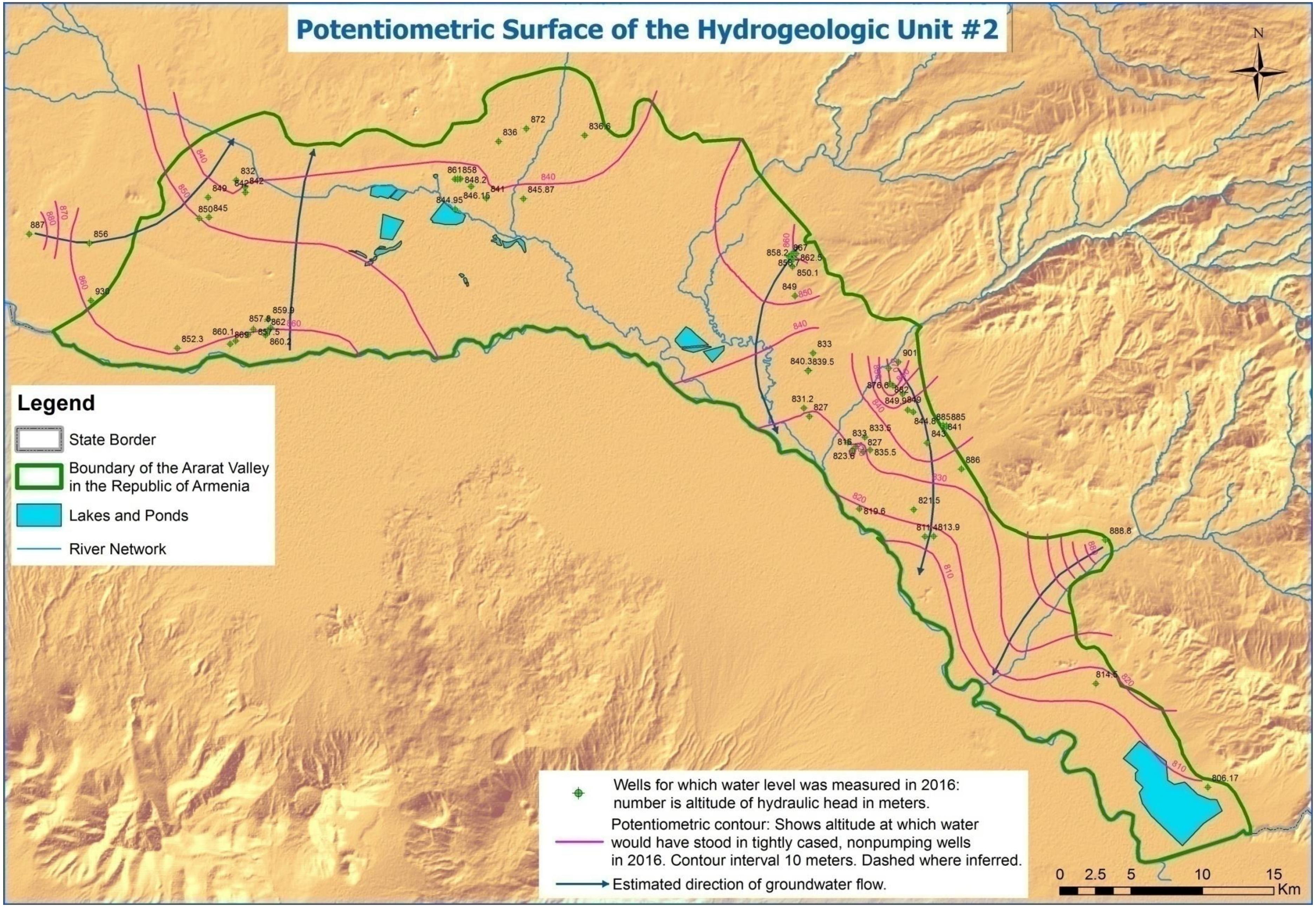


Figure 9: Potentiometric Surface of the Hydrogeologic Unit #2 ***(Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, 2017)***

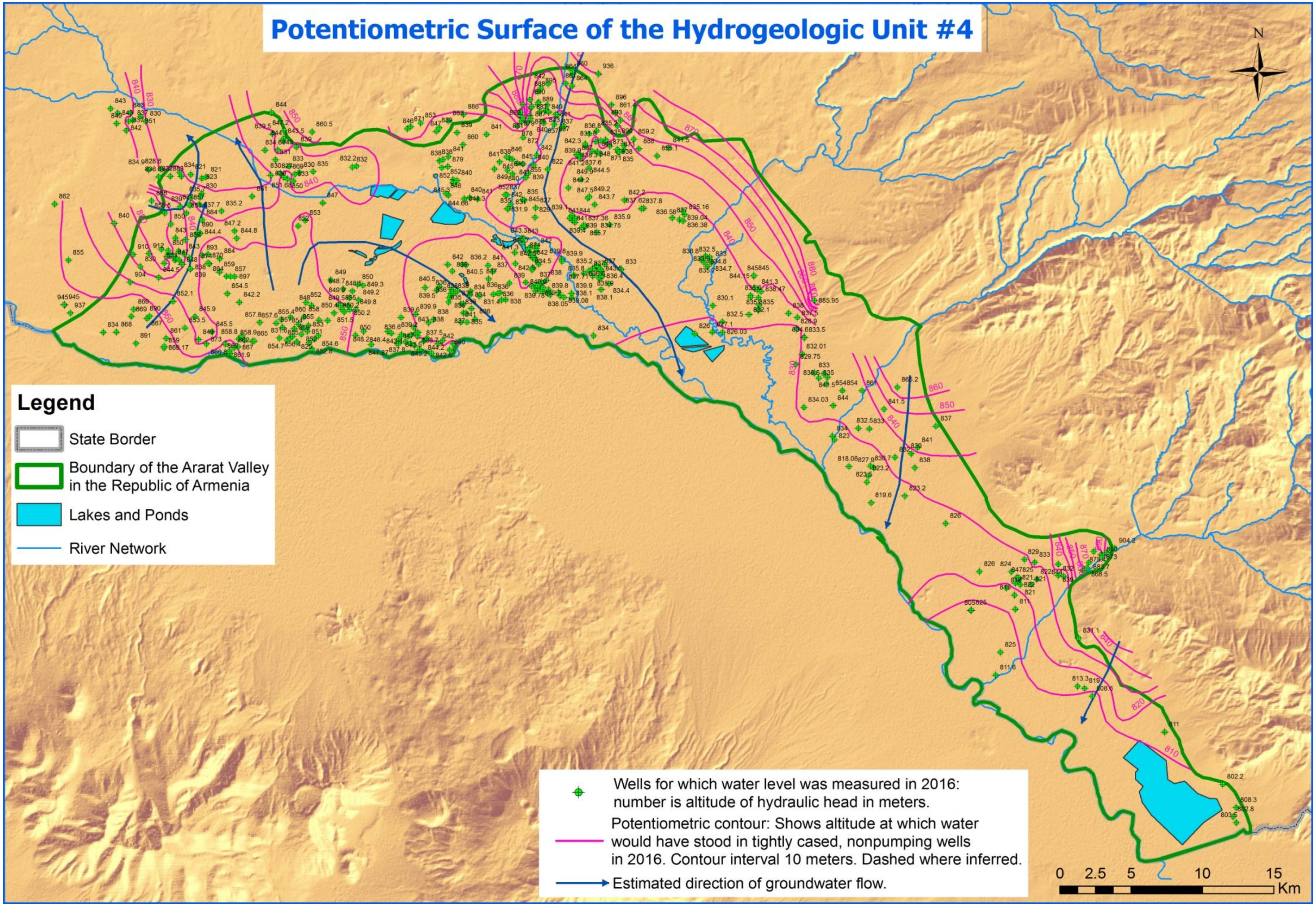


Figure 10: Potentiometric Surface of the Hydrogeologic Unit #4 ***(Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, 2017)***

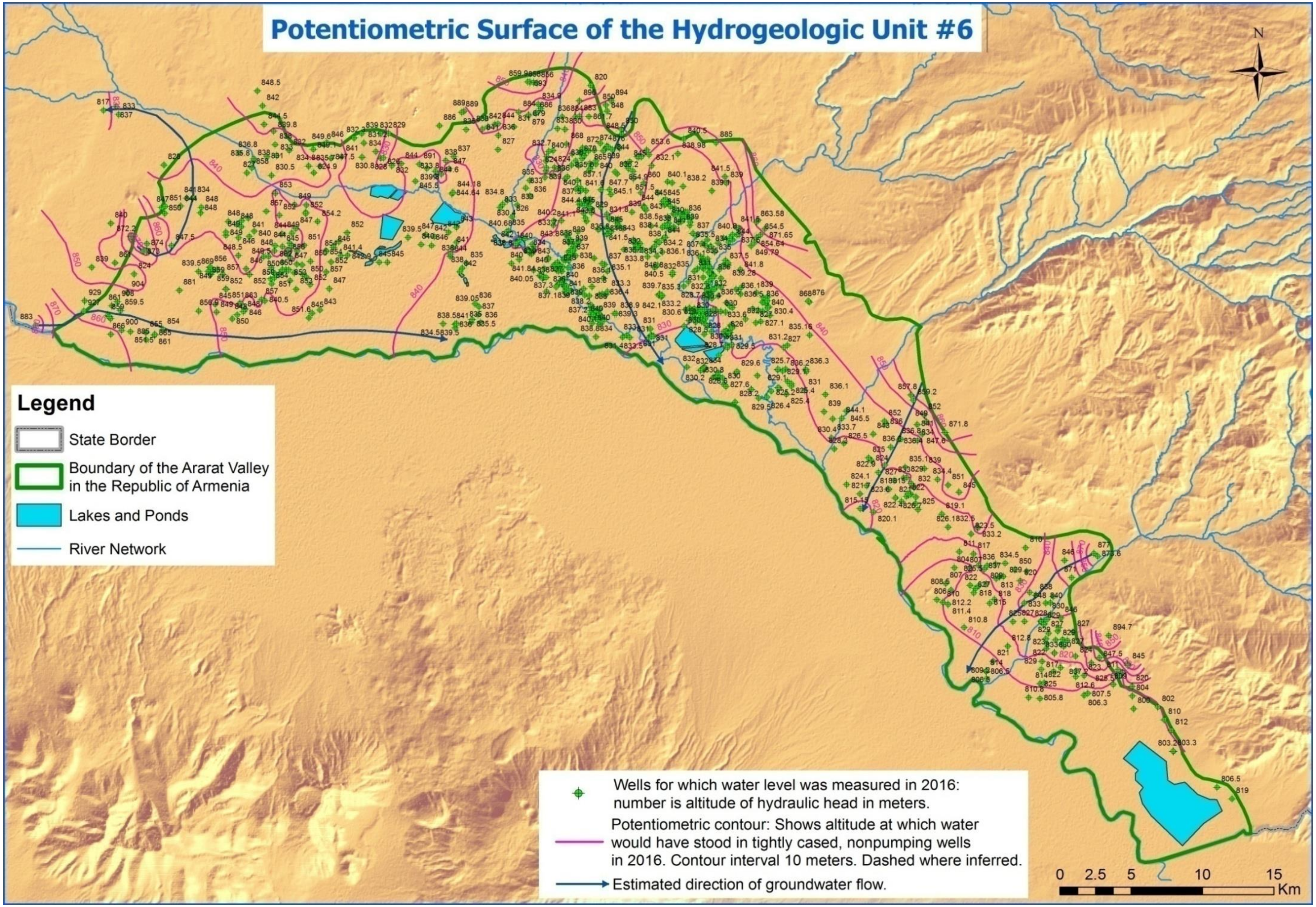


Figure 11: Potentiometric Surface of the Hydrogeologic Unit #6 ***(Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, 2017)***

