CITY OF ARLINGTON

HYDROGEOLOGIC CONCEPTUAL MODEL SUMMARY REPORT

JANUARY 2007

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HYDROGEOLOGIC CONCEPTUAL MODEL
SUMMARY REPORT

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DEFINITIONS, ACRONYMS, AND ABBREVIATIONS

The following is a glossary of technical terms, acronyms, and abbreviations used in this report. The purpose of this glossary is to provide a reference for readers who are less familiar with terms often used in technical discussions about hydrogeologic concepts.

Alluvial - Produced by the action of a stream or river.

Aquifer - A hydrostratigraphic unit that yields significant (economically feasible) amounts of water to wells; also called a "water-bearing" unit.

Aquitard - A hydrostratigraphic unit that does not yield significant amounts of water to wells. An aquitard can store large quantities of water, but it only allows slow vertical (upward or downward) movement of groundwater into other units. Because some aquitards are large in aerial extent, relatively large volumes of water may flow through them.

Base flow - The component of streamflow fed by groundwater discharging to the stream.

Br - Bedrock

Confined aquifer - An aquifer that is overlain by an aquitard (a confining unit) and contains groundwater under sufficient pressure to rise above the top of the aquifer. Also known as an artesian aquifer. In some cases, groundwater levels may be above land surface, and wells completed n the confined aquifer may flow.

CWSP - Coordinated Water System Plan

DNR - Washington State Department of Natural Resources

Ecology - Washington State Department of Ecology

GIS - Geographic Information System; a computer-based system that provides an interface between many types of graphical and non-graphical data over geographic areas.

Glacial drift - All sediments transported and deposited by glaciers; includes tills, outwash, glacio-lacustrian deposits, kames and more.

Groundwater divide - An imaginary no-flow line on a water table (or potentiometric surface) contour map. Groundwater on one side of the line flows in one direction; groundwater on the other side flows in the opposite direction.

Hydraulic conductivity - A coefficient of proportionality describing the rate at which water can move though a porous medium, commonly expressed in units of feet per day (ft/day) or centimeters per second (cm/sec). It is equal to the transmissivity of an aquifer divided by its saturated thickness.

Hydraulic gradient - The change in total head (or water level) with a change in distance in a given direction; the coefficient of proportionality that expresses the “driving force” of groundwater flow.

Lacustrine - Produced by lakes.

Mudflow - A flowing mixture of fine grained earth material with a high degree of fluidity. A mudflow may also transport rocks, trees, and other debris, and is usually associated with a volcanic event such as an eruption.

NAVD – North American Vertical Datum

NGVD - National Geodetic Vertical Datum

Non-glacial - Refers to those geologic processes that occurred during periods when glaciers were not present

NRCS - Natural Resources Conservation Service

Outwash - Sand and gravel deposited by melt water streams from a glacier

Perched - Groundwater occurring in a saturated zone (all the pore spaces filled with water) that overlies another zone that is not saturated. It is typically a saturated sand or gravel overlying a silt or clay, which in turn overlies *unsaturated* sand or gravel.

Pleistocene - The period in geologic history between about 2 million to 10,000 years ago. Also known as the time of glaciers, or the “ice age.”

Pro-glacial lake - A lake that forms just beyond the frontal margin of an advancing or retreating glacier; it is generally in direct contact with the ice.

Qal - Modern alluvium deposited by rivers

Qog - Older gravel deposited prior to Vashon time

Qtb - Transitional beds; silt and clay deposited in proglacial lakes

Qva - Vashon advance outwash deposits

Qvr - Vashon recessional outwash deposits

Qvt - Vashon till

Recessional - Refers to processes and sediments deposited by a retreating glacier

Recharge - Portion of hydrologic cycle that enters the subsurface and adds water to the groundwater system

Reservation - Quantity of water set aside by Ecology for specific purposes such as domestic well drilling and stock watering (for the purposes of this report, it is referenced in the Stillaguamish River in-stream flow rule.

Specific capacity - A measure of how much water a well can produce; specifically, the rate of discharge from a well per foot of drawdown at that rate, expressed in gpm/ft. Specific capacity usually decreases with continued pumping over time, even though the pumping rate remains unchanged.

Stade - A describing the *time* (as opposed to a rock unit) of a glacial episode. For example the Vashon stade is the time that Vashon glacial episode occurred.

Stage - The level or elevation of a river.

Static water level - A water level measurement obtained from a well under non-pumping conditions, when water levels are not changing in response to recent pumping.

Storativity - Also referred to as “storage coefficient,” a measure of the volume of water an aquifer releases from or takes into storage per unit surface area of an aquifer per unit change in head. It is expressed in dimensionless units.

Surface Water - Bodies of water on the earth’s surface, such as rivers, streams, creeks, lakes, and ponds.

Tertiary - The period of geologic history between 65 million and 2 million years ago. It is also known as the “age of mammals.”

Till - Unstratified, poorly sorted glacial drift deposited directly by a glacier; these sediments are “smeared” along the bottom of a glacier; as such, they are typically very dense and compact. Till often looks like concrete and is often called “hardpan” by well drillers.

Transmissivity - A measure of an aquifer’s ability to transmit water; the rate at which water is transmitted through 1 foot of aquifer width under a 1:1 hydraulic gradient. Transmissivity equals the hydraulic conductivity of an aquifer times its saturated thickness. It is commonly expressed in gpd/ft, ft2/day, or m2/day. Also indicated as “T”.

Unconfined aquifer - An aquifer that is not overlain by a confining unit and in which pore water pressure is atmospheric; water levels in such an aquifer lie below the top of the aquifer.

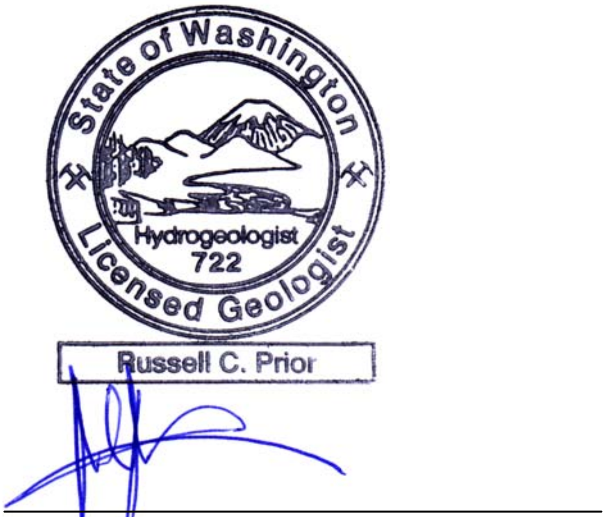
USGS - United States Geological Survey

WAC - Washington Administrative Code

WRATS – Water Rights Application Tracking System

SIGNATURE

This report, and Pacific Groundwater Group's work contributing to this report, were reviewed by the undersigned and approved for release.



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1.0 INTRODUCTION

This report summarizes Pacific Groundwater Group's conceptual hydrogeologic model in the vicinity of the City of Arlington.

This conceptual model will be used to complete other groundwater-related work such as wellhead protection capture zone delineations, production well construction, feasibility of aquifer storage and recovery, and water-rights studies.

1.1 SCOPE

The work described in this report is based on a scope of work developed by PGG and City staff. In general, the scope was divided into phases and this report presents the results of a portion of Phase I. Subsequent phases as currently configured include Phase II, which will be used to develop a dynamic tool for water resource management and Phase III, which includes undefined continuing ser-vices. Such continuing services could in-clude production well development, development of an aquifer storage and recovery (ASR) system, groundwater and stream monitoring, and water rights consulting.

