Aquifer Characterization in the lower Skagit River Valley, Northwest Washington State

Thesis Proposal for the Master of Science Degree,
Department of Geology, Western Washington University,
Bellingham, Washington

Henry O. Williams
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Advisory Committee Members:

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Dr. Robert Mitchell, Thesis Committee Chair

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Dr. Doug Clark, Thesis Committee Advisor

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Dr. Jon Riedel, Thesis Committee Advisor

1. Introduction

The Skagit River, its tributaries, and unconfined glacial aquifers are an important water resources for salmon habitat, agriculture, municipalities, and industries in the lower Skagit basin. Unfortunately, these resources are being threatened by receding glaciers and reduced meltwater due to a warming climate compounded by increasing groundwater withdrawals driven by development and agricultural practices in the basin. Prior research by the USGS and others demonstrated that groundwater extracted near the Skagit River floodplain reduces baseflow to the river (Savoca et al., 2009a&b; HDR 2017 and 2019). Since 2001, the Skagit River has been under instream flow rules that restrict groundwater usage (WADOE, 2023). Instream flow rules were established in part to ensure adequate streamflow to support salmon habitat and the guaranteed fishing rights of the Upper Skagit and Swinomish Indian Tribes in the Skagit valley. However, how aquifers in glacial outwash deposits in the lower valley above the floodplain connect to the river is poorly understood. For management purposes it is important to understand how aquifers above the alluvial deposits in the floodplain contribute to the Skagit River and its tributaries and if those aquifers are inter-connected. I propose to develop a hydrogeologic framework to better characterize the groundwater resources in the lower Skagit valley.

My objective is to use well-log data, gravel pits, natural stream exposures, recent geomorphic mapping, hydrogeologic studies, borehole data and lidar data to create cross sections and a 3D conceptual model of the hydrogeologic framework to characterize the glacial terrace and alluvial deposits between Sedro-Woolley and Grandy Creek (Figure 1). Outcomes will determine the connection between upper and lower aquifers between Muddy, Grandy and Alder Creek and test the hypothesis that the upper aquifers may be disconnected from the lower aquifers and be used as a water resource without impacting tributary and river streamflows (Figure 2).

2. Background

2.1 Study Area

The Skagit River discharges into Skagit Bay west of Mt Vernon, WA and drains into a basin that covers a total area of 3,115 square miles in Canada and northwest Washington State (Figure 1). Relief in the watershed varies from sea level at the mouth to 10,786 ft at the top of Mt. Baker and 10,541 feet at the top of Glacier Peak. The watershed contains about 39 square miles of glacier ice (Bandaragoda et al., 2015) that historically has helped sustain summer streamflows. The

Sauk, Cascade and Baker rivers are major tributaries to the Skagit River upstream of the study site (Lee and Hamlet, 2011; Figure 1). My study focuses on a sequence of glacial and alluvial deposits in the lower-middle Skagit valley in the vicinity of Hamilton, WA east of Sedro-Woolley and west of Concrete, WA (Figures 1 and 2).

Flow in the Skagit River is supported by glacier meltwater, seasonal precipitation and runoff, groundwater, and is partly controlled by five major dams (Gorge, Diablo, Ross, Upper and Lower Baker). The average annual discharge near Mt. Vernon, WA is about 16,500 cfs, with an average annual minimum of 10,500 cfs, and maximum annual discharge of 23,140 cfs (USACE, 2013; Drost and Lombard, 1978). These hydrologic conditions of the river support five species of salmon that pass through the river annually. In particular, the Skagit River supports the largest run of Chinook Salmon in the Puget Sound along with the largest runs of Pink and Chum Salmon in the United States (Connor and Pflug, 2004). Lower Skagit Valley is developed and intensively used for agriculture and there are several small communities within the basin. Humans have changed the area from its natural, original conditions by the installation of hydraulic dams, erosion control structures, levees, and extensive logging. Due to human-made changes, some species of salmon like steelhead and chinook are threatened in the valley (Lee and Hamlet, 2011).

2.2 Climate/Hydrologic Conditions

The Skagit River basin has a maritime climate with wet, humid winters, and mild, dry, summers. The lower Skagit Valley floor has a maritime climate but gets wetter east of Marblemount then dries into a continental climate in upper Skagit due to the rain shadow effect of the Olympic Mountains. Sedro-Woolley, west of my study area, has a 30-year average annual precipitation of 46.6 inches, and about 75% of all precipitation occurs between October-April (Table 1). Due to orographic effects, the higher elevations can receive 140-190 inches of water-equivalent precipitation (Drost and Lombard, 1978). Glaciers and groundwater are critical river base-flow sources to the Skagit River during the drier summers as snow melt diminishes. Much of the glacier runoff is a combination of seasonal snow, firn, and glacial ice (Riedel and Larrabee, 2016). Of concern, though, is the predicted reductions in summer flows due to projected warming climates which will cause glaciers to recede, snowpack to diminish, and warmer drier summers and how these changes will impact instream discharges as groundwater demands increase due to projected development (Figure 3; Frans et al. 2018; Roop et al., 2020).

Although there are no data on groundwater recharge for my study area, there are data from the Nookachamps River basin just south of the Skagit River (Savoca et al., 2009a). The Nookachamps surficial geology matches the exposed glaciomarine drift found on the west side of my study area's glacial terraces (west of Figure 2), but the Nookachamps has different surficial units compared to the east end of my study area where my study area has more outwash while the Nookachamps has more hardpan (Figure 2; WADNR, 2016). The Savoca et al. (2009a) study reports that about 35% of the annual precipitation in the Nookachamps region goes to surface runoff, 32% is lost from evapotranspiration, and 33% becomes groundwater recharge. HDR is planning to conduct seepage runs along some of the creeks in the upper bench in my study area that may be useful for determining groundwater-surface water interactions and recharge in the glacial terrace. Details on individual unit recharge rates will be briefly discussed in the hydrogeology section (Table 2)

2.3 Geological Setting

Between 375-120 Ma, accretion of multiple terranes expanded the Washington State coastline westward. During the Cretaceous period (100 Ma), arc/uplift occurred due to the linkage of plutons and was followed by the Eocene extensional deposits ~40 Ma and the formation of the Cascade Volcanic Arc ~35 Ma. These tectonic events do not appear to have played a big role in the shape or route of the modern river or surface geology but are still important for bedrock geology (on high mountain walls). Starting ~2.6 Ma, Pleistocene glaciation occurred over the North Cascades (Haugerud and Tabor, 2009). During the Quaternary, glacial erosion and deposition altered the western Cascades and created the modern Skagit River watershed (Riedel et al., 2007).