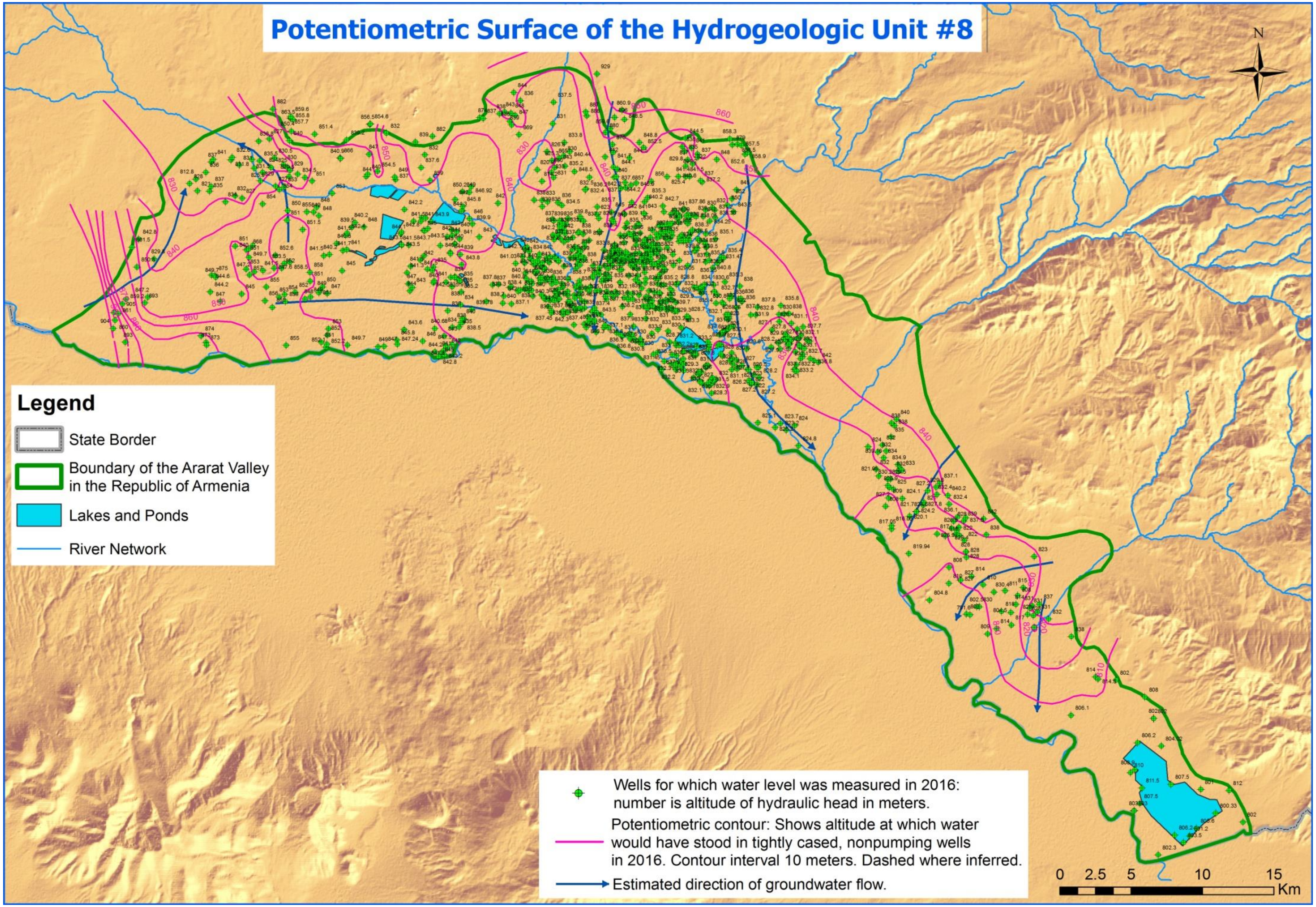


Figure 12: Potentiometric Surface of the Hydrogeologic Unit #8 ***(Source: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, 2017)***

4. THREE-DIMENSIONAL MODEL OF THE ARARAT VALLEY GROUNDWATER BASIN

4.1. Methodology

Modeling of the three-dimensional (3D) structure of the Ararat Valley groundwater basin is one of the main components of the Conceptual Model. The ASPIRED team implemented the following consecutive steps for modeling the 3D structure of the groundwater basin:

1. Storing the hydrogeologic data into a geo-spatial database;
2. Analyzing the wells stratigraphy and defining the main hydrogeologic units;
3. Creating a geodatabase on well locations and lithology within the AHGW tools;
4. Constructing the 3D images of wells;
5. Constructing the geo-rasters for the main hydrogeologic units;
6. Constructing the 2D cross-sections for the main hydrogeologic units;
7. Constructing the 3D model of the groundwater basin; and
8. Calculating the total volumes for each main hydrogeologic unit.

The paragraphs below present detailed methodology for implementing the above-mentioned steps, using Training Materials on Stratigraphic and Groundwater Modeling with AHGW, GMS, and MODFLOW programs developed by AQUAVEO [12].

Step 1: Storing the hydrogeologic data into a geo-spatial database

This section presents the minimum set of hydrogeologic data needed for modeling of the 3D structure of the groundwater basin. The following two main datasets are needed for constructing the geo-spatial database:

- Static data on the wells, including well identification number (well ID), location (geographic latitude and longitude in metric format), absolute altitude above sea level (in meters), depths (in meters), purpose of use, type of aquifer, etc. This dataset can be generated either from well logs or the results of inventory (see sample data table in the Figure 13 below).

Well_ID	X	Y	LandElev	Ftype	WellDepth	AqCode
17	444005.3	4439695.1	835	Fish farming	95	Confined
18	445851.4	4439971.6	834	Fish farming	85	Confined
19	445845.8	4440187.4	836	Fish farming	85	Confined
21	485840.9	4398894.9	816	Irrigation Drinking-household	120	Confined
22	484427.6	4401471.9	821	Previously irrigation	75	Confined
23	485366.7	4399833.0	817	Previously irrigation	100	Confined
24	478527.3	4402435.7	805	Fish farming	148	Confined
25	478268.3	4402550.5	807	Fish farming	148	Confined
26	477949.0	4402357.2	804	Fish farming	148	Confined
27	479115.6	4401805.2	807	Previously fish farming	148	Confined

Figure 13: Sample data table on wells (Well Table) ***(source: AQUAVEO, 2018)***

- Morphologic and hydrogeologic data, including well ID, altitude, stratigraphic layer ID, stratigraphic layer name, stratigraphic layer width, the thickness of the stratigraphic layers, as well as elevation values of tops and bottoms for each stratigraphic layer. Depending on the complexity of the lithology, this table is commonly called a "Borehole Table" and is comprised of several records to describe the stratigraphic structure of one well (Figure 14).

ID	Well ID	Ftype	Ref Elev	From Depth	To Depth	Thickness	Top Elev	Bottom Elev	Layer Name	Layer ID
1	17	Non-Permeable	832.0	0.0	4.0	4.0	832.0	828.0	Loam	1
2	17	Permeable	832.0	4.0	28.0	24.0	828.0	804.0	Gravel	2
3	17	Non-Permeable	832.0	28.0	31.5	3.5	804.0	800.5	Clay	3
4	17	Permeable	832.0	31.5	68.0	36.5	800.5	764.0	Gravel	4
5	17	Non-Permeable	832.0	68.0	70.0	2.0	764.0	762.0	Clay	5
6	17	Permeable	832.0	70.0	105.0	35.0	762.0	727.0	Basalt	8
7	18	Non-Permeable	832.0	0.0	4.0	4.0	832.0	828.0	Loam	1
8	18	Permeable	832.0	4.0	28.0	24.0	828.0	804.0	Gravel	2
9	18	Non-Permeable	832.0	28.0	31.5	3.5	804.0	800.5	Clay	3
10	18	Permeable	832.0	31.5	68.0	36.5	800.5	764.0	Gravel	4
11	18	Non-Permeable	832.0	68.0	70.0	2.0	764.0	762.0	Clay	5
12	18	Non-Permeable	832.0	70.0	110.0	40.0	762.0	722.0	Basalt	7
13	19	Non-Permeable	831.0	0.0	4.0	4.0	831.0	827.0	Loam	1
14	19	Permeable	831.0	4.0	28.0	24.0	827.0	803.0	Gravel	2
15	19	Non-Permeable	831.0	28.0	31.5	3.5	803.0	799.5	Clay	3
16	19	Permeable	831.0	31.5	68.0	36.5	799.5	763.0	Gravel	4
17	19	Non-Permeable	831.0	68.0	70.0	2.0	763.0	761.0	Clay	5
18	19	Non-Permeable	831.0	70.0	110.0	40.0	761.0	721.0	Basalt	7
19	20	Non-Permeable	835.0	0.0	3.6	3.6	835.0	831.4	Loam	1
20	20	Permeable	835.0	3.6	26.3	22.7	831.4	808.7	Gravel	2
21	20	Non-Permeable	835.0	26.3	28.0	1.7	808.7	807.0	Clay	3
22	20	Permeable	835.0	28.0	63.0	35.0	807.0	772.0	Gravel	4
23	20	Non-Permeable	835.0	63.0	65.0	2.0	772.0	770.0	Clay	5
24	20	Non-Permeable	835.0	65.0	93.0	28.0	770.0	742.0	Basalt	7
25	21	Non-Permeable	833.0	0.0	3.6	3.6	833.0	829.4	Loam	1
26	21	Permeable	833.0	3.6	26.3	22.7	829.4	806.7	Gravel	2
27	21	Non-Permeable	833.0	26.3	28.0	1.7	806.7	805.0	Clay	3
28	21	Permeable	833.0	28.0	63.0	35.0	805.0	770.0	Gravel	4
29	21	Non-Permeable	833.0	63.0	65.0	2.0	770.0	768.0	Clay	5
30	21	Non-Permeable	833.0	65.0	90.0	25.0	768.0	743.0	Basalt	7