Phase I includes several tasks and one is documented in this report, namely: Task I.1 Develop Hydrogeologic Conceptual model. Several subtasks were outlined and are documented in this report:

- Subtask 1.1 – Existing Data Collection and Review
- Subtask 1.2 – Ecology Well Log Collection, Digitization, and Management
- Subtask 1.3 – Develop Hydrogeologic Cross-Sections
- Subtask 1.4 – Map Groundwater Flow Direction
- Subtask 1.5 – Map Other Hydrogeologic Features – including recharge, transmissivity, and aquifer boundaries
- Subtask 1.6 – Conceptual Model Summary Report

This work was authorized by Mike Wolanek of the City of Arlington on August 8, 2006.

1.1.1 Use of This Report

The report documents Pacific Groundwater Group's understanding of the groundwater system in the Arlington area based on existing hydrogeologic information. Such an understanding is referred to as a "conceptual hydrogeologic model". This report is designed as a reference—tables and figures are all included at the end of the text—and is a dynamic document subject to change as more information becomes available. The goal of this report is to provide a basis for further assessments, which could include:

- Identifying data gaps where insufficient data exist to evaluate issues that are important from a municipal water supply standpoint
- Providing a basis for understanding where future supply development might occur
- Suggesting locations and subsurface conditions conducive to aquifer storage and recovery
- Providing a framework for developing and modifying wellhead protection capture zone delineations

1.2 GROUNDWATER STUDY AREA

The groundwater study area comprises 90 square miles centered approximately about Arlington's 8.3 square mile city limits and its 23 square mile Coordinated Water System Plan (CWSP) service area. The study area includes lowland and upland areas. Lowland areas include: the upstream portion of the main stem of the Stillaguamish River, downstream portions of both forks of the river, and the northern portion of the Marysville trough. Upland portions include the western portion of Arlington Heights, the northern portion of the Getchell Plateau, the northeastern portion of the Tulalip Plateau, and the southern portion of the East Stanwood Plateau. Figure 1 shows the groundwater study area as well as the physiographic areas noted above.

1.3 CITY OF ARLINGTON WATER SUPPLY

The City of Arlington currently supplies water from two main sources—the Airport Production Well and the Haller Park Well Field (Figure 1).

The Airport well is located on the eastern side of the airport (Figure 1). This well is 185 feet deep, 10-inch diameter, and appears to tap fine sand beneath the Marysville Sand deposit. Two well logs exist for this well. The first (available on Ecology's web site) is dated May 1965 and appears to inaccurately summarize the soils and water level information that was indicated on the original log, which is dated 1945. This report uses the information from the original well log.

The static water level for the Airport Production well is reported as 102 feet *elevation* in the original log. In the well log downloaded from Ecology, this has been erroneously reported as a depth-to-water. This information provides a basis for choosing the validity of one log over the other since a water level elevation of 102 feet fits the regional picture while a depth-to-water of 102 feet does not.

Recent testing by Pump Tech in 1996 indicates that the well is capable of pumping about 600 gpm with about 60 feet of drawdown (written communication Pump Tech to Terry Castle, 1996).

The Haller Park Well Field consists of three wells: Well Nos. 1R, 2, and 3. These wells are shallow and of variable construction. They tap alluvuial sand and gravel along the shore of the Stillaguamish River just downstream of the confluence of the North and South Forks (Figure 1). This well field has previously been determined to be "groundwater under the influence of surface water" (GWI) and as such was recently upgraded and tested. Testing occurred for each of the wells (PGG, 2000A; PGG, 2000B; and PGG 2002A) during upgrading and a filtration system was also constructed.

- Well No. 1R was drilled in April 2002 using 20-inch drilling casing; it is finished with an 18-inch diameter screen and 16-inch steel production casing. The use of oversized drilling casing would have allowed installation of a filter pack if deemed appropriate; however, it was deemed not necessary due to the well graded sandy gravel encountered. The surface seal was placed prior to final removal of the 20-inch drilling casing. Relatively high manganese in the water causes this well to be the last call well among the Haller Park wells. It yields 570 gpm with about 6.5 feet of drawdown after 4.5 hours of pumping. Well No. 1R replaces the original Well No. 1, which was drilled prior to December 1961 when the well log indicates the well was tested. This was a dug well that was constructed of 36-inch diameter concrete casing.
- Well No. 2 appears to have been constructed at the same time and in the same way as the original Well No. 1. It was tested in May 2000 during an overhaul of the well field. It now produces 570 gpm and is one of the City's main producers.
- Well No. 3 appears to be a reconstruction of a 15-foot diameter dug well that was drilled in the 1920's. The well was deepened from 22.6 feet to its current depth of 37.2 feet. Well No. 3 is 60-inches in diameter. Well No. 3 has two pumps installed; each one is capable of 570 gpm. Well No. 3 was tested in the fall of 2000. This well is usually pumped a 570 gpm but with the second pump is capable of 1140 gpm except during low-water-level times of the year. We have not been able to find a log that documents this reconstruction.

1.4 WELL NUMBERING SYSTEM

The well numbering system used in this re-port corresponds to the system used by the USGS. It is based on the rectangular subdi-vision of public land by township, range, section, and ¼-¼ section (40-acre tract). For example the City's Airport Production well is number 31/5-22F. The 31/5 stands for Township 31 / Range 5 (all townships in this report are north of the Willamette Meridian and all ranges are east; therefore, the north and east designations are assumed in this report and not indicated). The number 22 stands for the section that the well is located in and the "F" stands for the ¼-¼ section—in this case it is the SE ¼ of the NW ¼ of section 22. The letter designation of the ¼-¼ section starts in the NE ¼ of the NE ¼ and winds west, then east sequentially through the section. The letters "I" and "O" are omit-ted so the letter designations range from "A" to "R".

1.5 VERTICAL DATUM

The vertical datum used in this report is based on North American Vertical Datum of 1988 (NAVD-88), which differs from the National Geodetic Vertical Datum of 1929 (NGVD-29) used by the USGS. The differ-ence in the vicinity is 3.6 feet with the NAVD datum being lower than NGVD. Therefore, an elevation of 10.0 feet in NGVD 29 would be 13.6 feet in NAVD 88.

1.6 WARRANTY

The work was performed, and this report prepared using generally accepted hydro-geologic practices used at this time and in this vicinity, for exclusive application to groundwater study area and for the exclusive use of the City of Arlington, Washington. This is in lieu of other warranties, express or implied.