The valley, as it exists today, was strongly shaped between ~29-11.7 ka during the last major glaciation that included alpine glaciers and the Cordilleran ice sheet (Riedel, 2017). The alpine glaciers and continental ice sheets were separate from each other and advanced and receded in two different stages (Armstrong et al., 1965). The varying climates lead to some areas being ice free at some times and other times completely covered in ice. Glacier fluctuations and the advance of alpine glaciers that blocked the valley resulted in large glacier lakes forming in the lower Skagit valley floor (Riedel, 2017). The glacier fluctuations also resulted in a complex sequence of glacial deposits on the north side of the valley within the study area, including the upper bench (herein referred to as the glacial terrace; Figure 2). The entire glacial terrace on the east side of my study area is a result of the damning and glaciation of the valley by the Cordilleran ice sheet (Riedel, 2017). Starting in 29 ka and during the Evans Creek Stade, alpine glaciers dominated most of the valley mountain area, but started to retreat by 21 ka and were absent by the time the continental ice sheet arrived (Riedel et al., 2010). When the Vashon Stade began (~19 ka), between 18-16 ka the Cordilleran ice sheet advanced into the basin, depositing advanced glacial outwash, advanced glacial lacustrine, and glacial till and by 15 ka began to retreat through the valley leaving behind a complex sequence of recessional outwash (Riedel, 2017; Armstrong et al., 1965). These three deposits are exposed on the east side of the terrace (Figure 2). The western portion of glacial terrace is quite different and includes glaciomarine and glaciolacustrine deposits from the marine waters that flooded the valley to elevations of ~100 m 13.6 ka (Dethier et al., 1997). Between 13.7 and 11.6 ka, alpine glaciers briefly advanced but quickly receded and the shape of the modern valley is due to erosion by three styles of glaciations; the valley floor deposits were shaped by the deposition within proglacial lakes, directly from glacial till, outwash/outburst floods, and glacial fluvial and Holocene alluvium from the Skagit River.

The modern Skagit Valley was also affected by Glacier Peak volcanic eruptions. A lahar discharging to the Puget Sound via the Stillaguamish River occurred 11,700 years that redirected the Sauk River into the Skagit River. Over the past 6,000 years, there have been multiple lahars that have been less impactful but flowed into the lower Skagit Valley leaving deposits from Rockport to Mount Vernon (Beget, 1982). Mt Baker erupted 13,000 and 9,500 years ago but these had little impact on the recent history of the Skagit River (Scott et al., 2020).

2.4. Geological Units

A hydrogeologic framework for an area just south and west of the study area in Nookachamps Creek basin was produced by USGS in 2009 (Savoca et al., 2009a). I defined and labeled both geologic and hydrogeological units using the WADNR 100k surface geology database (WADNR, 2016) and the nomenclature of Savoca et al. (2009a). Most of the units in the study area come from the Holocene-Pleistocene, some from Tertiary and one from Jurassic/Pennsylvanian periods (Table 2). Note that the WANDR units are generalized (mapped at 100k) for all of western Washington. Jon Riedel has mapped the study area in more detail (unpublished) that will inform my hydrogeologic framework (Figure 4).

The most important units for my study are the near-surface unconsolidated Quaternary units including glacial outwash, glacial till and alluvial (river) deposits from the Late Pleistocene and Holocene (Figure 2 and Table 2). On the east side of the terrace, alluvium (Qa) defines most of the Skagit floodplain and is dominantly coarse grained with mix of cobble gravel and sand that continues to get finer and eventually almost entirely sand by Sedro-Woolley (Riedel, 2023). Glacial outwash (Qgo, Qga) dominates much of the glacial terrace and consists of loose sand and gravel, with areas of boulders, cobbles, and lenses of silt (Savoca et al., 2009a; WADNR, 2016). The primary differences between the outwash and the alluvium are that the outwash is coarser grained boulder and cobble gravel (proximal to ice or from outburst floods) to sand (distal), while the alluvium includes more silt and fine sand, and change. Glacial till (Qgt) found north of the outwash bench is sediment deposited beneath a glacier and typically includes compacted clay, sand, silt, and gravel, and some boulders (Savoca et al., 2009a; WADNR, 2016). There are some alluvial fan deposits (Qaf) that are poorly sorted gravel, silt, and sand (Savoca et al., 2009a; WADNR, 2016). Other units (in gray in Figure 2) are bedrock units that range in age from Eocene to Jurassic (WADNR, 2016). However, on the west side, glaciomarine outwash (Qgom(e)) is the dominant deposit, with some exposure of lahars in floodplain (Savoca et al., 2009a; WADNR, 2016; west of Figure 2). Below much of the terrace on both the east and west side, there are glaciolacustrine deposits (Qgl) that are underneath the geological units already described. It contains some gravel but is mostly sand that continues to get siltier as depth increases (Riedel, 2023). The surficial geological units in the Nookachamps were cataloged into hydrogeologic units based primarily on their hydraulic conductivity characteristics (Savoca et al., 2009a).

2.5 Hydrogeologic Units

I follow the nomenclature of Savoca et al. (2009a) to describe hydrogeologic units in my study area. Geologic deposits that produce sufficient groundwater yields to pumping wells have high hydraulic conductivities and are classified as aquifers. Aquitards and aquicludes have low hydraulic conductivities that do not readily transmit water and form confining units. The units in Table 2 fall into two categories: 1) unconsolidated aquifers Qa, Qga, Qgo, Qgom(e) and Qaf typically consist of moderately to well-sorted alluvial and glacial outwash deposits composed of sand, gravel, and cobbles, with minor lenses of silt and clay and high hydraulic conductivities; and 2) confining units that serve as aquitards typically consist of units having low hydraulic conductivities such unconsolidated poorly sorted compacted glacial till (Qgt), and glaciolacustrine (Qgl) (Savoca et al., 2009a; Table 2). There are also bedrock units (J, Ec) that serve as aquicludes and include older units from the Jurassic to Eocene that have little to no hydraulic conductivity.

According to Savoca et al. (2009a), alluvium (Qa), alluvial fan deposits (Qaf), glacial outwash (Qgo, Qga), and glaciomarine outwash (Qgom(e)) conduct water at about 47-48 feet/day; glacial till (Qgt) and glaciolacustrine (Qgl) deposits conduct water at about 26-13 feet/day; and bedrock units (J,Ec) have an average hydraulic conductivity of 0.13 feet/day (Table 2). Aquifer recharge rates associated with the hydrogeologic units are estimated based on their hydraulic conductivities (Figure 5). Again, these are generalized units that may not reflect actual hydrogeologic conductivities of the actual units in the study area.

2.6 Recent Hydrogeologic studies:

Hydrogeologic studies have been conducted near my study site to characterize groundwater movement and groundwater-surface water interactions (HDR, 2017 and 2019; Savoca et al., 2009a). These studies determined that pumping from unconfined aquifers in the lower valley could jeopardize instream flows, and the closer the wells are to the river, the greater the loss of water to the river (HDR, 2017; Savoca et al., 2009a). HDR also determined that there may be aquifers in the glacial terrace that are not connected to the lower floodplain aquifers or the Skagit River (HDR, 2019). HDR (2017) concluded that there are also two different types of aquifers: unconfined and confined aquifers with geological units similar to those in my study area. I will use cross sections of the floodplain area (Figure 6) developed by HDR in the development of my hydrogeologic characterization of study area.