Figure 14: Sample data table on wells lithology (Borehole Table) ***(source: AQUAVEO, 2018)***

As soon as the mentioned datasets are accumulated in the Microsoft Excel format, they should be transferred into a geo-spatial database under the AHGW tools. As an intermediate step, this transfer could require using the text files. This mean that the Excel table should first be converted into the text file and then imported into the geodatabase under the AHGW Tools (see also Step 3 of this methodology). After the conversion, there is a need to verify that both tables contain "Well_ID" field through which they can be interlinked. This linking is crucial for proper generation of 3D images of the wells in further steps of the task.

Step 2: Analyzing the wells stratigraphy and defining the main hydrogeologic units

The complexity of the hydrogeologic structure of the groundwater basin requires grouping the stratigraphic layers of the wells into bigger hydrogeologic units. Such consolidation of the stratigraphic layers into the hydrogeologic units should be based on lithology and water-bearing potentials of the layers and would require the technical assistance of hydro-geologists (Figure 15).

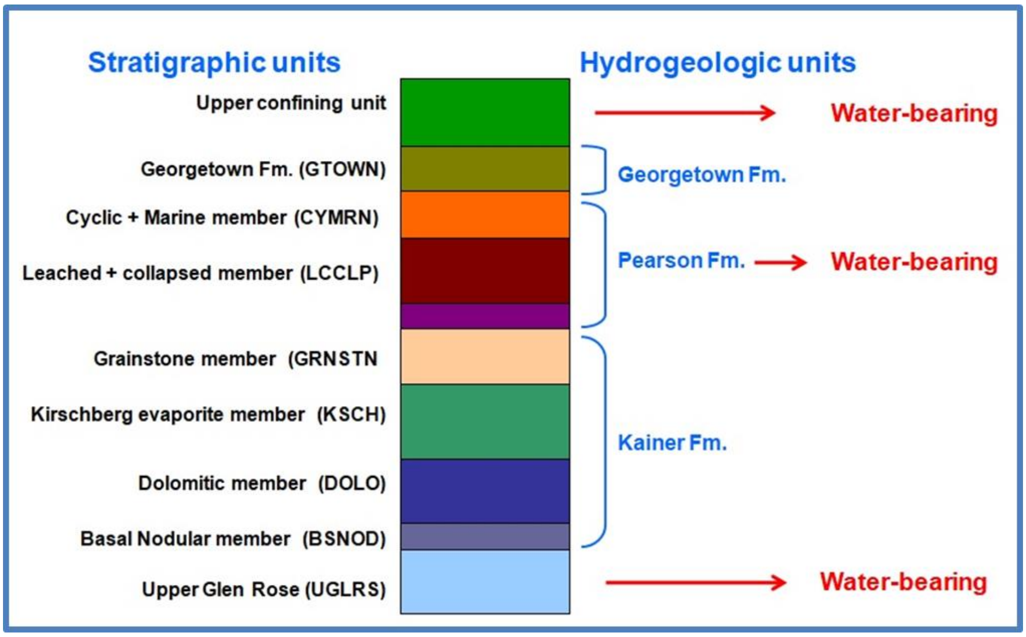


Figure 15: Grouping the stratigraphic layers into hydrogeologic units *(source: AQUAVEO, 2018)*

As a result of consolidation, the newly created hydrogeologic units will get unique identifiers (HGUID). Then each record in the Borehole Table created in Step 1 should be updated with these HGUIDs. In addition, each hydrogeologic unit will be assigned to so-called "Horizon ID", which shows the number of the ceiling for the given hydrogeologic unit started from the bottom layer of the groundwater basin. Figure 16 demonstrates the correlation between the HGUID and Horizon ID. The Horizon IDs will then be used in generating the geo-rasters for the main hydrogeologic units (see Step 5 of the methodology).

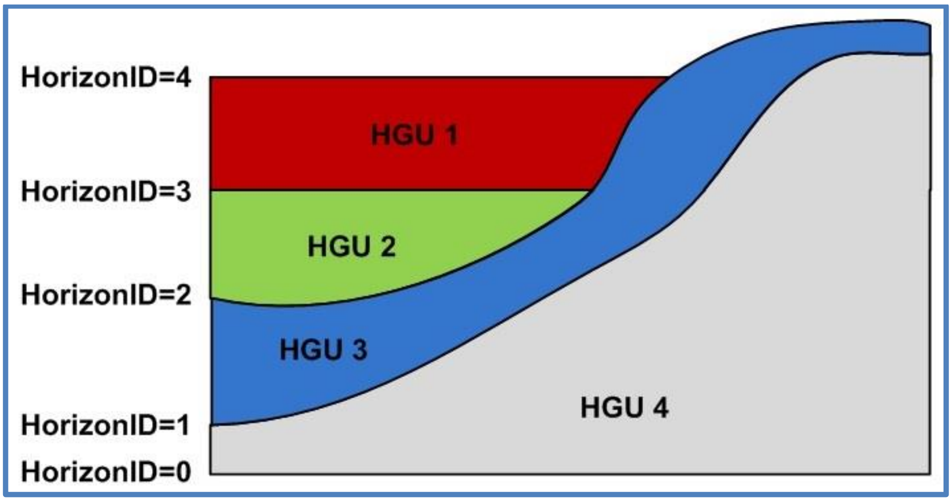


Figure 16: Hydrogeologic Unit IDs and Horizon IDs *(source: AQUAVEO, 2018)*

Step 3: Creating a geodatabase on well locations and lithology within the AHGW tools

To create a geodatabase in AHGW Tools, the “Create Blank AHGW Geodatabase” command of the Groundwater Analyst Tool should be used. After naming the geodatabase, the proper coordinate system and projection should be defined. For Armenia the WGS-1984 coordinate system is recommended with the UTM Zone 38N Projection. In the newly opened geodatabase it is recommended to create two tables (“HydrogeologicUnit” and “BoreholeLog”) and two shape files (“Well” and “BoreLine”).

The static well data table should then be exported to the “Well” shapefile, while the well lithology data table - to the BoreholeLog table and BoreLine shapefile of the AHGW Geodatabase. The spatial linkages between the BoreholeLog table and Well shapefile are to be provided through *HGUID* field (see Figures 17 and 18).