2.0 SUMMARY OF FINDINGS

- Two aquifers exist in the area that are of interest for future municipal supplies. These are herein called the upper aquifer and the deep aquifer. The upper aquifer is typically the first groundwater encountered excepting small occurrences of perched groundwater. In lowland areas the upper aquifer includes several deposits including sand and gravel of glacial and alluvial origin. Beneath upland areas, the upper aquifer is found in advance glacial outwash and can be as much as 200 feet below the ground surface.
- Groundwater in the upper aquifer generally flows westerly but is complicated by the landforms in the vicinity. For example, upper aquifer groundwater flows easterly off the east bluff of the Getchell Plateau before turning westward in alluvial sediments. A groundwater divide exists in the upper aquifer in the southern portion of the groundwater study area. This groundwater divide is south of the WRIA 5 and WRIA 7 boundary, which means that the groundwater basin here is not coincident with the surface water basin.
- The deep aquifer as defined in this study is the saturated sand and gravel material that is frequently encountered immediately below the transitional beds. The general occurrence of it is in the southwest portion of the groundwater study area. It also appears to occur within a bedrock trough mapped east of the South Fork Stillaguamish River.
- The potentiometric surface elevation of the deep aquifer ranges from a high of over 200 feet in the northern portion of the Getchell Plateau to less than 50 feet in the western portion of the study area. Groundwater flow is generally toward the west.
- The most promising area for future municipal water supply development will be in the Marysville Trough where relatively high transmissivities combined with shallow water levels contribute to well yield potential on the order of 500 to 1000 gpm. Similar yields may be available beneath the Getchell Plateau where the deep aquifer exists; however, little information regarding the deep aquifer transmissivity exists. The northern portion of the Getchell Plateau will likely not support a municipal well that is designed to tap the upper aquifer because of low saturated thicknesses.
- Bedrock occurs at relatively shallow depths underneath a large portion of the groundwater study area. While this has been well established in the northern and eastern portions of the study area where bedrock crops out along Pilchuck Creek and on the crest of the Getchell Plateau, respectively, the existence of relatively shallow bedrock beneath the Marysville Trough in the southern portion of the study area has not previously been recognized.
- Annual recharge to the groundwater system as a whole ranges from less than 20 to greater than 40 inches per year. In areas of interest to Arlington's municipal water supply the recharge is 25 to 30 inches per year. This amounts to over 800 gallons per minute per square mile. Recharge to the deep aquifer has not been estimated but will be equal to the recharge noted above minus the amount of water discharging from the upper aquifer. Such discharge could be to wells, springs, and/or surface water features.

3.0 SUMMARY OF METHODS

The methods used to collect and analyze data for this project are described in this sec-tion.

3.1 DATA COLLECTION AND PREVIOUS INVESTIGATIONS

The basic data collected for developing this hydrogeologic conceptual model were well logs downloaded from the Washington State Department of Ecology's (Ecology) well log database. In addition, we collected pertinent existing information for the area, which included printed studies by the USGS, private consultants, and documents already in PGG offices. GIS data were also obtained and loaded onto PGG computers. The City of Arlington provided historical groundwater level data of the Haller Park wells and Stillaguamish River stage data in the vicinity of Haller Park.

3.2 WELL LOG DATABASE

PGG downloaded 1880 well logs located in the groundwater study area. The download included logs for wells greater than 25 feet deep and included only water well logs. A subsequent download of resource protection well logs resulted in only 32 logs that were generally useful. Even these are grouped (several wells clumped at an individual site) and provide little useful information. During the study, a decision was made to obtain well logs for wells that tap the shallow alluvial aquifer. This download included wells that were greater than 8-inches in diameter and were less than 50 feet deep. The majority of this download produced wells that were 36-inches in diameter. This download included 185 wells located in selected sections that coincide with the mapped occurrence of the alluvial deposit.

The downloaded information includes PDF files of the actual well logs and a text file that includes physical data for each well. The text file included fields for well owner, well depth, location, and other parameters. But important data such as depth-to-water are not included. Therefore PGG added several fields to the database by hand. By maintaining the same order of downloaded well logs with entries in the text file, additional physical data can be easily input. A data dictionary of information provided directly by Ecology and information added by PGG is presented in Appendix A.

PGG added the following information to the database:

- Depth-to-water
- well yield
- drawdown
- depth of drill stem during air test
- depth to rock

Based on this information, it is possible to calculate the specific capacity of the well, which, in turn, can be related to aquifer transmissivity; therefore, PGG also added those two fields to the database. A printed copy of the well database is included in Ap-pendix A.

After compilation of the well log database, a subset of 245 well logs was printed for use in constructing the cross-sections. This subset includes logs for wells greater than 250 feet deep and occasional shallow wells used for specific purposes; for example, all of the City's water supply wells were included to show the tapped units. Forty-one of these were chosen for the cross-sections and the construction details of these wells are presented in Table B-1. Logs for the 41 wells used in our cross-sections are also included in Appendix B. The wells were chosen based on location, depth, and professional judgment regarding the usefulness of the information.

As an aid to using the database for searching specific groupings of wells (for example, all wells shallower than 75 feet in T31/R5) the Excel spreadsheets were input into a Microsoft Access relational database. This database is relatively simple and contains two well tables, which were downloaded from Ecology independently of each other.

3.2.1 Groundwater Level Mapping

Data supplied by Ecology and depth-to-water data input by PGG were used to complete a groundwater elevation contour map. Using GIS techniques, the ground surface elevation of each well was generated based on the northings and eastings supplied by Ecology. The depth-to-water data were then subtracted from the ground surface elevation data yielding groundwater elevation. Finally, the groundwater elevation data were contoured.

This technique works well except that, in ¼-¼ sections with steep topography, the generated ground surface elevation data can be wrong (the exact location of each well is not known). Therefore, a buffer surrounding each well was mapped and if the topography within this buffer changed by more than 50 feet, the data point was not used.

3.2.2 Groundwater Recharge Mapping

The quantity of water that infiltrates is related to the amount of annual precipitation and the soil type that occurs at the ground surface. Thomas, et al (1996) presents a relationship between annual precipitation and annual recharge for two different surficial soil conditions. Precipitation incident upon clean granular soils (outwash relation) generates more recharge than if the precipitation falls upon fine grained soils or bedrock (till relation).

PGG used the equations of the lines shown in Thomas, et al (1996) to create groundwater recharge maps. The equations are:

Outwash Relation: $R = 0.9\,P - 12$

Till Relation: $R = 0.56\,P - 6.3$

Where:

R = annual recharge (inches)

P = annual precipitation (inches)

Contoured precipitation data were gridded then geology data were pixilated. The result is a geo-referenced recharge map that is discretized into 500 square-foot areas.

3.2.3 Aquifer Transmissivity

Aquifer transmissivity (T) is a fundamental aquifer parameter that describes an aquifer's ability to yield water to wells. In the Arlington groundwater study area values of T range from very high at Haller Park to very low in some thin deep water bearing zones.

Transmissivity is usually reported based on results of a constant-rate pumping test. However, the vast majority of wells do not have long-term pumping tests conducted on them; rather, they have simple documentation of yield and drawdown.

In such cases (without pumping test data), PGG has estimated the transmissivity of the various aquifers using data input into the well log database. Using the well yield and drawdown information, the specific capacity

(Cs) of each well was calculated. The transmissivity (T) was then estimated using a simple empirical relation between Cs and T (Driscoll, personal communication). The relation

T (gpd/ft) = Cs (gpm/ft) * 2000

yields a value for T in gallons per day per foot (gpd/ft).

Average and median values of T were calculated using this relation for several aquifers in the vicinity. The population of the selected wells is based on the area (T/R-Section) to be considered, estimated well depths based on cross-section information, and on water level elevation.

Except where pumping test data exist, the values of T provided in Section 5.1 are based on specific capacity information. In some cases, the well logs indicate a well yield of, say, 25 gpm with 0 feet of drawdown. Zero values of drawdown were input as 0.01 feet, otherwise we could not perform a T calculation (cannot divide by 0). With low values of drawdown, the calculated T values likely exceed reality. Similarly, very high values of drawdown would yield unrealistically low values of T. Therefore, high and low values were not included in our estimates.