2.7 Significance

A more thorough hydrogeologic framework in the lower Skagit is important to aid in water resource management decisions to sustain instream flows during the summer, especially as the climate warms. Since 2001, the Skagit River has been under an instream flow rule that restricts river water withdrawals and prohibits new domestic groundwater well development when stream levels are below healthy levels (WADOE, 2023). Without these restrictions, unlimited water withdrawal could lead to instream flow conditions that are unsuitable for healthy salmon runs. Protecting streamflow quantity and quality will also sustain the tribe’s rights to fish, insured by the Treaty of Point Elliot, 1855 (WAOIA, 2023). It is also important to note that about 25% of all the water withdrawn in the Skagit Valley is used for agricultural irrigation with nearly all of irrigation water coming from groundwater (Drost and Lombard, 1978).

Glaciers in the North Cascades were once a large source of late-summer streamflow in the Skagit River. However, between 1959 to 2009, glacier recession has caused a 28% decrease in glacier contributions to summer streamflow resulting in a higher reliance on groundwater to support baseflows (Riedel and Larrabee, 2016). Projected warming climates will cause glaciers to recede by as much as 50% (Bandaragoda et al., 2015; Frans et at., 2015; Figure 3). Five to twenty percent less precipitation is also projected in summers, further decreasing future summer streamflow which will in turn place a strain on Indigenous people, farmers, salmon runs, and other municipal and industrial water users (UW, 2021).

3. Methodology

To characterize the aquifer system in the lower-middle Skagit Valley and determine the connection between lower aquifers and the upper glacial terrace aquifer, I will develop a hydrogeologic framework using well-log data, recent geomorphic mapping and hydrogeologic studies, deep borehole data, Lidar, and ArcGIS software tools. My scope of work includes:

1. Characterizing the surface and subsurface glacial stratigraphy using related literature, exposures along streams, gravel pits, a new 300 ft well, and well logs accessed from the Washington Department of Ecology database (WADOE, 2023). I will verify well-log locations of the Ecology wells and develop a well-log database with stratigraphic identification and hydraulic properties.
2. Monitoring groundwater levels in three deep groundwater wells in the glacial terrace and three shallower wells in the floodplain using a combination of water-level tapes and pressure transducer data loggers. I will use the Geology Department's survey-grade GPS (Emlid Reach RS2+) to accurately determine locations and elevations of the monitoring wells;
3. Creating three north-south 2D cross sections and one east-west 2D cross section within the study area using well logs, supporting literature, and an ArcMap add-on called the Xacto Cross Section Tool (Carrell, 2021);
4. Producing a 3D hydrogeologic conceptual model framework using my glacial terrace well-log database, the HDR floodplain well-log database (HDR 2017, 2019), and Aquaveo's Arc Hydro Groundwater Subsurface Analyst 3.5® in ArcGIS Pro (Aquaveo, 2022);

5. Synthesizing the results, i.e., determine upper and lower aquifer connections (or lack thereof) and aquifer connections to instream flows and aquifer volumes.

3.1 Well Log Database

The creation of a hydrogeologic framework requires the use of groundwater well logs gathered from the Washington State Department of Ecology's (Ecology) well database (WADOE, 2023). Nearly 1000 well logs are within my study area, mostly in the lower floodplain. Well logs contain important information including water levels, pumping rates, the approximate location of the well, depth of the well and deposits encountered when drilling. Many of these have been used in past studies (HDR, 2017 and 2019; Savoca et al., 2009a&b; WADOE, 2014). Typically, the biggest limitation of the Ecology well logs is the location accuracy. Well logs can contain well location within a Township Section and Range (TSR) along with a nearby address/owner. Address and owner data is the most accurate and desirable. The TSR data can be quite vague and can be mislocated by as much as a quarter mile. If necessary, I will relocate the wells by confirming the TSR address and tax parcel using Skagit County's survey website and ensuring the GIS point shapefile matches the location set on the well log and relocating if necessary. I will remove wells that lack location information or have inaccurate locations.

I will also be using HDR's 2017 and 2019 well log database for the lower aquifer in my 3D conceptual model. I will remove or add wells based on other limitations as well such as well depth (deeper wells more useful than shallower wells), geology interpretation, and when the well log was created. This is especially important when there are multiple wells in proximity of each other or with wells in the upper aquifer area which has had very limited well log usage among researchers. Deep bore-hole data from gravel pits will also be incorporated if available. To be consistent with other hydrogeologic studies in the area, I will also be using Standard English units (e.g., feet) throughout my research.

There are very few deep wells in the glacial terrace, especially between Alder and Grandy Creek (Figure 2). To properly characterize and analyze hydrogeologic characteristics in this area, a 310-foot monitoring well was installed near Alder Creek in late March 2023 (Figure 2). The well was logged by a licensed geologist and the stratigraphic information will be incorporated into my 2D cross sections and 3D hydrogeologic conceptual framework.

I will also monitor three deep wells in the glacial terrace and three shallower wells in the floodplain for water table fluctuations. Wells in the glacial terrace include: a well in the town of

Hamilton, one private well near Grandy Creek, and our 310 ft research well. The three wells in the floodplain have private owners and are near Grandy Creek. I will monitor via engineering measuring tape (with a sensor attached that will beep when contact with water is made) and the survey grade GPS. The wells will be measured once a month on the third Thursday of the month. Groundwater monitoring will be done to determine groundwater fluctuations throughout the year and be used as part of the calculations in the 3D hydrogeologic framework.

Using the well-log information, I will define hydrogeologic units based on stratigraphic breaks (e.g., gravel and sand, silt, and clay) much like what was used by the USGS and HDR. Hydraulic conductivity of the hydrogeologic units will be estimated using literature values (e.g., HDR, 2017 and 2019; Savoca et al., 2009a) or from pump-test data from the well log. Pump-test data collected by well drillers can be used in a modified Theis equation to estimate the hydraulic conductivity. Gendaszek (2014) describes the Theis relation, and the assumptions required for its application.

3.2 3D Hydrogeologic Framework

I will use my well-log database and monitored groundwater levels to create a 3D hydrogeologic conceptual framework and accompanying 2D cross sections covering Muddy, Alder, and Grandy Creek. I will use the Aquaveo Arc Hydro Groundwater Subsurface Analyst 3.5® in ArcMap (Aquaveo, 2022) for the 3D conceptual model and the ArcGIS Xacto Cross Section Tool for the 2D cross sections. I have been working on three north-south cross sections across the glacial outwash terrace for the past six months using the Xacto tool and have developed drafts (Figure 7). While these drafts provide some initial insight onto what the subsurface hydrogeologic network looks like, an east-west longitudinal cross section will be developed that includes only the upper bench deep wells to give better insight of the east-west variation of the glacial terrace stratigraphy. The Aquaveo's Subsurface Analyst is licensed in the Geology Department, and I will use it to create 3D fence diagrams, geovolumes, and aquifer volume estimates. Aquaveo recently released an ArcGIS Pro beta version, however, until it is officially released, I will exclusively use Subsurface Analyst in ArcMap to prevent data loss during a beta test. If it is officially released for Pro, I will transfer all work onto ArcGIS Pro, as ArcGIS Pro is generally much faster and user friendly.