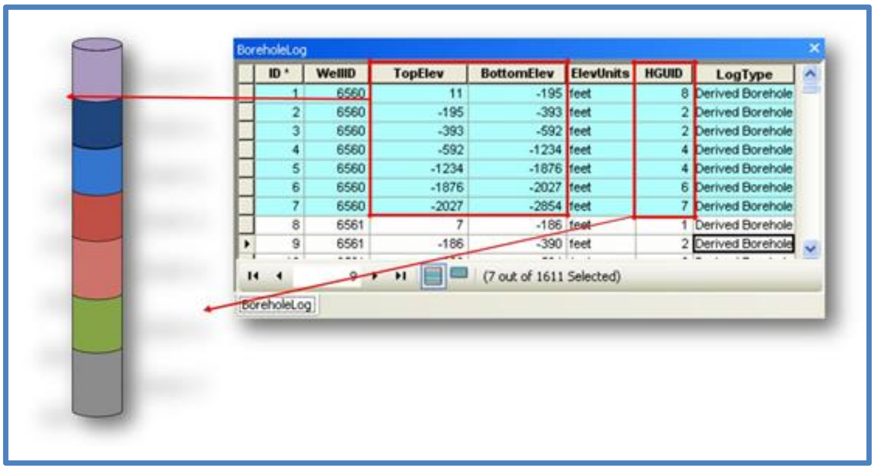


Figure 17: Sample BoreholeLog table with HGUID field *(source: AQUAVEO, 2018)*

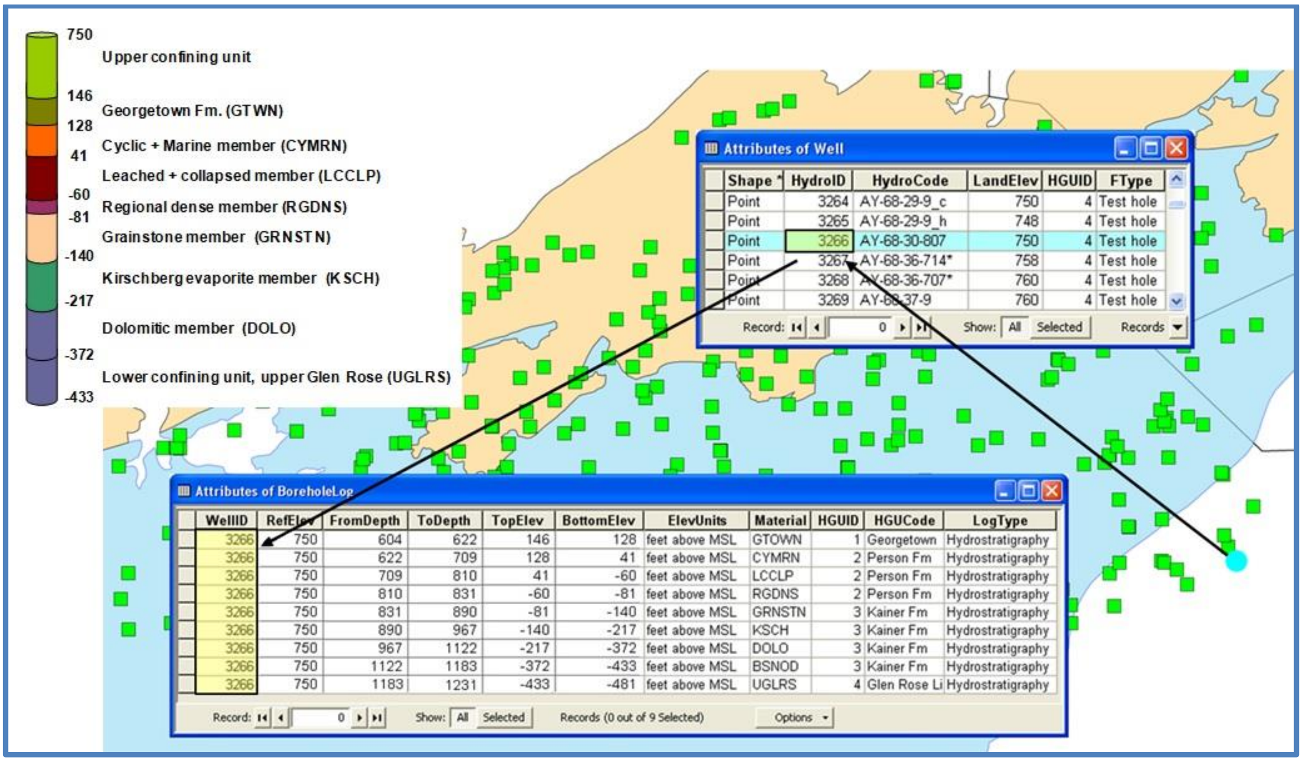


Figure 18: Spatial linkages between the Well and BoreholeLog tables through the WellID field *(source: AQUAVEO, 2018)*

The hydrogeologic units are inputted and maintained in the *HydrogeologicUnit* table of the AHGW Geodatabase. Each hydrogeologic unit has a unique identifier stored in the *HGUID* field, which is a key field used for linking the hydrogeologic unit to the *BoreholeLog* table and *BoreLine* shapefile.

In addition to the above-mentioned data tables and shape files, the AHGW Geodatabase should also contain a vector layer on the boundary of the modeling area and a raster image on the elevations of the area under consideration. The LandSAT 30m Digital Elevation Model (DEM) can be used for this purpose (freely available through the USGS Earth Explorer website https://earthexplorer.usgs.gov).

Step 4: Constructing the 3D images of wells

As soon as data in *Wells* shapefile and *BoreholeLog* table are properly linked through the HGUID field, it is possible to construct the 3D images of the wells using the Geoprocessing Tool under the ArcScene package. This tool will create the 3D images of the wells and store them in *BoreLines* shapefile based on the locations of the wells (*Wells* shapefile) and their lithologic structures (*BoreholeLog* table) according to the main hydrogeologic units. Combining the well geometry (x, y) and the vertical data stored in the *BoreholeLog* table the tool describes a set of 3D geometries (x, y, z). The visualization of the 3D images is also possible within the ArcScene package (Figure 19).

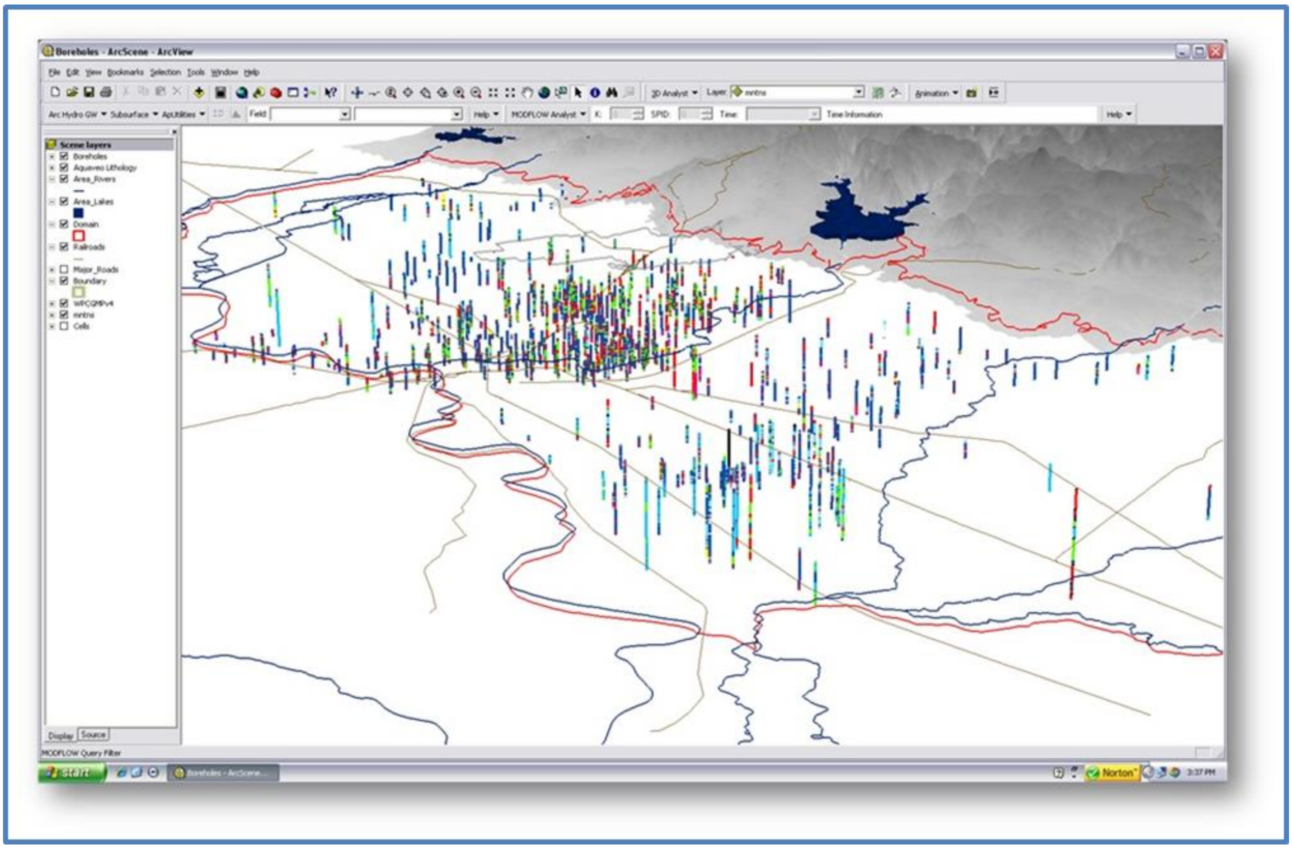


Figure 19: 3D images of the wells based on the main hydrogeologic units visualized in ArcScene package *(source: AQUAVEO, 2018)*

Step 5: Constructing the geo-rasters for the main hydrogeologic units

Constructing the geo-rasters requires creating a GeoRaster Catalog for storing and indexing raster datasets within the AHGW extension. After this step is completed, geo-rasters for each hydrogeologic unit based on the data stored in *Borelines* shapefile and *BoreholeLog* table are constructed, as described below:

- Create a point shapefile for each hydrogeologic unit by running the “BoreholeLog table to 3D points” tool under the AHGW extension;
- Use the “Interpolate 3D points to rasters” tool under the AHGW extension to generate the raster images though interpolation of the point data; and
- Load the newly generated raster images into the GeoRasters raster catalog.

The GeoRasters raster catalog stores the tops and bottoms of formations indexed with HorizonID.

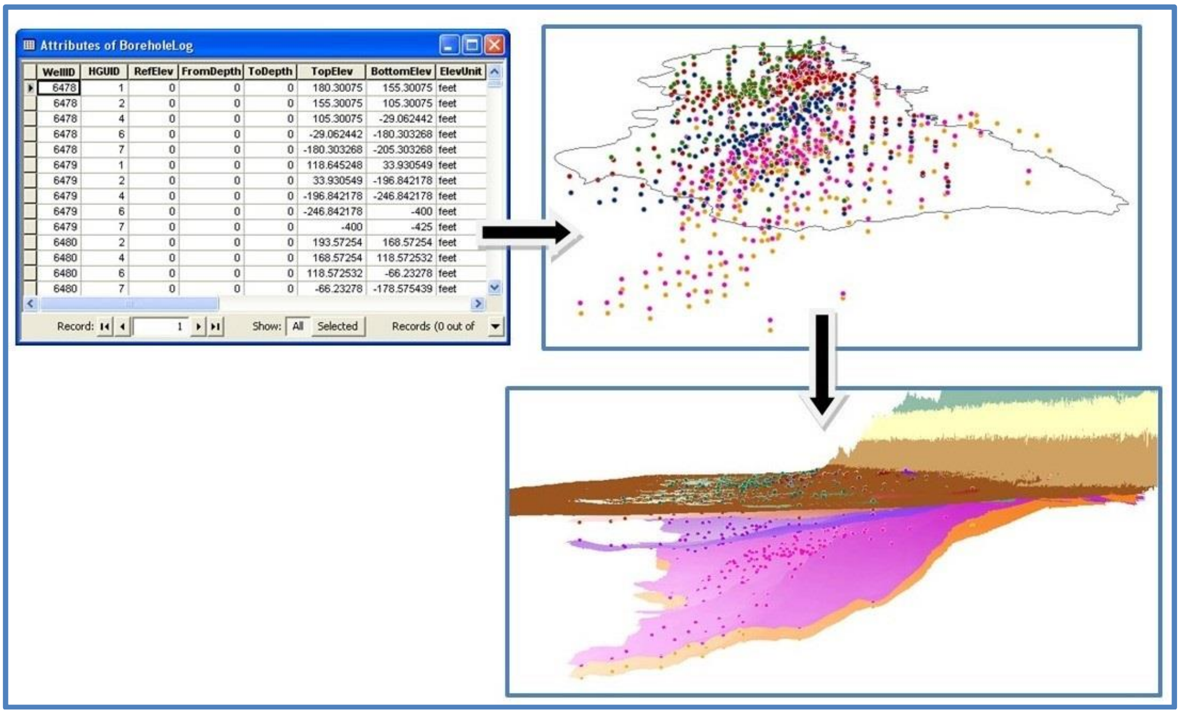


Figure 20: Steps to construct the geo-rasters ***(source: AQUAVEO, 2018)***

After constructing the geo-rasters, all the main hydrogeologic units are defined in the following approach:

- The first geo-raster presents the bottom of the deepest hydrogeologic unit;
- The second geo-raster presents the bottom of the second hydrogeologic unit from the bottom which is at the same time the ceiling of the deepest hydrogeologic unit;
- …
- The last geo-raster presents the bottom of the first uppermost hydrogeologic unit which is at the same time the ceiling of the second uppermost hydrogeologic unit; and
- The DEM is considered a ceiling of the first uppermost hydrogeologic unit (Figure 21).