3.3 OTHER INFORMATION

The following documents, maps, and con-sultant's reports were collected and re-viewed during development of the concep-tual model.

Geologic mapping completed by James Minard for the Arlington West and Arlington East quadrangles (Minard, 1985a, 1985b). This mapping was completed on 7½ minute quadrangles (scale of 1:24,000 or 1" = 2000'). This is the most detailed geologic mapping completed in the area and is the basis of more recently published mapping. Minard recognized several distinct recessional outwash deposits based on typical grain size, elevation, and location. For the purposes of this report, these recessional deposits have been grouped into one unit.

A report by Economic and Engineering Ser-vices, Inc. (EES, 1996) entitled *Snohomish County Groundwater Characterization Study* was reviewed. It provides generalized groundwater information for the study area including cross-sections, very general groundwater flow mapping, and descriptions of various aquifer systems.

A report by the USGS (Thomas, et al, 1996) entitled *The Ground-Water System and Ground-Water Quality in Western Snoho-mish County, Washington*. This regional-scale study includes cross-sections, subsur-face contour maps, and groundwater flow field maps. Just one cross-section in this re-port traces through our groundwater study area.

A report by Snohomish County Public Works titled *Draft Getchell Plateau Groundwater Investigation* (Kirtland, 2005), was reviewed. This report is limited to the Getchell Plateau upland and includes cross-sections and water level maps. It recognizes several aquifers including an alluvial aquifer that is described as along creeks and rivers but then maps the aquifer as occurring throughout the plateau. We have not relied heavily on this investigation.

The USGS completed a study entitled *Water Resources of the Tulalip Indian Reservation* (Frans & Kresch, 2004). This study includes a geologic map and cross-sections of the upland to the west of our groundwater study area.

SCS Engineers prepared a report *Hydro-geologic Evaluation, Rinker Arlington Fa-cility Expansion, Arlington, Washington* (SCS, 2006) in June 2006. This very site-specific report features groundwater contour data, cross-sections, and a simplified Modflow model. The cross-sections appear to be based on grain size of soils encountered and provide detail of only the materials that are of interest for gravel mining. Groundwater flow directions for the shallow aquifer defined in this report are toward the southwest. The horizontal gradients are high (steep) as flow sheds off the upland portion of the aquifer and become flatter in the alluvial materials of the Stillaguamish River.

3.3.1 GIS Data

Geographic Information System (GIS) data were collected from various sources. These (along with data sources) include:

- Parcels - Snohomish County
- Roads - Snohomish County
- Topography - U of W
- Hydrography - Snohomish County
- Geology - DNR
- Precipitation - NRCS
- Land Use - City of Arlington
- Basin and sub-basin boundaries and WRIA 5 boundary - Snohomish County

3.3.2 Groundwater Level Data

The City provided preliminary groundwater-level data collected from the Haller Park Well Field wells (Wollanek, personal communicaiton). These data from Well Nos. 2 and 3 clearly indicate the hydraulic coupling between the Stillaguamish River and groundwater heads in the Haller Park Wells. It appears that, during non-pumping periods, the groundwater head is higher than the surface water, indicating that the river is gaining in the Haller Park reach. With the wells pumping, the relationship is reversed and groundwater heads are drawn down below the river.

4.0 GEOLOGIC FRAMEWORK

The geology of the Arlington area is characterized by typical Puget Lowland surficial geology and stratigraphy. In addition, because the city is located near the Cascade foothills, bedrock also plays a role in the regional geology. The surficial soils lay on top of a bedrock surface that dips (slopes) to the west. Bedrock crops out in the northern and eastern portions of the study area. In general, the bedrock, which is typically continental and marine sedimentary rock, is not useful for municipal water supply because yields are generally poor. Therefore, this report does not include detailed information such as bedrock type, structural geology, or amount of fractures.

4.1 REGIONAL GEOLOGY

Layering of the surficial soils results from the repeated incursions of glacial ice into the Puget Sound lowland. Many such incur-sions have been documented and range in age from about 13,500 to nearly 1 million years old. The repetitive nature of the ice advance has created a complex layering of soils that were deposited during glacial and non-glacial times.

In general, glacial deposits are considered to have coarser texture, higher permeability, and greater water transmitting capacity than non-glacial deposits. Glacial deposits include recessional and advance outwash sand and gravel deposits that support many of the area's major aquifers.

Non-glacial sediments are considered to be fine grained and tend to form aquitards. These aquitards limit movement of groundwater and serve to protect underlying water bearing zones from surface activities. They also form confining layers above confined aquifers.

This simplified conceptual model of glacial/non-glacial deposits giving rise to aquifers and aquitards is complicated by deposition of fine grained soils during glacial times and by deposition of coarse grained soils during non-glacial times. Glacial deposits not only include coarse grained soils that were deposited near the advancing and retreating ice front—they also include glacial till and pro-glacial lake deposits of clay and silt, neither of which provides water to wells in significant quantities. Non-glacial deposits include recent river alluvium in the Arlington area. The Stillaguamish River Alluvium forms an important aquifer that supplies most of the City's water supplies.

Finally, alpine glaciation has also complicated the picture in the vicinity. The valleys of the North and South Forks of the Stillaguamish contain deposits associated with alpine glaciation (Thomas, et al, 1996). At the mouths of these valleys, deposits from continental and alpine glaciation mix, creating a complex web of deposits. The cross-sections in this study do not attempt to depict this level of complexity and the geology presented in them is based on a continental glacial regime.

4.2 HYDROGEOLOGY OF THE STUDY AREA

In the Arlington area, the unconsolidated deposits are associated with deposition of river alluvium, deposition during the most recent glacial ice advance into the region, and deposition during the preceding non-glacial period. The last glacial episode is known as the Vashon stade of the Frazier glaciation. It began in the Puget Sound area approximately 15,000 years ago and lasted for about 1500 years (Thomas, et al, 1996). Deposits associated with this glacial stade are identified with “Vashon” in the naming convention.

4.2.1 Surface Water Features

Arlington sits at the confluence of the North and South Forks of the Stillaguamish River, which has a total basin area of 700 square miles. Interestingly, the headwaters do not reach the crest of the Cascade Mountains due to a quirk in topography near Darrington. A low topographic divide , separates the North Fork Stillaguamish from the northward flowing Sauk River[1]. The Sauk River drains the area between the eastern boundary of the Stillaguamish Basin and the Cascade crest, diverting water northward to the Skagit River.

The main stem of the Stillaguamish River is 17.8 miles long emptying into Puget Sound at Port Susan. Average flow of the Stillaguamish is around 3,000 cfs, with winter flows above 4,000 cfs and average summer flows less that 1,000 cfs. The average stage height at Arlington is 53.4 feet (NAVD88) based on data from the Snohomish County gage at the railroad bridge located at the confluence of the North and South Forks (Wolanek, e-mail communication).

The Stillaguamish River basin is regulated under a recently promulgated instream flow rule—Chapter 173-505 WAC (Ecology 2005). This rule establishes instream flows for all reaches of the Stillaguamish and its tributaries. Figure 2 compares the flow quantities established in the rule with the average daily flows per month of the Stillaguamish River main stem based on a gauge maintained by Snohomish County (Snohomish County, on-line). Highlights of the rule that pertain to Arlington water supply issues are presented in the following bullets:

- The effective date of the rule is September 22, 2005.
- The total future consumptive withdrawal from the basin cannot exceed 300 cubic feet per second (cfs) as measured at Ecology’s gage (#05A070)[2] located at river mile 11.2. Specific limitations on withdrawals for specific reaches and specific periods are also promulgated in the rule.
- Future appropriation of water from Portage Creek is not allowed. This includes groundwater that is determined to be hydraulically connected to Portage Creek.
- A reservation of 5 cfs (3.2 million gallons per day or MGD) is established to allow development of domestic wells (individual or group) that are exempt from water rights permitting. Ecology will monitor use and will provide annual updates of the amount of reserved water that is allocated.