3.3 Data Synthesis

I will use the conceptual hydrogeologic framework to determine the connectivity between upper and lower valley aquifers. Instream flow and groundwater level monitorin data collected as part of a larger study will also be reviewed and analyzed to determine the upper and lower aquifers connectivity. Connections between the upper and lower aquifer will be determined based on observed changes in stratigraphy between benches, water table fluctuation consistency between both benches and even via stream discharge from the HDR hydrologic project in streams like Alder Creek. I will also compare my conceptual model to other local hydrogeologic frameworks in the lower Skagit River basin (Savoca et al., 2009a&b; HDR 2017 and 2021).

4. Expected Results

With correct well locating, and revised cross sections, I expect that the 2D cross sections will give some initial results on the hydrogeologic characteristics within the east end of the study area. Using wells in the floodplain from previous studies and including unused wells in the glacial terrace will provide more information on the relationship between the upper and lower benches and differences between east and west sides of the terrace. The addition of a new deep well near Alder Creek will provide essential data to begin characterizing the upper bench. By the time all the wells are revised, a draft hydrogeologic framework can be started, as I will have sufficient information from the lower (floodplain) wells and the upper wells to begin observations on the connection between upper and lower bench between Grandy and Muddy Creek.

As my facility with Arc Hydro Groundwater improves, I will be able to translate all 2D cross section work from Xacto to Arc Hydro and do other tasks to create a 3D hydrogeologic framework. I hope to include general groundwater movement, water table fluctuations, conductivity differences, and recharge estimates into the model and create a framework for the upper and lower bench of the Skagit Valley. This will display whether the upper and lower benches are connected or not. This will have implications for policy related to instream flow, water rights, and owner usability.

5. Potential Issues

A potential issue is the time required to learn new software. New software can significantly improve the project results but the time necessary to develop competency may delay some progress. Driller well-log complications may also be a problem. In addition to well location challenges, there are uncertainties in the stratigraphic descriptions in well-driller logs made by well drillers who are not geologists. I need to make educated judgments to be consistent in my interpretations of deposits. Another issue is the large distances between some wells and as illustrated in Figure 4, the geology is complex. If wells are too far from each other, changes in stratigraphy may be misrepresented. None of these potential issues are anticipated to provide insurmountable obstacles but identifying them in advance is useful.

6. Dissemination Plan

I plan on sharing my work through both presentations and publications.

On April 27, 2023, I displayed preliminary work at the Puget Sound Chapter AEG Student Night to area geologists in Seattle, WA. I presented a poster of the completed draft Xacto cross sections. Not much feedback was provided, but the study progress presented seemed to be well received. I plan to present my results at the 2024 AEG Student Night.

I plan to present at the 14th Washington State Hydrogeology Symposium in April of 2024 and possibly at the fall annual 2024 AEG or GSA conference.

When the thesis is complete, I plan to send my research to the Western CEDAR publications and/or publish it through HDR in thesis form or as a written tech memo/journal article.

7. Project Timeline

During Fall 2022, I completed a GSA Proposal and began my initial work plan for cross sections. During Winter 2023, I finished a draft thesis proposal, and completed a rough draft of my Xacto Cross sections. I also presented at AEG Student night on 4/27 to get some initial feedback from area professional geologists. In Summer 2023, I will complete my thesis proposal, improve my three north-south 2D cross sections, learn how to use Arc Hydro, monitor groundwater levels in six wells, and determine well surface elevations with a Survey grade GPS. I will also begin writing my thesis. The summer project activities will continue into the Fall but with more meetings with my thesis committee. I also should have a 3D hydrogeologic framework accomplished through Arc Hydro and will begin data analysis. Winter 2024, I anticipate completing data analysis and written thesis in close consultation with my committee. In Spring 2024, I will be completing final revisions, and will defend my thesis after approval and then submit a copy of my completed thesis to the library special collections.

Major Tasks Table:

TASK	04/23	05/23	06/23	07/23	08/23	09/23	10/23	11/23	12/23	01/24	02/24	03/24	04/24	05/24
Lit. Review/ Raw Data Gathering	X	X	X	X	X	X	X	X	X	X	X	X	X	
Creation of 2D Cross Sections	X	X	X	X	X									
Creation of 3D Hydrogeologic Framework		X	X	X	X	X	X	X	X	X	X			
Modeling Analysis					x	X	X	X	X	X	X	X	X	
Thesis Writing		X	X		X		X	X	X		X	X		
Thesis tabling and defense														X

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9. Tables

Table 1: 1981 – 2010 temperature (°F) and precipitation (inches) normals recorded at the Sedro-Woolley 1 E, WA Coop weather station (Sedro Woolley).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean Max. Temperature	46.7	49.6	54.0	58.8	64.5	69.0	74.0	75.0	69.5	60.2	50.6	45.1	59.8
Mean Temperature	40.9	42.4	46.1	50.1	55.5	59.8	63.5	63.9	59.1	51.6	44.7	39.6	51.5
Mean Min. Temperature	35.0	35.1	38.3	41.5	46.4	50.7	53.0	52.8	48.8	43.0	38.7	34.1	43.2
Mean Precipitation	5.9	3.6	4.4	3.8	3.2	2.8	1.5	1.7	2.6	4.8	7.3	5.0	46.5

Table 2: Geologic and Hydrogeologic units derived from Savova et, al. (2009a).

Hydrogeologic Unit	Geologic Units within Hydrogeologic unit	Hydrogeologic Conductivity (Feet per day)
Unconsolidated Aquifers	Qa, Qga, Qgo, Qaf, Qgom(e)	47-48
Unconsolidated Confining Units (Aquitard)	Qgt, Qgl	26-13
Bedrock (Aquicludes)	J,Ec	0.13

Qa = Alluvium
Qga, Qgo = Glacial Outwash
Qaf = Alluvial Fan deposits.
Qgom(e) = Glaciomarine Outwash
Qgt = Glacial Till
Qgl = Glaciolacustrine
J, Ec = Bedrock/Jurassic/Eocene units