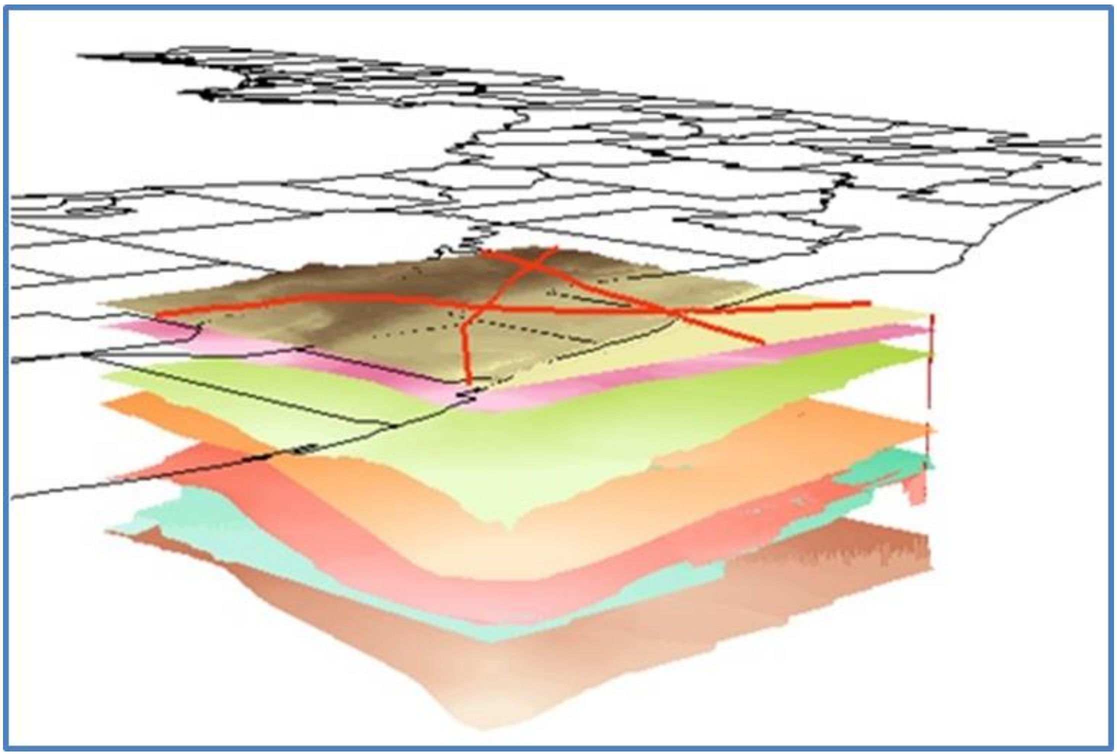


Figure 21: Visualization of the geo-rasters in ArcScene package ***(source: AQUAVEO, 2018)***

Step 6: Constructing the 2D cross-sections for the main hydrogeologic units

Generating 2D cross-sections is an interim step between geo-rasters and the three-dimensional image of the groundwater basin. To construct the cross-sections of the groundwater basin, the *Raster to GeoSections* tool should be used under the AHGW Subsurface Analyst component. Each cross-section will contain the 2D image of the hydrologic units that are present at given location (see Figure 22 below).

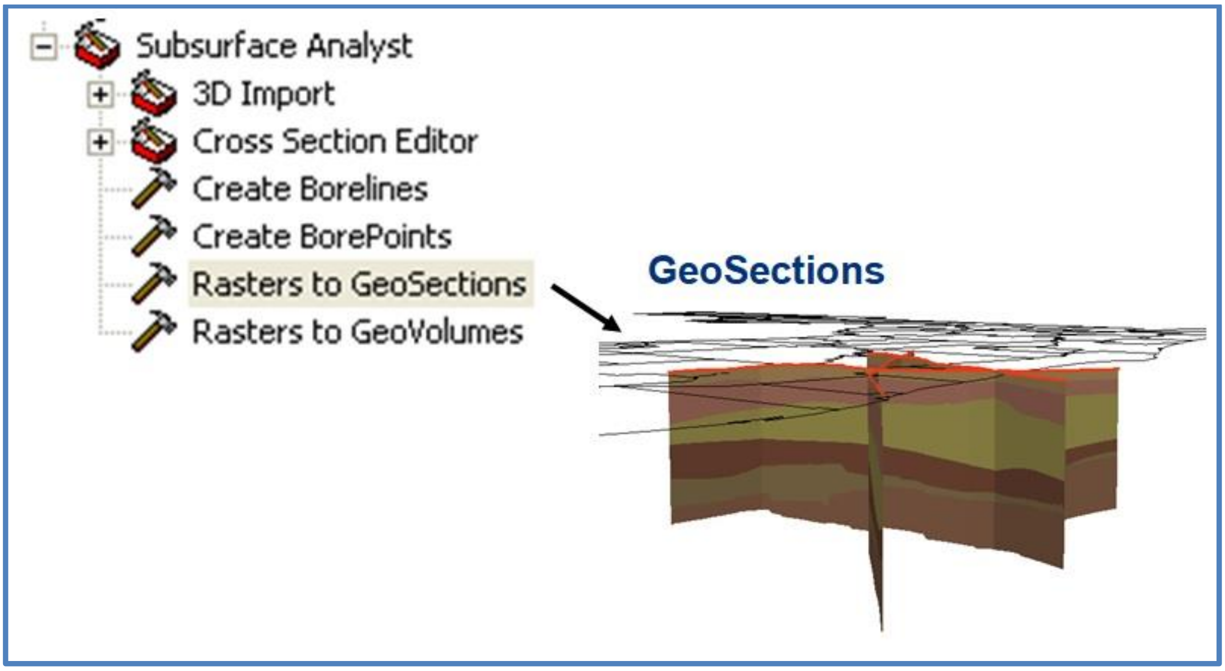


Figure 22: Creating 2D cross-sections ***(source: AQUAVEO, 2018)***

The cross-sections allow greater control of interpolation and lead to improved accuracy of the future 3D image. There is no limit to number of cross-sections for the given groundwater basin. Generating more cross-sections can lead to higher accuracy of the interpolation and the 3D image process. The visualization of the 2D cross-sections is done in the ArcScene package (see Figure 23 below).

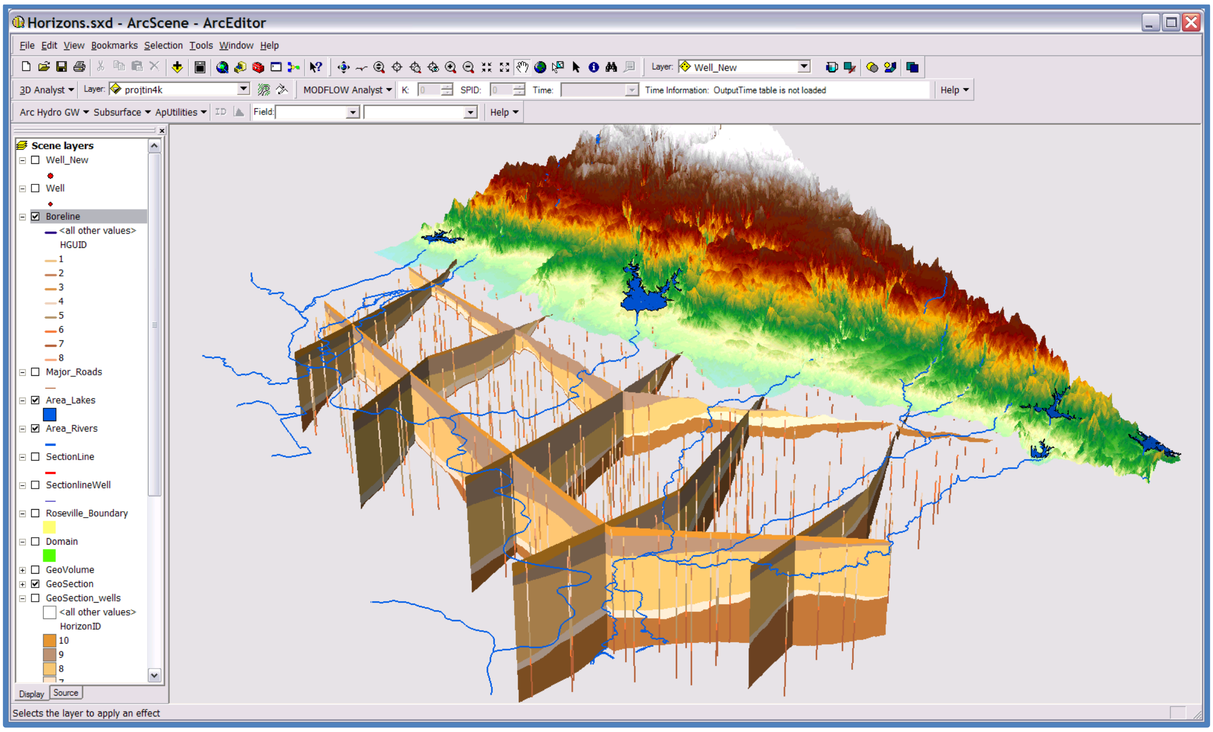
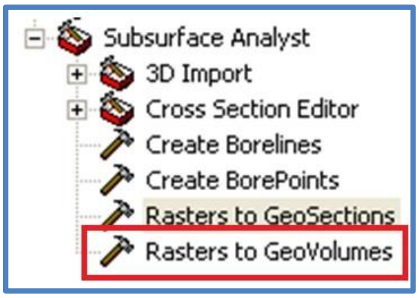


Figure 23: Visualization of the cross-sections in the ArcScene package *(source: AQUAVEO, 2018)*

Step 7: Constructing the 3D model of the groundwater basin

Based on the geo-rasters generated in Step 5 and 2D cross-sections obtained in Step 6, it is possible to construct the 3D images of the main hydrogeologic units and the entire groundwater basin using the AHGW Tools by running the *Polygon to TIN* tool for the geo-rasters. The tool constructs the Triangulated irregular network (TIN) for each geo-raster. The TIN is a representation of a continuous surface consisting entirely of triangular facets. Associated with 3D data (x, y, and z) and topography, TINs are useful for the description and analysis of general horizontal (x and y) distributions and relationships.