[1] The genesis of this divide has not been investigated for this report; it may be an alpine glacial deposit, volcanic mudflow (lahar), or landslide.

[2] This gauge is located on the main stem at Interstate 5.

- Ecology retains 1 cfs of surface water and 20 acre feet per year (6.5 million gallons) of groundwater for stock watering.

Details of groundwater/ surface water interaction for specific reaches of the surface water network are beyond the scope of this study. However, as specific issues arise, for example, groundwater development in the Portage Creek area, specific hydraulic continuity studies will need to be undertaken. Such studies could include stream gauging and seepage surveys, shallow aquifer groundwater level monitoring along with stream stage monitoring (transducer studies) and aquifer specific studies including pumping tests and groundwater flow mapping.

4.2.2 Stream Gauging

In hydrogeologic environments such as that occupied by Arlington, stream gauging is an important component of groundwater investigations. Three agencies currently monitor surface water flows in the Stillaguamish basin with several gauges:

- The USGS maintains two gauges in the basin. These are the oldest gauges in the basin, having been established in 1928.
- Ecology maintains twelve gauges in the basin. Manual stage height only is collected in four of these; the remaining eight gauges have real-time flow reporting. Several gauges in this set include water quality parameters.
- Snohomish County also maintains several gauges in the area; seven include flow data or automatic stage height data collection.

A few details of each gauge are presented in Table 1; gauge locations are shown in Figure 1.

Portage Creek is currently not monitored for stage or flow. However, it's location near the city and near potentially transferable water rights, suggests that future investigation would be useful. Detailed information regarding the hydraulic continuity of the creek to the groundwater system is currently not available and could be provided in future submittals to the City.

4.2.3 Hydrogeologic Units

This section provides descriptions (occurrence, thickness, general location, and potential for municipal water supply development) for each of the hydrogeologic units that are represented in the cross-sections. Figure 3 presents a stratigraphic column of the units described in this section. The figure shows the vertical relationships of the units to each other.

Alluvium – Qal

This unit includes alluvium deposited by the various streams in the study area. This unit typically comprises clean sand and gravel with cobbles and boulders. The most important expression of this unit in the study area is next to the main stem of the Stillaguamish River. The unit ranges in thickness from zero to about 30 feet (Minard, 1985a). The Haller Park Well No. 1 replacement well encountered 34 feet of sand and gravel before encountering bedrock. This is likely a coalescence of Qal and underlying Qvr. Distinguishing one unit from the other in well logs is difficult and, fortunately, the distinction is not useful or needed from a water supply standpoint.

Future municipal water supply development could include use of this unit. Many existing water rights are perfected in the Qal and relatively easy transfers might be possible to the Haller Park well field due to obvious answers to the “same body of water” questions.

Vashon Recessional Outwash – Qvr

The Vashon Recessional Outwash was deposited during Vashon recessional time as the Vashon Puget lobe melted. The deposit consists of loose, clean, sand and gravel. Minard (1985a, 1985b) mapped several unique deposits within this unit including the Arlington Gravel in the Arlington Heights area, and the Marysville Sand in the Marysville Trough. For this study, we have grouped the separately mapped occurrences into one unit. The combined Qvr reaches thicknesses of up to about 130 feet and is typically about 100 feet thick. This is the unit that is being mined for sand and gravel by many mining operations in the vicinity including the Rinker Pit north of Arlington.

In many places, the Qvr occurs directly beneath the Qal creating a single aquifer. The most important location is near Arlington where the Stillaguamish River Alluvium is deposited directly on top of Qvr.

Future municipal water supply development from Qvr sources, which occur independently of other units, is unlikely. In places where this deposit forms a discrete aquifer, the relatively susceptible nature of the deposit and proximity to the surface indicate potential water quality concerns. In addition, the likelihood of significant well yield is low because saturated thicknesses are generally small.

Vashon Till – Qvt

Vashon till was deposited directly beneath the Vashon ice lobe during its advance. The deposit consists of an unsorted mixture of very dense, gray to brownish gray, gravelly, silty sand and is often referred to as “hardpan” in drillers’ logs. Its density is caused by the direct compaction of the glacial ice. The Qvt often mantles the tops and sides of hills and due to its silt content impedes vertical movement of water (aquitard). The largest mapped occurrence of Qvt is on the Getchell Plateau where it appears to be over 100 feet thick. Vashon till has been eroded away in the Marysville Trough.

Vashon Advance Outwash – Qva

This deposit comprises a fining downward sequence of gravel, sand, and occasional silt and was deposited by meltwater streams issuing from the advancing Vashon ice lobe. Regionally, it is an important water supply aquifer and its presence in the Arlington area is known based on many outcrops in the Arlington area. This deposit typically consists of dense to very dense, brown, fine to medium sand; it contains gravel and silt in varying quantities.

The Qva is generally about 200 feet thick beneath the study area uplands and is thinner—presumably due to erosion—in lowland areas. The amount of saturation within the unit varies widely.

Where enough saturation exists, the Qva's potential for municipal water supply development is good. The southern portion of the Getchell Plateau is one such area as is the south-central portion of the groundwater study area beneath the Marysville Trough.

Quaternary Transitional Beds - Qtb

This deposit comprises fine grained silt and clay that was deposited in the pro-glacial lake, which formed during the advance of the Vashon ice lobe. It is readily identifiable in well logs as a relatively thick occurrence of silt and or clay. Sometimes fine sands and occasional fine gravel (pebbles) are also observed in well logs.

This unit is considered an aquitard, which provides resistance to groundwater flow. A few domestic wells appear to tap this unit but typically only small quantities of water are obtained. From a water supply standpoint, this unit is important because is provides protection from anthropogenic sources of contamination to deeper aquifers.

The Qtb is relatively thin (less than 50 feet) in the immediate vicinity of Arlington. It generally thickens to the west and appears to be about 300 feet thick in the west-central portion of the study area. According to the USGS, this unit is generally about 100 feet thick and has a maximum thickness of 400 feet (Thomas, et al, 1996).

Quaternary Older Gravel – Qog

The Older Gravel comprises granular soil that is often observed immediately underneath the Qtb unit. Many well logs indicate that gravel or sand & gravel occur at this horizon. This unit is a subset of undifferentiated units (Qu) defined by the USGS (Thomas, et al, 1996) that occurs between the Qtb and the bedrock. In the cross-sections the Qog is highlighted as a discontinuous blue colored unit.

As shown on the cross-sections, the Qog is generally around 100 feet thick. However, because most domestic wells simply tap the upper few feet of an aquifer, very few wells penetrate the entire thickness of the Qog and therefore the true thickness is largely unknown.

The potential for future municipal water supply development within the Qog is relatively high. It occurs in locations appropriate for Arlington, appears to be relatively productive, and is well insulated from surface activity. It appears to be present beneath at least a portion of the Maryville Trough and has been identified in several areas beneath the Getchell Plateau—both of these areas have been suggested for possible municipal water supply. Although little transmissivity data are available, its great depth and high confinement suggest large columns of water available for drawdown, which in turn suggests potentially high well yields. Finally, its occurrence beneath the Qtb silt/clay unit indicates that the unit is generally protected from surface activity.