10. Figures

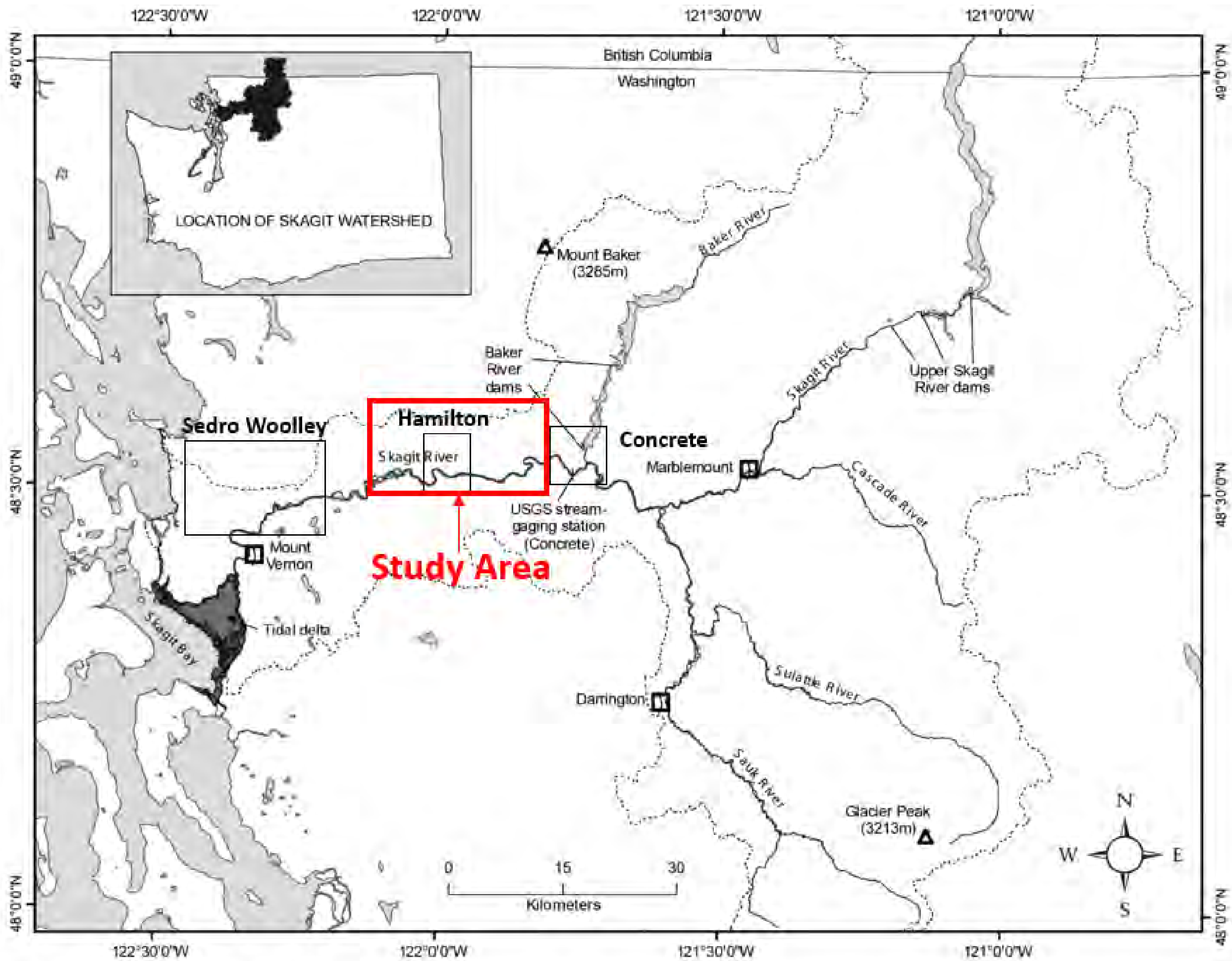


Figure 1: Skagit Watershed ranging from South Canada, Cascades Mountains, Sauk River to Mt Vernon. Officially, the Skagit River begins near the Canadian border and ends at Mt Vernon. The study area, Town of Hamilton, Sedro-Woolley, and Concrete also labeled on map too. (Modified from Greene et al., 2005).

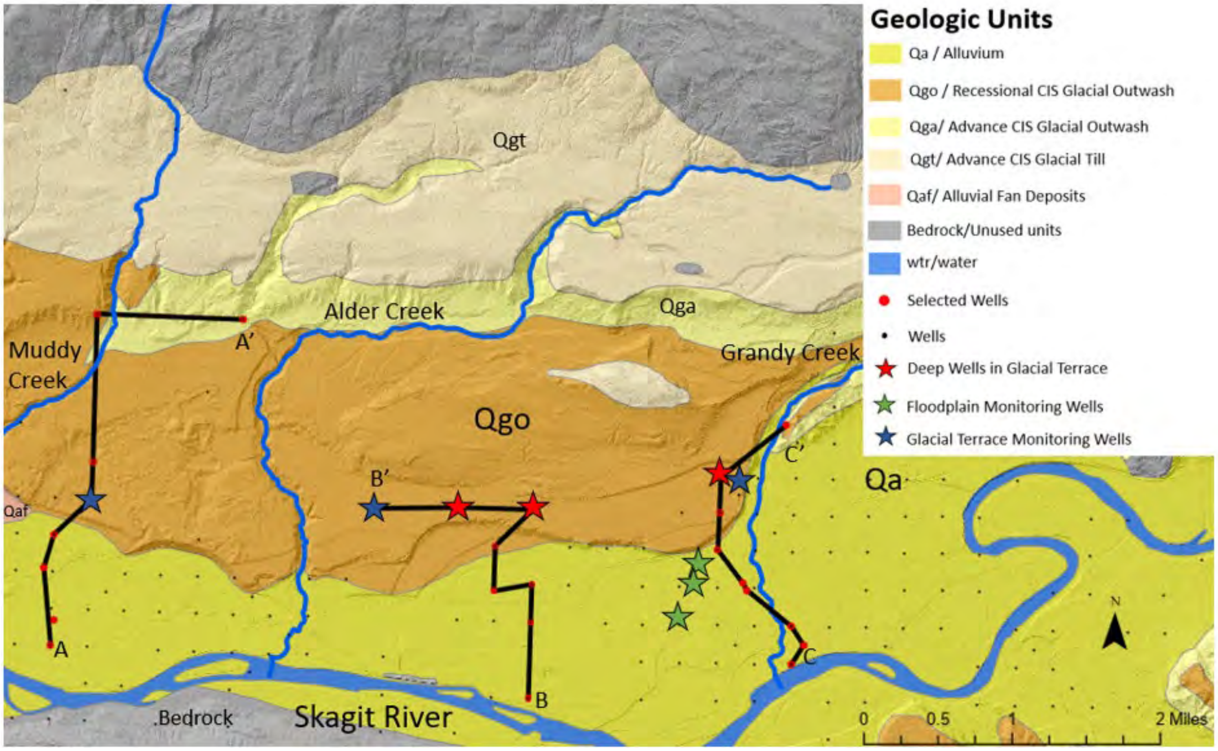
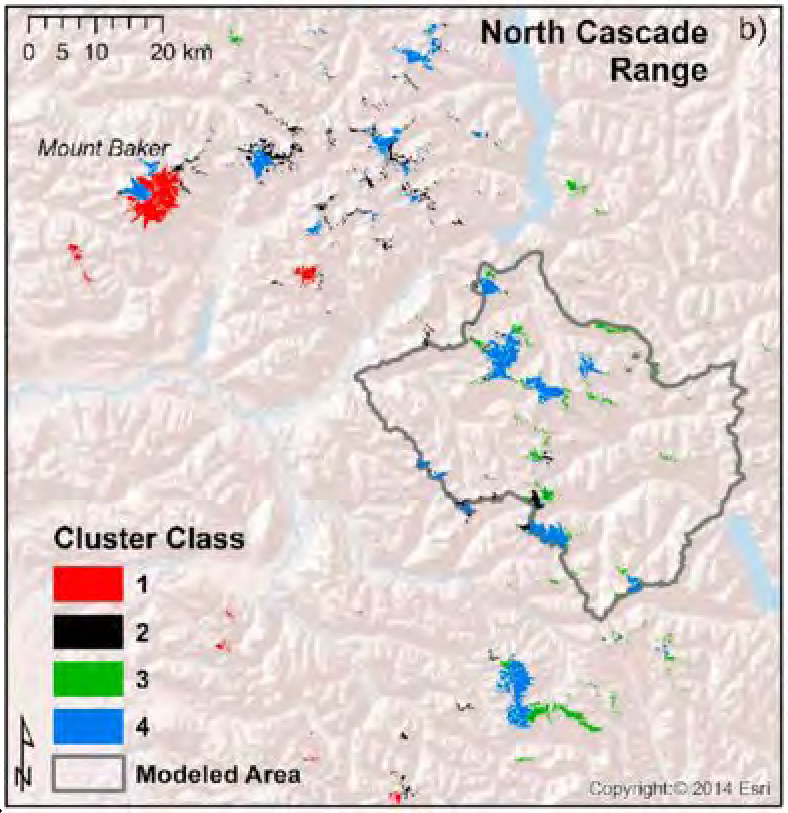