After generating TINs for geo-rasters, the *Rasters to GeoVolumes* tool under the AHGW Subsurface Analyst should be used for constructing the 3D images of the hydrogeologic units and the entire groundwater basin. The visualization of the 3D image is done in the ArcScene package (see Figure 24 below).



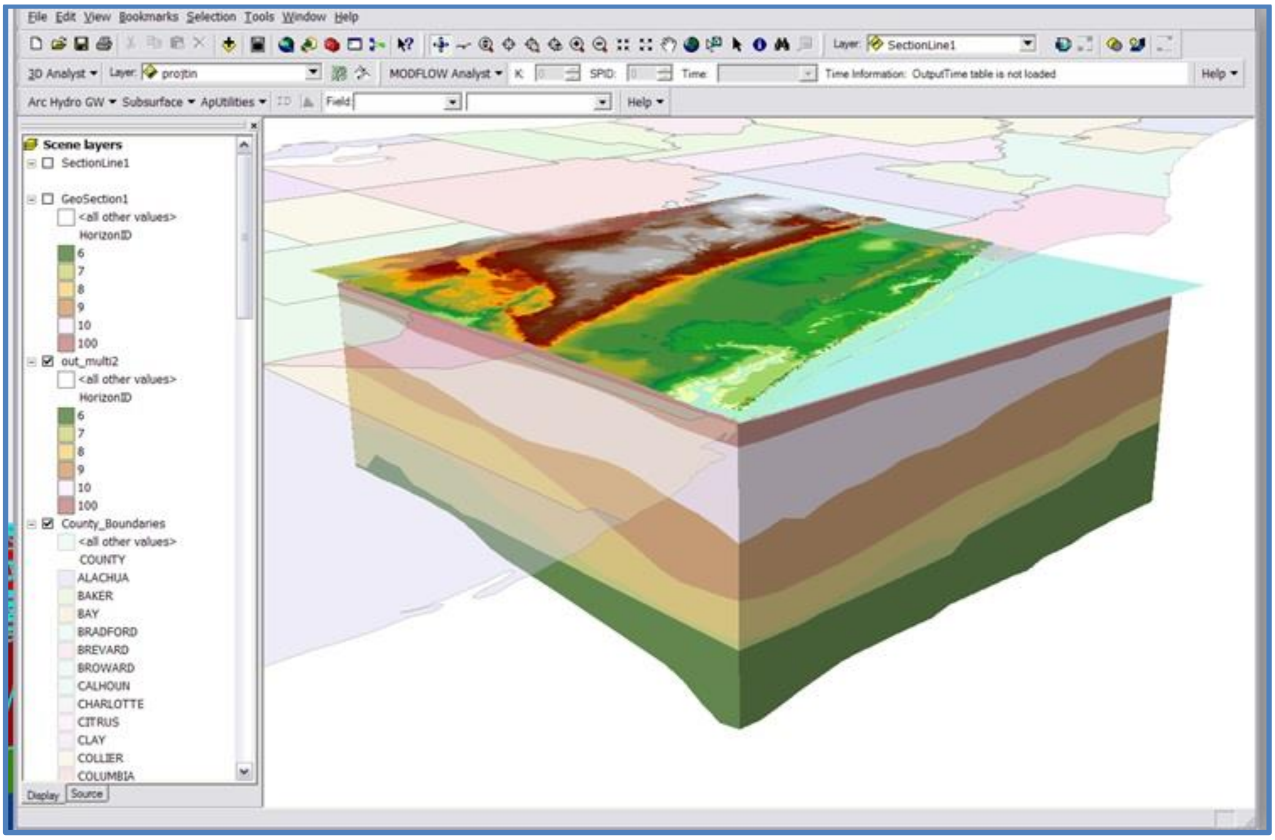


Figure 24: Visualization of the groundwater basin 3D model in ArcScene package *(source: AQUAVEO, 2018)*

Step 8: Calculating the total volumes for each main hydrogeologic unit

After generating the 3D structures for the main hydrogeologic units, it is possible to calculate the total volumes of each unit – the numerical values expressed in cubic meters. To do that, one would run the "Add Z Information (3D Analyst)" geoprocessing tool in the AHGW GeoVolume multi-patch feature class. This tool will add information about elevation properties of features in a Z-enabled feature class. Each 3D shape is examined and the data on elevation will be appended to the attribute table of the input feature class. This tool will also add the volume of each multi-patch feature to the attribute table in a "Volume" field as long as the multi-patch is closed.

Is Closed 3D geoprocessing tool in the AHGW GeoVolume multi-patch feature class can be used to verify that the geo-volumes of all hydrogeologic units are closed. This tool will add a new field called *IsClosed* that indicates whether a given feature is closed.

If any of the geo-volumes are not closed, the "Surface Difference" geoprocessing tool should be used to calculate the volume between two surfaces for each triangle. This would require an intermediate step, such as creating TINs for each surface and summing the volumes for each triangle in the output dataset.

4.2. Main Outcomes

The ASPIRED Project built the 3D structure of the Ararat Valley groundwater basin was built using the methodology described in the previous section of this report. An ArcGIS extension called *Arc Hydro Groundwater* (AHGW) *Tools* was used for this purpose.

4.2.1. Locations of Wells and their Lithologic Structure

The 3D lithologic model of the Ararat Valley groundwater basin is based on 2016 well inventory data of the Ararat Valley, including the geographic coordinates of the wells, altitude above sea level, stratigraphy (rock structure, thickness, and depth), and geological structure of rocks (see Figure 25 for the locations of the wells).

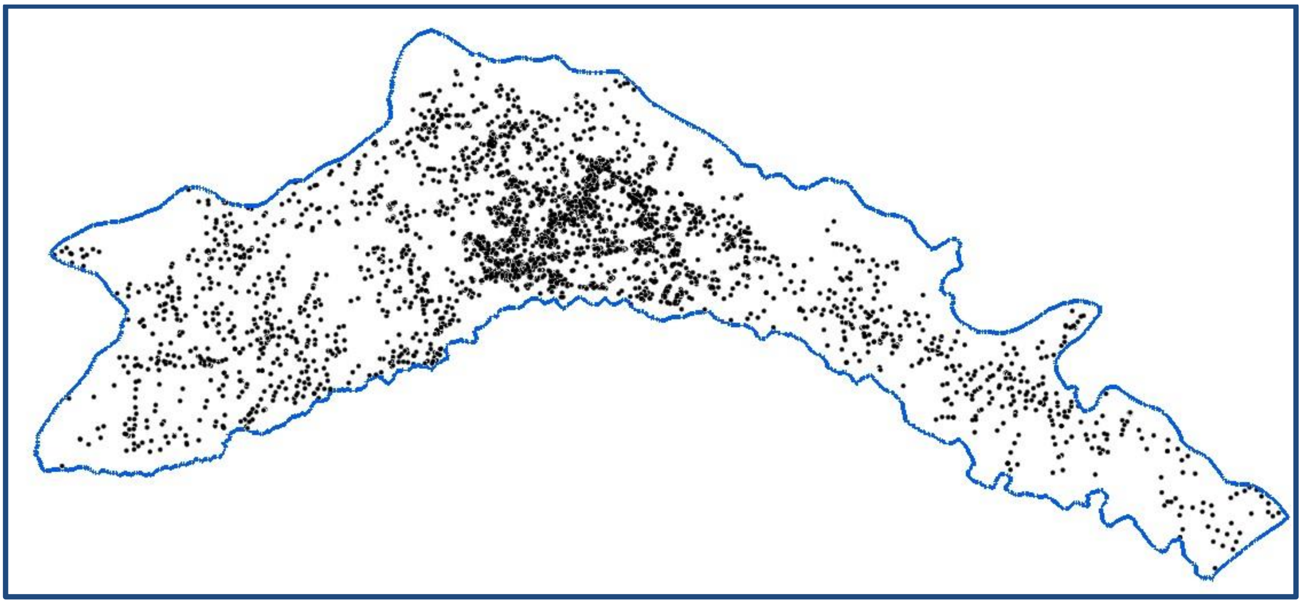


Figure 25: Location of the wells in the Ararat Valley according to 2016 inventory data *(Source: ASPIRED Project)*

Each of more than 2800 wells was linked to its lithologic structure, with the lithologic structure of each well grouped into one of the nine main hydrogeologic units presented in the previous chapter of this report. Figures 26 and 27 show 3D visualizations of the well lithology under different perspectives.