Bedrock – Br

As indicated in Section 4.0, the bedrock is not an important source of groundwater in the study area. The bedrock surface generally dips (slopes) to the west so the glacial materials range in thickness from zero north and east of the city to around 1200 feet (Jones, 1996) beneath the Tulalip Plateau.

4.2.4 Hydrogeology of the Groundwater Study Area

The hydrogeology of the groundwater study area is depicted in Figures 4 through 7. Figure 4 is a simplified geologic map that shows the horizontal distribution of the various hydrogeologic units as defined above and Figures 5, 6, and 7 present five hydrogeologic cross-sections. The surficial geology depicted in Figure 4 is from digital mapping provided by DNR at a scale of 1:100,000 (DNR, online). The cross-sections depict the vertical distribution of the various hydrogeologic units. Cross-section traces are shown in Figure 4.

Decisions regarding the use of particular well logs were based on professional judgment, well depth, and well location. PGG used professional judgment when choosing one well log over another (see discussion of the two well logs available for the Airport production well in Section 1.4). The general quality of the log, information included, and other qualitative criteria were used to make decisions. In general, a bias toward deeper well logs was used as the depth criterion. And finally, well logs located in areas otherwise void of subsurface information were used as needed.

The cross-sections were drawn based on a subset of well logs from our initial download. Because this subset includes well logs for wells that were over 250 feet deep, it appears in the cross-sections that upper units (Qva, Qvr, and Qal) do not have wells that tap them. This is an artifact of the method used to select wells for use in the cross-sections.[3]

There are, in fact, many wells that tap these upper units that are not presented in the cross-sections. As a way to gauge the existence of shallow wells that are not shown, each cross-section shows a trace of the water table (or potentiometric surface if confined). For example, in section D-D' (Figure 6) the left-hand (southern) portion shows a relatively large thickness of Qva with no wells; however, the high water table here indicates the likelihood that wells do tap the Qva here. On the other hand, the central portion of the cross-section indicates low water table conditions suggesting that few wells tap the Qva in this area.

Occurrence of Bedrock

A significant finding of this study is that bedrock occurs at relatively shallow depths underneath the groundwater study area. While this has been well established in the northern and eastern portions of the study area where bedrock crops out along Pilchuck Creek and on the crest of the Getchell Plateau, respectively, the existence of relatively shallow bedrock beneath the Marysville Trough has not previously been recognized.

[3] An exception to this is the presentation of Arlington's Haller Park Well No. 1 replacement in cross-sections B-B' and E-E'. This well was used to present the vertical relationship of the Haller Park wells to the various hydrogeologic features.

Since the bedrock forms the bottom of the groundwater basin in the study area, we have completed a map that depicts the top of the bedrock surface. Figure 8 is a contour map of the top elevation of the bedrock surface in the study area. This map can be considered the bottom confining unit and provides a basis for estimating maximum depth of exploration for groundwater supplies for Arlington.

The surface depicted in Figure 8 is quite different than that published by other investigators (Jones, 1996; Thomas, et al, 1996). The interpretation presented in this report is based on three lines of evidence:

- PGG has personal knowledge of the existence of bedrock at Haller Park at shallow depths. This information includes a video log that was completed on the original Well No. 1, and samples collected during the drilling of the replacement well. The video indicated that 30 feet of bedrock was encountered in the original well (starting at 35 feet) and the replacement well was advanced 3 feet into bedrock. In addition to this personal knowledge, City records indicate that bedrock was encountered within 112 feet of the ground surface by H.O. Meyer in 1961 (Meyer, written communication).
- A well log (31/5-33R) in the south-central portion of the study area indicates that over 300 feet of bedrock was encountered. This well was drilled by Hayes Well Drilling in 1974. This firm has an excellent reputation with regard to the information they provide and we obtained a copy of the original well log from them.[4] We see no reason to dispute the information provided on the well log.
- Finally, PGG digitized the depth to bedrock in 379 well logs in the study area. These depths were converted to elevation, which was contoured to complete the bedrock elevation contour map. Most of the logs are located in the northern and eastern portions of the study area.

Occurrence of Qog

The depiction of Qog in the cross-sections indicates that it is generally found immediately beneath the Qtb. On the cross-sections, the Qog is shown as dark blue, discontinuous beds of water bearing material. Other area investigators do not call out the Qog as a separate unit, rather, Thomas, et al (1996) and Frans & Kresch, (2004) ascribe soils beneath the Qtb as belonging to undifferentiated quaternary deposits (Qu). In this report, the Qu, as defined in the earlier studies (ibid), is defined as occurring between the Qog and Br.

The presence of Qog beneath the airport area is surmised based on the log for a well located two miles northwest. Well 31/5-17F encountered sand and gravel at 572 feet deep beneath a thick sequence of silt and clay (correlated with Qtb). This well is shown in cross-section B-B’ (Figure 5).

Transitional Beds

The transitional beds (Qtb) appear to be an important, regionally extensive aquitard throughout the study area. These silts and clays were deposited in the pro-glacial lake that formed at the

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[4] The copy that was downloaded from Ecology was hard to read and could explain why the USGS apparently did not include the information in their study.

front of the advancing Puget lobe during Vashon time. They represent deposition during the transition from non-glacial conditions that occurred prior to the glacial advance and full glacial conditions during the advance. Although the contact between the Qtb and the overlying Qva is shown in the cross-sections as abrupt, it is generally considered to be gradational because both deposits were laid down in one continuous depositional regime—that being the advance of the Vashon ice lobe.

On cross-section C-C' (Figure 6) an occurrence of the Qtb unit is shown east of the bedrock outcrop on the Getchell Plateau. This occurrence is queried (**Qtb?**) because it is not known if the great thickness of clay encountered in well 31/6-8L correlates with Qtb. A double check of the well's address coincides with the T/R-Section location. Therefore, we believe that there is a trough in the bedrock at this location that could have been inundated by the Vashon pro-glacial lake allowing for deposition of Qtb.

Occurrence of Qva, Qvr, and Qal

It is important to note that many places in the cross-sections show the three upper hydrogeologic units in hydraulic continuity. For example, the central portion of section B-B' (Figure 5), as it crosses the Marysville Trough, indicates that all three units form one contiguous aquifer. This relationship between the post-glacial Qal and Qvr units and the underlying Qva unit occurs in areas where the Vashon Till (Qvt) is missing (likely eroded during the deposition of the Qvr). Another place is in the northwestern portion of section A-A' (Figure 5). Here, groundwater that occurs in the upland Qvr deposit flows into the underlying Qva then into the Pilchuck Creek alluvium occurrence of the Qal.

The close relationship that these three units have with each other suggests that they are parts of one upper aquifer and this is described in more detail in Section 5.1.

There are places where the Qva appears to be separated from the Qvr by the Vashon Till. Although the till limits the vertical hydraulic connection, its discontinuous occurrence allows water to move from one to the other relatively easily. An example of this is shown in section E-E' (Figure 7) where Qvt crops out just north of where the section crosses the Stillaguamish River. It appears that the till separates upper and lower occurrences of Qvr. Based on the location of the cross-section trace, this is true; however, the Qvt is shown to pinch out just west of the cross-section trace. This pinch-out allows water to flow easily from the upper occurrence of the Qvr to the lower one; such flow would occur out of the plane of the section.