Figure 2: Geological map of Skagit Valley Study Area. Cross Section Pathways are also included, and streams are labeled as well. A new deep well is located directly below B' on the center pathway.

A.


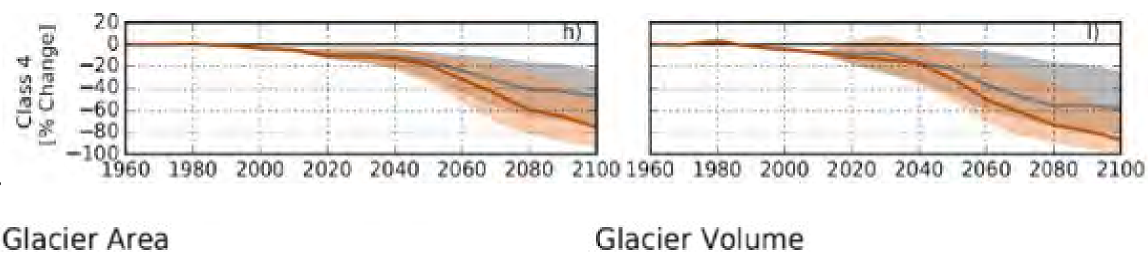
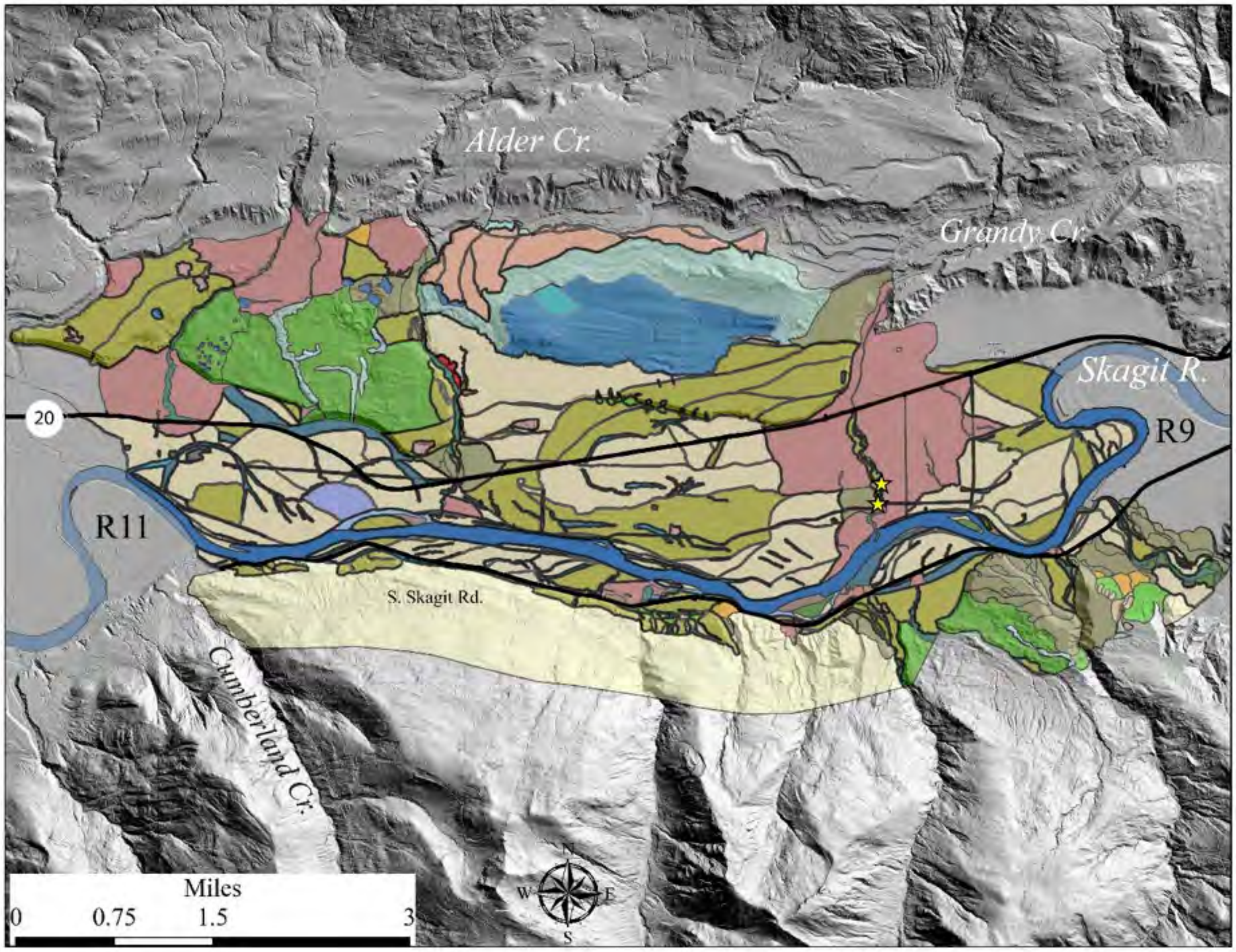
B.