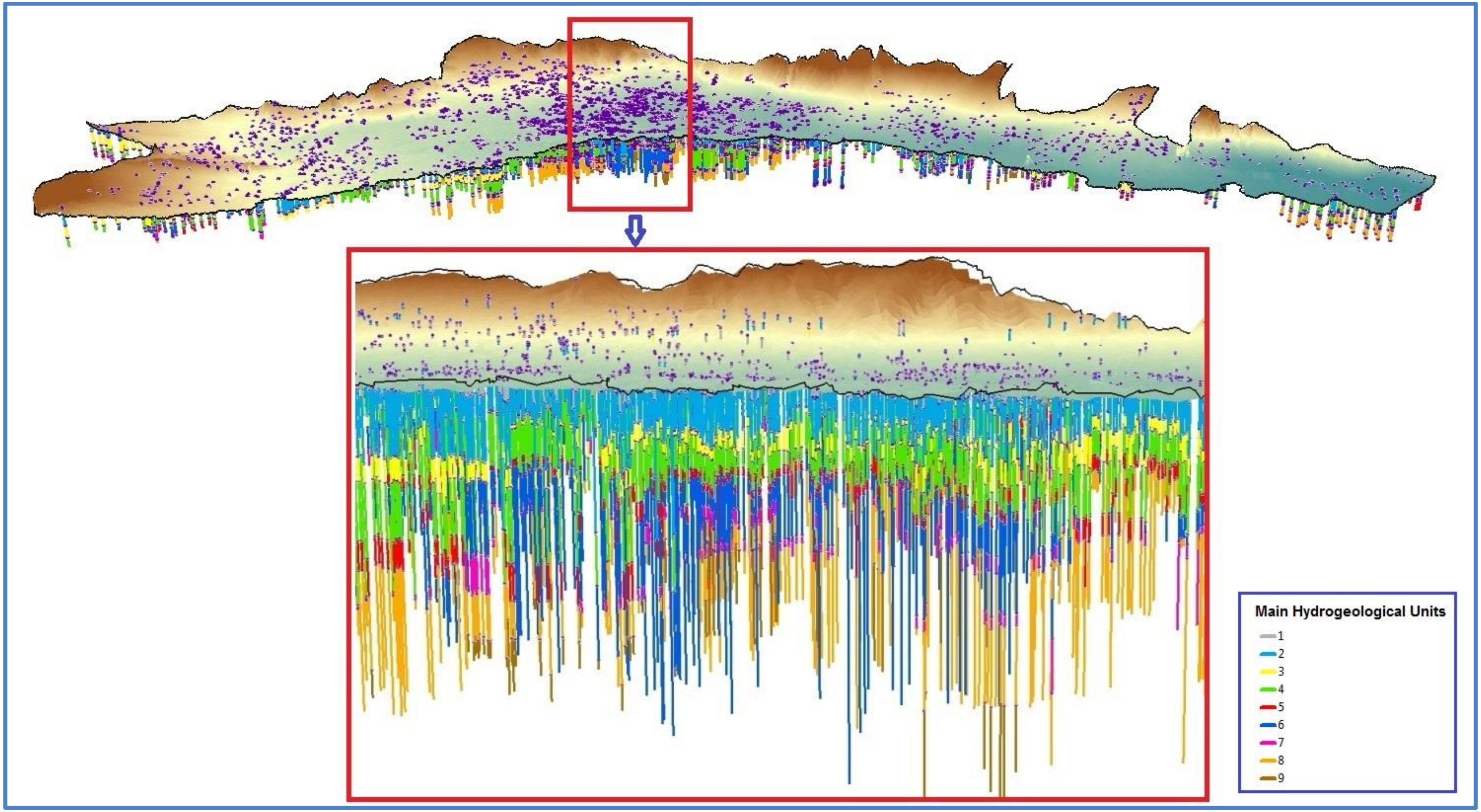


Figure 26: The 3D visualization of the borehole lithologic structure in the Ararat Valley ***(Source: ASPIRED Project)***

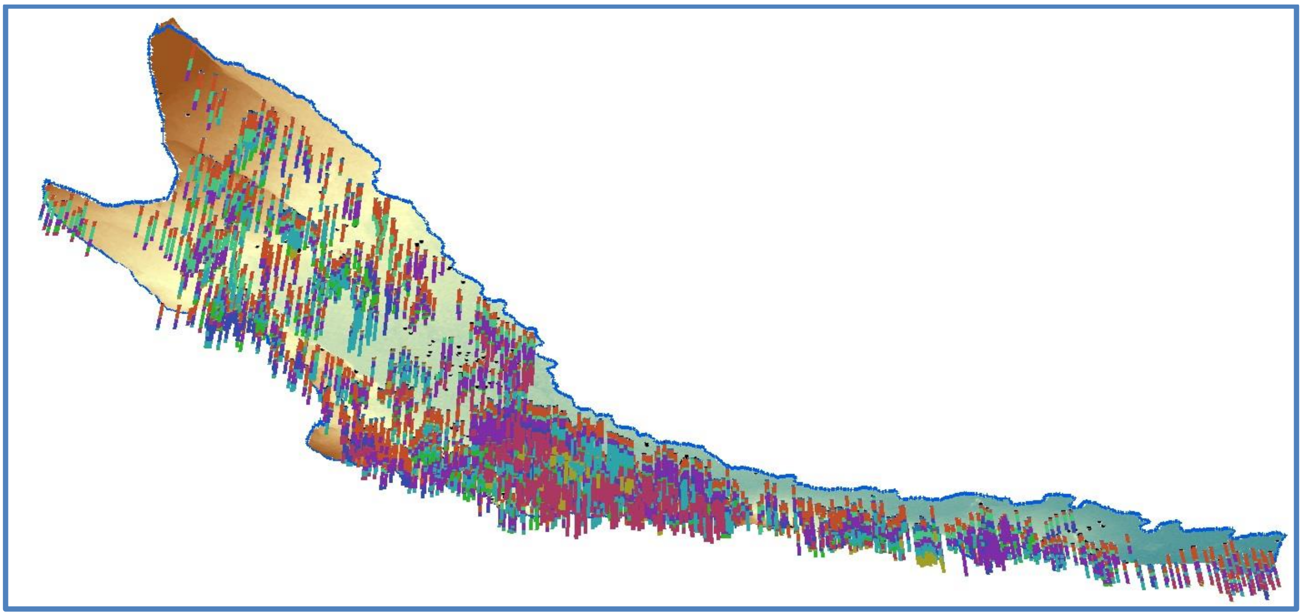


Figure 27: The 3D visualization of the well lithologic structure in the Ararat Valley ***(Source: ASPIRED Project)***

The presented datasets of the well lithologic structure were used to develop 2D cross-sections of the Ararat Valley groundwater basin.

4.2.2. Hydrogeologic Cross-Sections

Five vertical cross-section lines from north to south direction and two cross-section lines from south-east to south-west direction were built for the Ararat Valley groundwater basin (Figure 28). For each cross-section, the grouping by the main nine hydrogeologic units were generated along the cross-section line (for a sample visualization, see Figure 29 on the next page). These 2D cross-sections serve as basic datasets for the generation of 3D structures for the hydrogeologic units through the AHGW package, by applying the interpolation method.

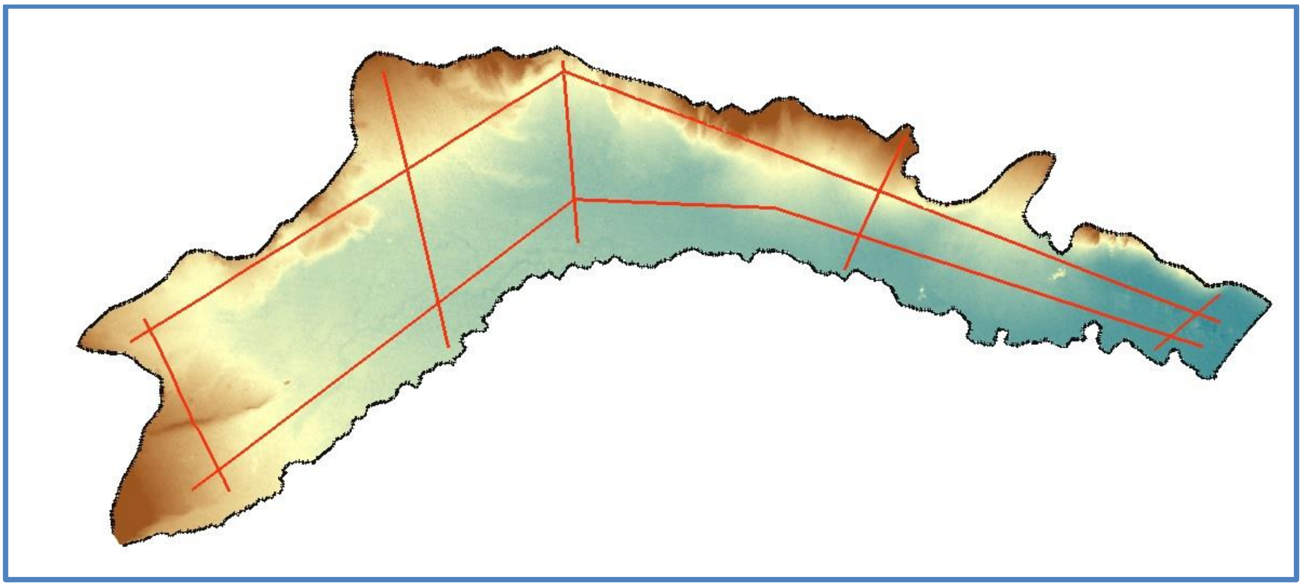


Figure 28: Cross-section lines of the Ararat Valley groundwater basin ***(Source: ASPIRED Project)***