5.0 GROUNDWATER

Earlier investigators have recognized several different aquifers within the vicinity. For example, Thomas, et al, (1996) indicates the existence of four aquifers in western Snohomish County. Kirtland (2005) indicates the existence of seven aquifers beneath the Getchell Plateau. While several separate aquifer bodies exist in the study area, PGG defines two aquifers that are herein referred to as the upper aquifer (usually unconfined) and the deep aquifer (confined). A third aquifer, encountered in surrounding bedrock, is discounted and not discussed further because it does not provide suitable quantities of water for municipal supplies. Table 2 compares the aquifers defined herein and those of earlier investigators.

PGG presents just two aquifers in this report because:

- Current thinking with respect to surface water/ groundwater interaction in the Puget Lowland suggests that separate management of aquifers is not needed.[5] For this reason, we have lumped the first expression of groundwater in the study area into one aquifer. These include the Qal, Qvr, and Qva occurrences of groundwater. The occurrences of groundwater within each of these units individually are herein called sub-aquifers.
- There are many locations within the study area where the upper hydrogeologic units are in direct hydraulic continuity with each other. For example, just west of Arlington, the Qal of the Stillaguamish River is in direct contact with the underlying Qvr. Also, in the Marysville Trough, the Qvr is directly underlain by Qva. Although the units are different because of depositional regime, grain size, and extent, they are really just different layers of a single upper aquifer.

Properties of individual aquifers are discussed in the following two sections. Aquifer property values presented in the report are based on data obtained from drillers' well logs. Table 3 presents a summary of aquifer properties as estimated by PGG and also presents the properties documented by the USGS (Thomas, et al, 1996) for comparison. The PGG estimates are based on the specific capacity data and are low compared to the measured data (for the Qal and Qog); with a few exceptions, the PGG estimates are similar to those reported by the USGS (Thomas, et al, 1996). A primary assumption of the specific capacity method for calculating transmissivity is that the well fully penetrates the aquifer—well construction that is rarely seen in domestic wells. Therefore, except for the two "measured" values, the data presented in Table 3, should be viewed as relative rather than absolute.

[5] The most recent documentation of this thinking is from an unpublished Ecology Water Resources Program Policy statement drafted 1-4-07: *DEFINING AND DELINEATION OF WATER SOURCES IN WATER RIGHT DECISIONS*. This document indicates "…the source has been historically defined as the aquifer or **aquifer system** [emphasis added] from which ground water is withdrawn…"

5.1 UPPER AQUIFER

Figure 9 presents groundwater elevation contours for the upper aquifer. In general, groundwater contours mimic topography except that the groundwater surface is more subdued than the topographic surface. As shown in Figure 9, groundwater flows from recharge areas in the uplands to discharge areas in the lowlands. Groundwater flows to the north, east, and west off the Getchell Plateau; generally to the south off the East Stanwood Plateau, generally to the west off of Arlington Heights, and generally toward the east off the Tulalip Plateau.

From these upland areas, groundwater then flows down the various river valleys, eventually discharging to low lying streams and to Puget Sound.

The cross-sections (Figures 5, 6, and 7) indicate the trace of the water table or potentiometric surface. This trace was generated by gridding the surface (Figure 9) then calculating the elevation of the trace along each cross-section. These traces were inserted into the previously existing cross-section drawings. This method of generating the cross-sectional view of the water table provides a means of including a much larger population of water level data than the few wells used for drawing the cross-section. For this reason, some of the water level symbols shown in the cross-sections do not coincide exactly with the water table trace. Another reason for this inconsistency is that the location of the cross-section wells is to the nearest ¼-¼ section and, although the wells are assumed to be located on the cross-section trace they likely are not.

The upper aquifer is subdivided into three separate occurrences (sub-aquifers) based on the depositional environment, stratigraphy, and location. These sub-aquifers include the alluvial sub-aquifer (Qal) adjacent to the Stillaguamish River, the recessional sub-aquifer (Qvr) located in the Marysville Trough and Arlington Heights, and the Vashon Advance Outwash sub-aquifer (Qva) located underneath the recessional materials in the trough, beneath Arlington Heights, and beneath the surrounding plateaus.

5.1.1 Alluvial Sub-Aquifer (Qal)

The sub-aquifer within the Qal is important because it is tapped by Arlington's Haller Park wellfield. This sub-aquifer is considered susceptible because it is shallow, is not overlain by low permeability soils, and is very permeable. It is in direct continuity with the Stillaguamish River—resulting in Haller Park wells to be designated as GWI (groundwater under the influence of surface water). The City of Arlington recently constructed a state-of-the-art filtration plant as required for such groundwater sources.

The most significant occurrence of the Qal sub-aquifer is within the Stillaguamish River alluvium. Occurrences also exist in the North and South Forks of the Stillaguamish River and the Pilchuck Creek lowland. The latter two feed directly into the main stem sub-aquifer while the North Fork sub-aquifer is separated by a bedrock bounded channel about two miles upstream of the confluence.

The transmissivity (as measured from the pumping test completed on the Haller Park replacement well in 2002) is very high with a value of 700,000 gallons per day per foot (gpd/ft) although this value likely represents the combined thickness of Qal and Qvr at this location.

Because of its importance with respect to Arlington's water supply, we have constructed a groundwater flow map of the alluvial sub-aquifer (Figure 10). This map was constructed using well logs downloaded from Ecology's website (Ecology, online). The download included wells located within the Qal outcrop area (Figure 4), wells that are less than 50 feet deep, and wells between 8 and 48 inches in diameter. A total of 185 well logs were downloaded for this map. Most are dug wells—all but four are 36 inches in diameter or larger. Groundwater ranges from 100-feet elevation in the South Fork alluvium to less than 20 feet elevation at the downstream end of the study area. The horizontal gradient varies somewhat but is usually about 0.001.

5.1.2 Vashon Recessional Sub-Aquifer (Qvr)

Unconfined aquifers occur within the Qvr in several locations including the Arlington Heights, Marysville Trough, and in the East Stanwood Plateau. These are considered separate aquifers (from each other) because they are separated by topography and are also bounded in a vertical sense.

The Arlington Heights sub-aquifer comprises sand and gravel and is bounded by the lowlands for the North and South Forks of the Stillaguamish River, which effectively isolates—in a horizontal sense—the sub-aquifer from others. Here, the Qvr is underlain by Vashon Till, further isolating the sub-aquifer in a vertical sense.

The Qvr sub-aquifer as it occurs in the Marysville Trough comprises sand with some fine gravel (Minard, 1985a). This occurrence of the Qvr sub-aquifer is hydraulically connected to the Stillaguamish River main stem alluvial sub-aquifer and, in places, is directly connected to underlying advance outwash sub-aquifer. Therefore, our map of the upper aquifer (Figure 9) in the Marysville Trough area effectively maps the groundwater flow direction of the Qvr sub-aquifer.

The Qvr in the East Stanwood Plateau is discontinuous, shallow, and limited in thickness. In most places here, it occurs directly on top of Vashon till or bedrock. This occurrence of Qvr is not important from the standpoint of municipal supply and is not discussed further.

Transmissivities of the Qvr sub-aquifer vary depending on which occurrence of the sub-aquifer is being considered. For example, the Arlington Heights occurrence has a median estimated transmissivity of 2,200 gpd/ft. The Qvr sub-aquifer beneath the Marysville Trough has a median estimated transmissivity of 15,000 gpd/ft. The larger transmissivity values reported for the Qvr in the Marysville Trough may be a reflection of direct contact with the underlying Qva, which provides greater saturated thickness. The transmissivity of the combined occurrences of the Qvr sub-aquifer is estimated to be 7,500 gpd/ft.