Figure 3: Projected Model of Glacial changes in the North Cascade Range: A. Map of glacier areas in North Cascade Range. The modeled area is in the Skagit River basin. Cluster class 4 (in blue) represents glaciers on volcanos or high elevation peaks and tend to have cold winters and summers. B. Modeled projected change in glacier area and volume over time. The blue trend line is the median using GCM models with lower greenhouse gas emissions. The brown trend line is the median using GCM models with higher greenhouse gas emissions. (Source: Frans et al., 2018).


Alder Cr.
Grandy Cr.
Skagit R.
R9
20
R11
S. Skagit Rd.
Cumberland Cr.
Miles
0 0.75 1.5 3
N
W
E
S


Landform Legend for the Skagit Valley
ALLUVIAL FAN
BEDROCK BENCH
CHANNEL-DISTRIBUTARY SIDE
CHANNEL ICE MARGINAL
CHANNEL-MAIN
CHANNEL-POINT BAR
CHANNEL-PRIMARY SIDE
CHANNEL-RELIC MAIN
CHANNEL-RELIC SIDE
CHANNEL-RELIC TRIBUTARY
CHANNEL-SECONDARY SIDE
CHANNEL-TRIBUTARY
CHANNEL-TRIBUTARY SIDE
DEAD ICE TOPOGRAPHY
DEBRIS APRON
DEBRIS CONE
DEBRIS CONE TERRACE
DEBRIS FAN
ESKER
FAN TERRACE
FLUTED GLACIAL UPLAND
GRAVEL BAR
GULLY
GULLY FAN
HUMAN EROSION
HUMAN FILL
ICE WALL LAKE PLAIN
ISLAND
KAME TERRACE
KETTLE HOLE
LATERAL MORAINE
LEVEE
MASS MOVEMENT-DEBRIS AVALANCHE
MASS MOVEMENT-DEBRIS AVALANCHE TERRACE
MASS MOVEMENT-FALL/TOPPLE
MASS MOVEMENT-SLUMP/CREEP
PLEISTOCENE MORAINE
PLEISTOCENE TERRACE
POINT BAR TERRACE
SAND BAR
TERRACE
TERRACE-ISLAND
UNDIFFERENTIATED
VALLEY WALL
Location of a sample sent in for analysis
Legend for Terrace Compositions
SILT AND CLAY
LAHAR
MIXED-COMPLEX
SAND AND SILT
SAND AND SILT OVER GRAVEL

Figure 4: Surficial Landform Map of my Study Area. (Source: Riedel, 2022).

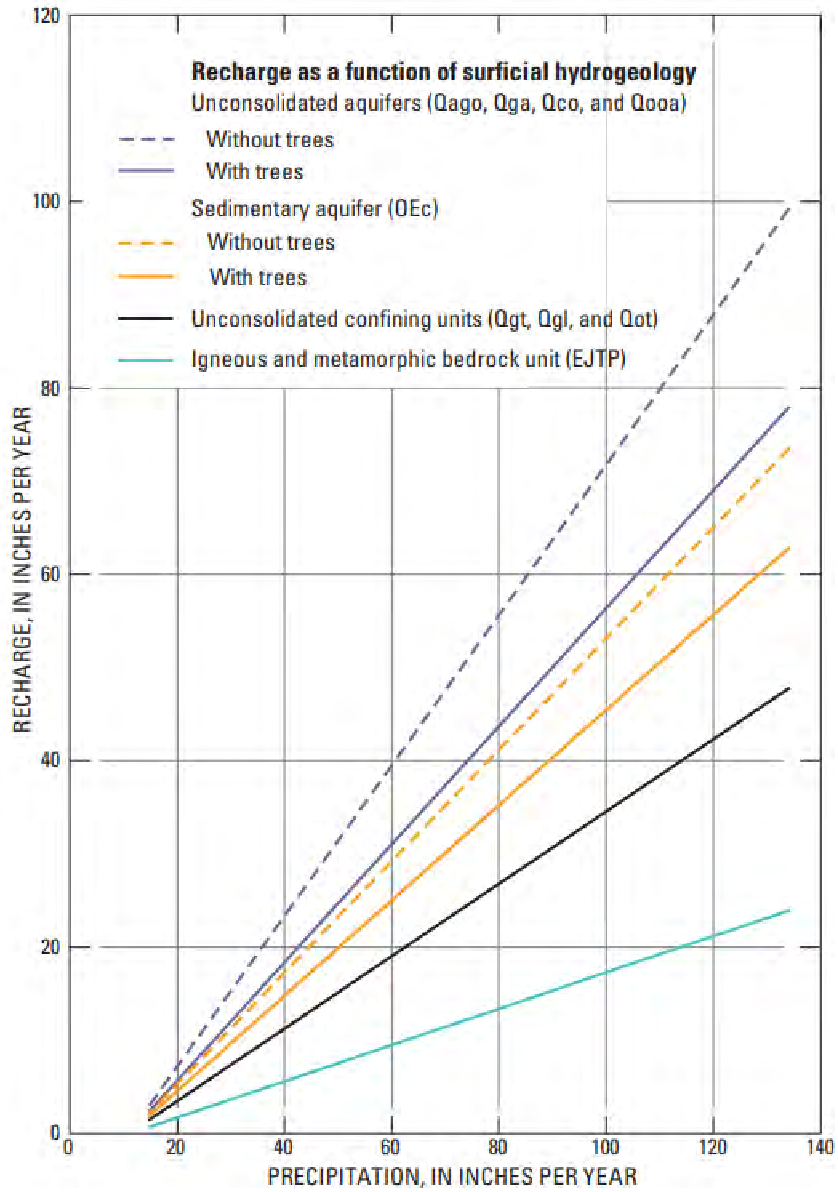
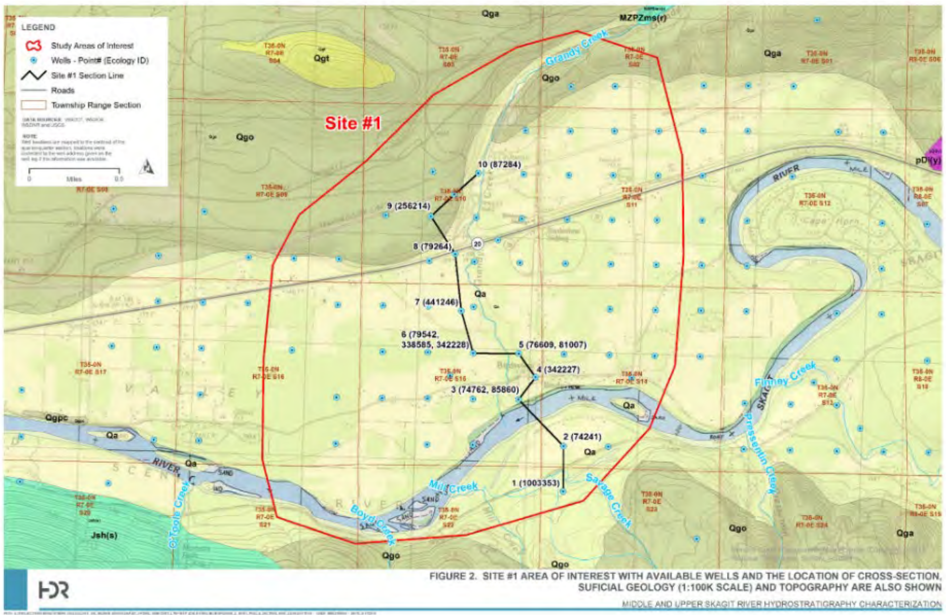
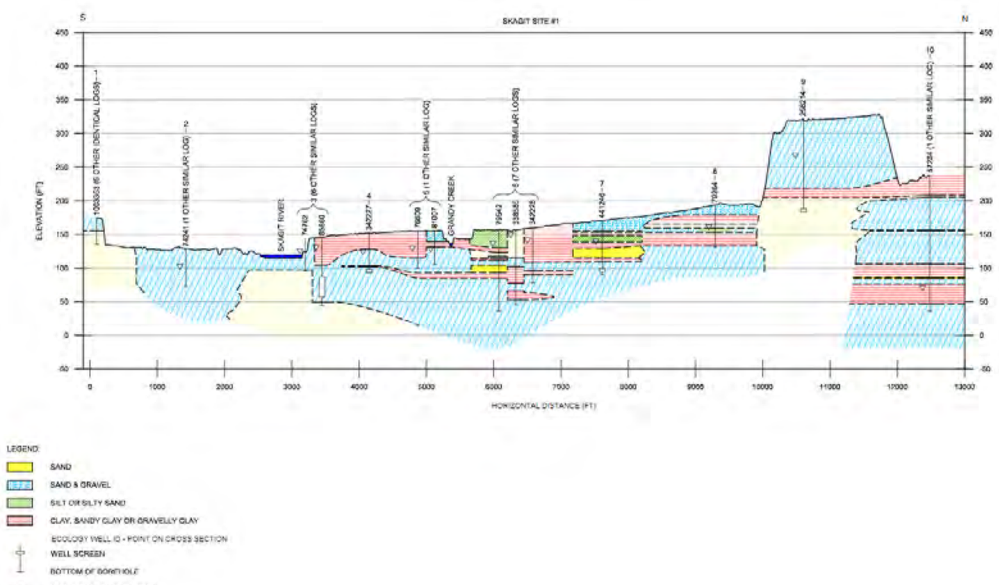