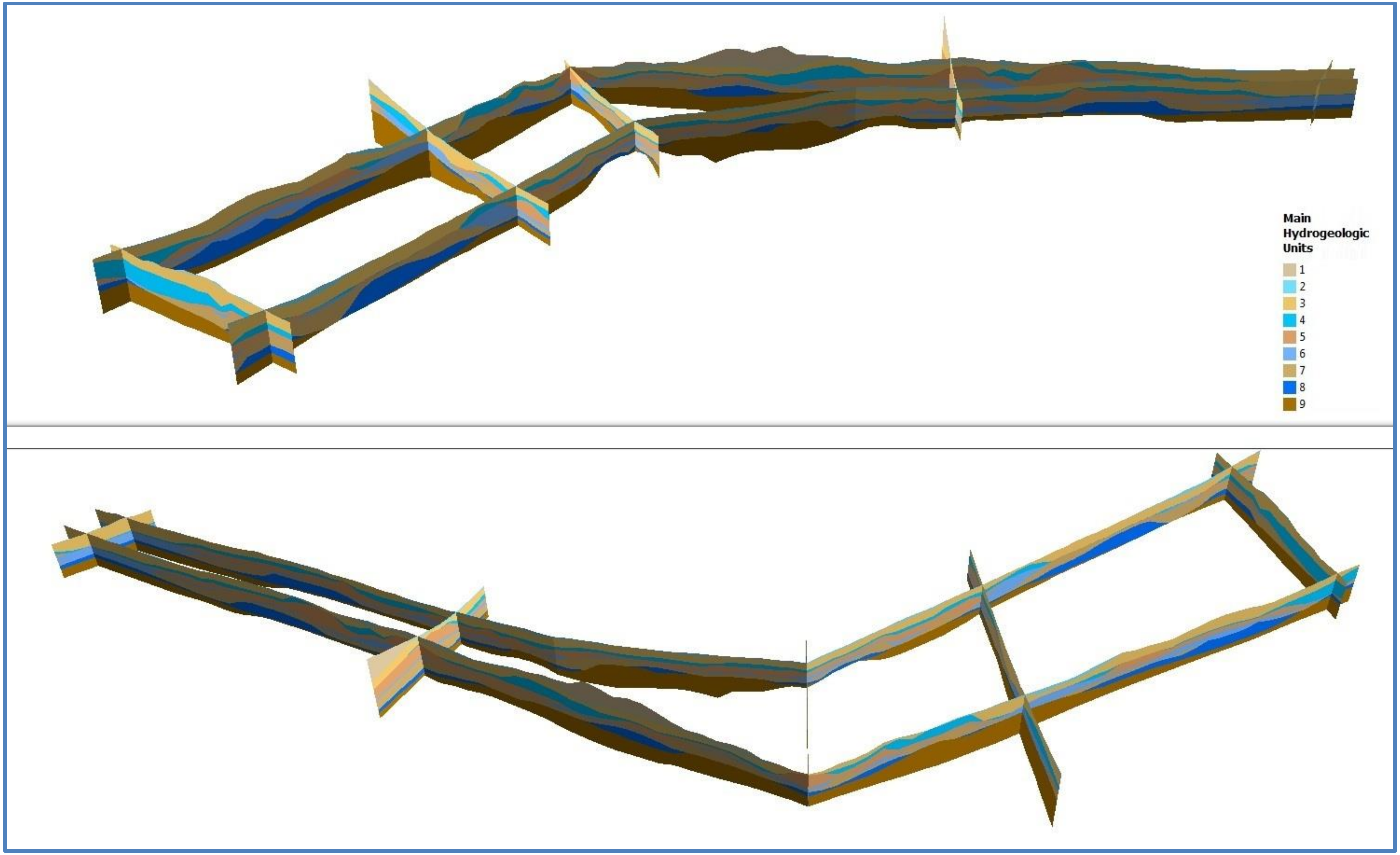


Figure 29: The 2D cross-sections of the main hydrogeologic units in the Ararat Valley groundwater basin ***(Source: ASPIRED Project)***

4.2.3. 3D Structures of the Main Hydrogeologic Units

The 3D structures of the main hydrogeologic units of the Ararat Valley groundwater basin were generated by applying the interpolation method in the AHGW package under the ArcGIS environment based on the lithologic structures of the wells and the 2D cross sections. The generated 3D volumes are raster images, which are visualized in the Arc Scene package (see Figure 30).

To calculate the numeric values of the volumes for each of nine hydrogeologic units, the ASPIRED team used the "Is Closed 3D" geoprocessing tool in the AHGW GeoVolume multipatch feature class to verify that the geo-volumes of all hydrogeologic units are closed. Since not all of them were closed due to complexity of the Ararat Valley aquifers, a TIN of the Ararat Valley groundwater basin was created. Afterwards, the Surface Difference geoprocessing tool in ArcGIS was applied to determine where each hydrogeologic unit was above the next below and the volume between the surfaces within each of those areas. The sum of the volumes for those areas where the raster was above the raster with the next hydrogeologic unit down was calculated.

Table 4 below presents the total volume for each of the nine hydrogeologic units and grand total volume of the Ararat Valley groundwater basin.

Table 4. Volumes of the main hydrogeologic units of the Ararat Valley groundwater basin

Unit ID	*Primary geological material*	*Lowest absolute altitude of the bottom of the layer (m)*	*Highest absolute altitude of the bottom of the layer (m)*	*Average thickness of the unit (m)*	*Water-bearing potential*	*Volume (m^3)*
1	Loam/clay	800.1	940.8	8	Low	6,330,194,705.51
2	Gravel	781.3	933.7	32	High	6,209,862,654.76
3	Clay	745.1	912.7	14	Low	39,370,744,226.27
4	Gravel	738.1	887.5	27	High	20,747,927,834.63
5	Dense basalt/clay	731.2	869.1	9	Low	26,290,435,682.97
6	Gravel	705.1	879.9	17	High	12,987,106,831.46
7	Dense basalt/clay	642.7	826.8	10	Low	33,278,242,350.14
8	Gravel/fractured basalt	638.5	828.5	23	High	16,109,360,935.98
9	Dense clay	630.0	756.6	22	Low	50,605,160,940.10
Total volume of the layers with **high** water-bearing potential						**56,054,258,256.83**
Total volume of the layers with **low** water-bearing potential						**149,544,583,199.48**
Grand total volume						**205,598,841,456.31**

Sources: Hydrogeologic Framework and Groundwater Conditions of the Ararat Basin in Armenia, 2017, USGS, ASPIRED and AQUAVEO, 2018

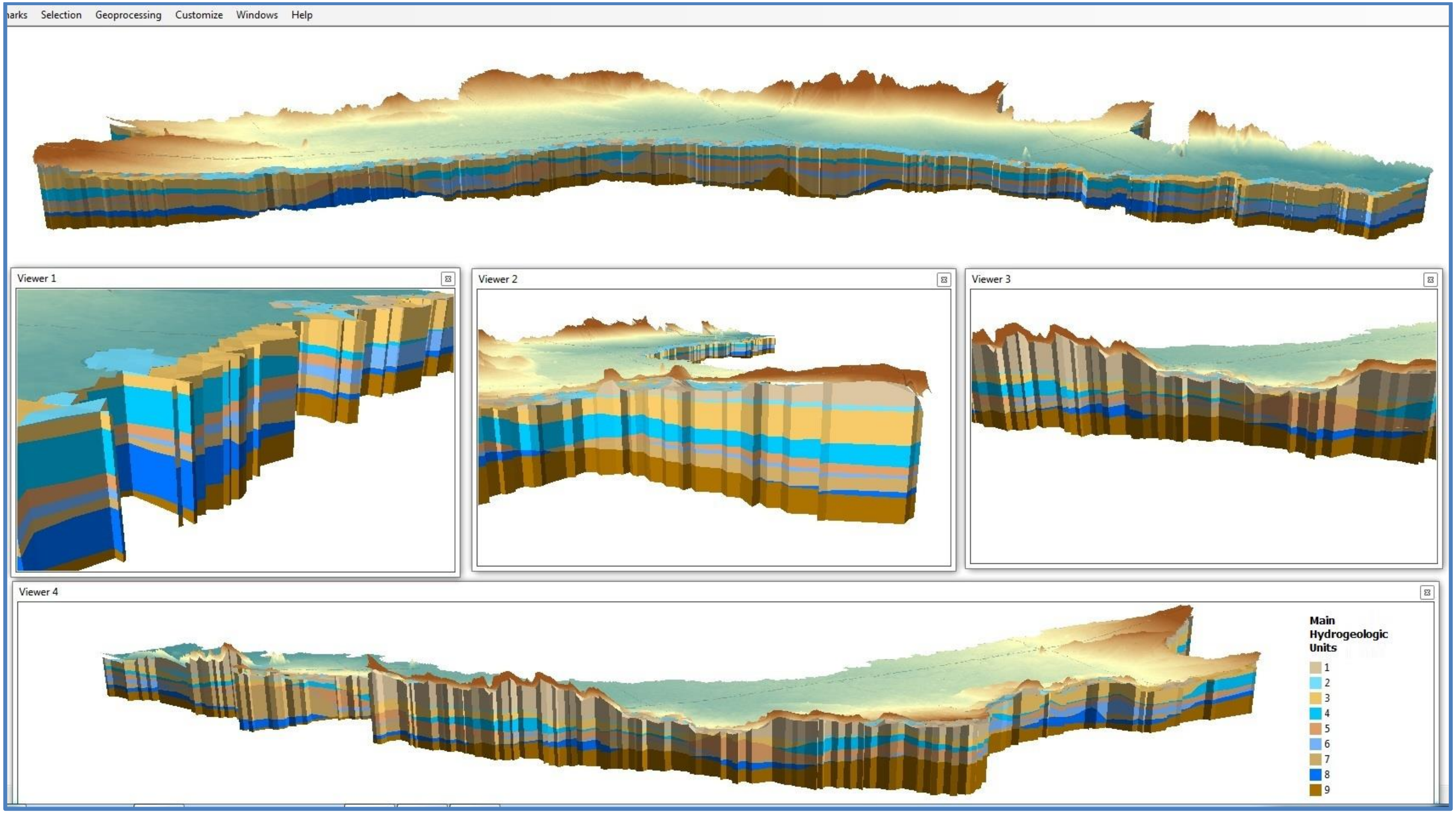


Figure 30: The 3D structures of the main hydrogeologic units in the Ararat Valley groundwater basin ***(Source: USGS, ASPIRED Project)***

5. NEXT STEPS

The ASPIRED team presented the digital hydrogeologic map of the Ararat Valley and the 3D model of the Ararat Valley groundwater basin to the main stakeholders of the ASPIRED Project in November 2018, namely the MNP, WRMA and EMIC. Following the meeting, ASPIRED began finalizing the above-mentioned deliverables based on the comments received from the stakeholders. The next steps for completing the Ararat Valley groundwater model and digital hydrogeologic map of the Ararat Valley are presented below.

1. **Designing a numeric Groundwater Flow model** for the Ararat Valley groundwater basin based on the finalized 3D structure, using the GMS package and MODFLOW tools. The ASPIRED team will use data from the 2016 inventory of groundwater wells, natural springs, and fish farms to generate the numeric groundwater flow. As a result of simulating the groundwater flow model for the Ararat Valley, the values of groundwater inflow, groundwater outflow and groundwater accumulation in the Ararat Valley groundwater basin under conditions of groundwater use will be obtained.

2. **Calculating the Water Supply and Demand Balance** for the Ararat Valley based on the numeric values obtained from the Groundwater Flow model. The water supply and demand balance will provide the following values for the year 2016:
   - Groundwater reserve;
   - Recharge rate and changes in groundwater reserve, conditioned by groundwater use in the Ararat Valley for various purposes; and
   - Sustainable rate of groundwater use: volume of groundwater that can be used from the groundwater basin without causing depletion of the aquifers (named also operational groundwater resources).

3. **Finalizing Hydrogeologic Map of the Ararat Valley** using the final results of the modeling and stakeholders' feedback.

The ASPIRED Project will implement the above-mentioned tasks under the guidance and coaching of the AQUAVEO experts, and in close collaboration with the hydro-geologists from EMIC. The ASPIRED Project will keep in regular contact with EMIC hydrogeologists on the progress in design of the Groundwater Flow Model. The results of the simulation as well as the calculated values of the above-described parameters will be presented to the main stakeholders of the ASPIRED Project in

July 2019. Final hydrogeologic map of the Ararat Valley will be integrated in the Ararat Valley Atlas, to be prepared in 2019-2020.

ANNEX A: BIBLIOGRAPHY

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