Figure 5: Recharge of hydrogeologic units. Legend displays from top to bottom highest to lowest recharge of the hydrogeologic units. (Source: Savoca et al., 2009a).



A.



B.

Figure 6: HDR Cross section at Grandy Creek. A. Map view of Cross Section Pathway. B. Cross Section View of Path. (Source: HDR, 2019).

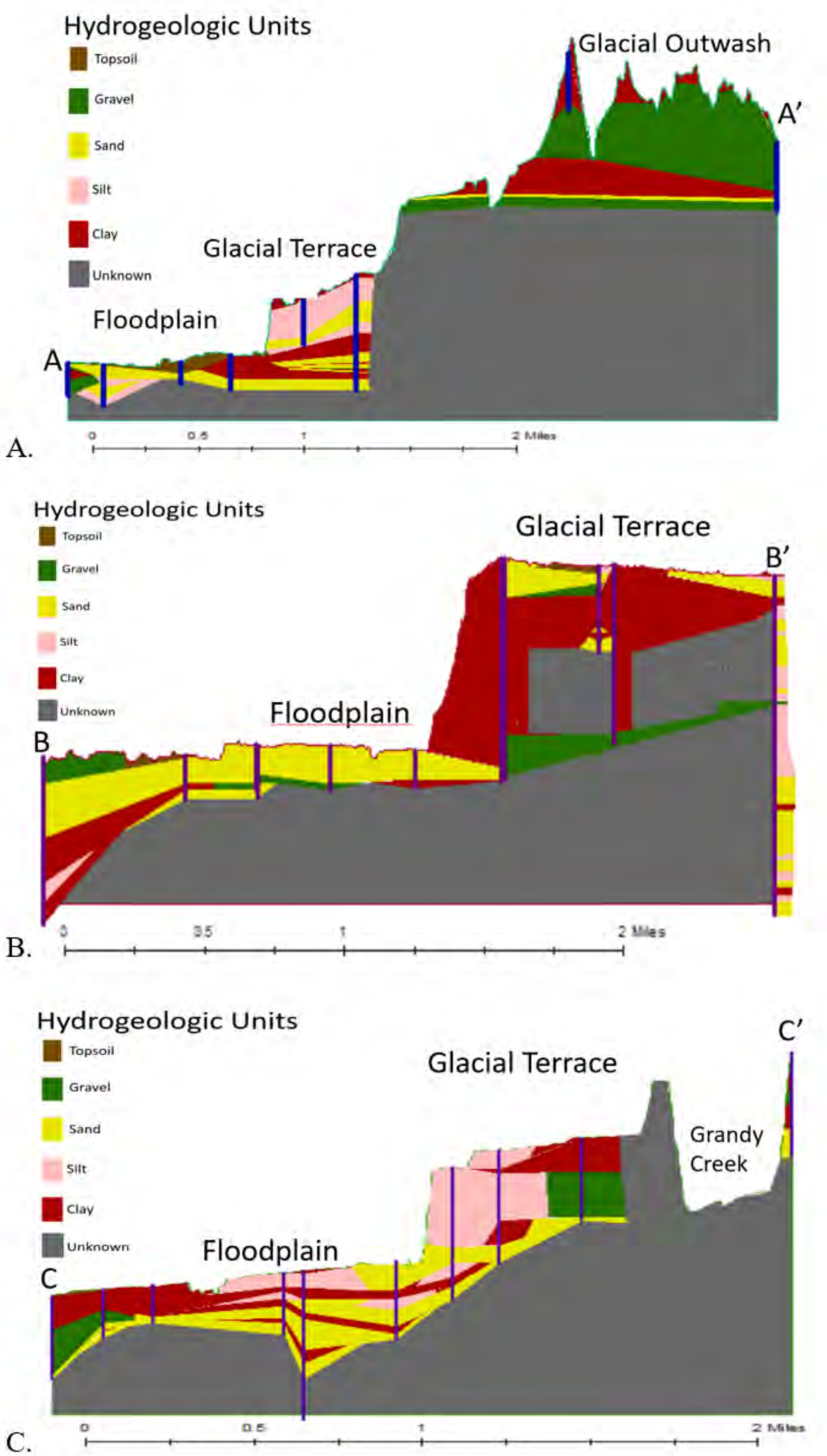


Figure 7: Cross Sections of Pathways: A. Muddy Creek B. Alder Creek C. Grandy Creek. Units defined by smallest grain size in well report.