5.1.3 Vashon Advance Sub-Aquifer (Qva)

The first occurrence of groundwater (other than small perched zones) in the Getchell and Tulalip Plateaus areas is likely within the Qva unit. Beneath these upland areas, sub-aquifers within the Qva can be either confined or unconfined.

The largest occurrence of the Qva is beneath the Getchell Plateau. Thomas, et al, (1996) and this study indicate that the Qva is the first sub-aquifer to be encountered beneath this upland. Kirtland (2005) identifies three shallow aquifers; however, those three occurrences are discounted in this study.[6]

Beneath the Getchell Plateau the Qva sub-aquifer ranges from 200 feet thick in the southern portion of the groundwater study area to less than 30 feet thick in the northern portion. As shown in cross-section D-D' (Figure 6) advance outwash (Qva) crops out on the northern flank of the plateau. Since no upper confining unit exists (the Qvt appears to be eroded away), groundwater is allowed to freely drain out the northern flank. This free draining causes groundwater heads in the northern portion of the Getchell Plateau to drop, significantly decreasing the saturated thickness of the Qva sub-aquifer.

The Qva unit provides water to wells in quantities that are attractive for municipal water supply sources. It appears that the airport wells tap this unit (cross-sections C-C' and E-E' and Thomas, et al, 1996). Future supply development for Arlington could include wells that tap this unit where enough saturation occurs in the Getchell Plateau area.

In the Marysville Trough, the Qva sub-aquifer is overlain by shallower zones within the Qvr but is typically hydraulically connected, forming one upper aquifer. The hydraulic connection results from the erosion of the Vashon Till (Qvt) in the Marysville Trough (Thomas, et al, 1996).

The transmissivity (T) of the aquifer tapped by the City's airport test well (PGG, 1993) is 50,000 gpd/ft. While we represent this well and the Airport production well as tapping the Qva, this T value likely represents the combined Qva and overlying Qvr.

Based on a median value of hydraulic conductivity, (Thomas, et al, 1996) we estimate that the transmissivity of the Qva in the Getchell Plateau area is about 2,700 gpd/ft. This value assumes thickness of 10 feet, which is the likely thickness of a well's open section.[7]

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[6] Kirtland (2005) suggests that three aquifers exist above the Qva aquifer beneath the Getchell Plateau. The three aquifers are: the alluvium, recessional outwash, and Vashon Till. No alluvial deposits are mapped on to the Getchell Plateau (DNR, online) and we therefore discount this occurrence; the Qvr as mapped by Kirtland is a small occurrence in the central portion of the plateau, that is outside of our groundwater study area; and Vashon till is not widely considered to be an aquifer.

[7] The USGS used well log information to estimate aquifer transmissivity (T); however, they published hydraulic conductivity data, which was calculated based on the estimated T. These calculations assume that the open interval for the well is equal to the saturated thickness of the aquifer.

5.2 DEEP AQUIFER (QOG)

The deep aquifer as defined in this study is the saturated sand and gravel material that is frequently encountered immediately below the transitional beds. In the cross-sections it is depicted as dark blue discontinuous beds. This aquifer is confined with heads usually about 200 feet above the top of the aquifer. The general occurrence of it is in the southwest portion of the groundwater study area. It also appears to occur within the bedrock trough mapped east of the South Fork. An outline of the Qog deposit is shown in Figure 11, which also shows contours of the top of the unit.

The elevation of the top of the deep aquifer surface ranges from about 100 feet to less than -400 feet with the highest occurrence located beneath the northern portion of the Getchell Plateau. The deepest occurrence is in the western portion of the study area.

Figure 12 presents a groundwater elevation contour map for the deep aquifer. The potentiometric surface ranges from a high of over 200 feet in the northern portion of the Getchell Plateau to less than 50 feet in the western portion of the study area. The hydraulic gradient is steepest as water flows off a buried bedrock ridge that trends northeast-southwest through the central portion of the study area. The magnitude of the gradient is 0.05 along the trend. The northern and western portions of the aquifer appear to have smaller horizontal gradients.

The median value of transmissivity (T) of the deep aquifer is 3300 gpd/ft. While this is not a high value for T the generally deep occurrence of this aquifer provides greater available drawdown and commensurate greater potential for high well yields.

5.3 RECHARGE

Recharge to the groundwater system comes mostly from incident precipitation. Minor amounts of recharge come from surface water bodies including lakes and some upstream reaches of streams. Downstream reaches are often associated with groundwater discharge and thus do not contribute to recharge.

The quantity of water that infiltrates is related to the amount of annual precipitation and the soil that occurs at the ground surface. Rainfall in the groundwater study area ranges from 44 inches per year (in/yr) to over 48 in/yr. The foothills located in the extreme eastern and northeastern portions of the study area have higher rainfall amounts but these areas account for only a small portion of the study area.

Using GIS techniques, PGG created a recharge map, which is presented in Figure 13. The basis of this map is annual precipitation (Daly and Taylor, 1998) and the distribution of two groupings of geologic units (Figure 2). The groupings used are based on those suggested by the USGS (Thomas, et al, 1996).

Recharge ranges from less than 20 inches per year to greater than 35 inches per year. The lower recharge occurs mostly in the uplands in the western portion of the study area. The high recharge exists in the northeastern portion where high precipitation falls upon relatively permeable soils

(Qvr and Qal). From the standpoint of future municipal water supply for Arlington, the Marysville Trough is most likely to be developed. Here the recharge is 25 to 30 inches per year. This equates to 825 gallons per minute per square mile.

Note that this recharge estimate is for the groundwater system as a whole and that recharge to the deep aquifer will be a portion of this total. The amount of recharge to the Qog aquifer depends on the amount of Upper Aquifer discharge, which includes:

- Subsurface discharge to streams (baseflow)
- Surface discharge to springs
- Water supplies pumped from the Upper Aquifer

Without detailed information about such discharges, reliable estimates of recharge to the Qog cannot be made.

6.0 RECOMMENDATIONS

Preparation of this hydrogeologic conceptual model has identified several issues that need additional study (data gaps). Since these issues have bearing on municipal water supply development, recommendations for future work are identified. Such recommendations are presented in this section. For each issue, an indication of the data gap is presented, followed by a summary of its importance to Arlington, followed by recommendations to fill the data gap.

6.1 DEEP AQUIFER

Delineation of the deep aquifer (Qog), such as flow direction and recharge, is based on few data points in the southwestern portion of the study area. Since this aquifer is potentially an important source of water for municipal water supply development, additional studies are warranted. Examples are indicated below:

6.1.1 Discharge Location of Deep Aquifer

As indicated in Figure 12, groundwater flow is shown flowing to the west toward Puget Sound. The 50-foot contour, which indicates this westward flow, is shown as a dashed line because its northern limb is based on one data point in Section 17 (T31N, R5E).

The ultimate discharge location of the Qog aquifer—is it Puget Sound or the Stillaguamish River?—has important implications with respect to water supply development in WRIA 5, which is closed by rule. If Qog groundwater ultimately flows into the Sound, development of the aquifer may have less effect on flows in the river than if the Stillaguamish is the sink for Qog water.

An evaluation of groundwater flow patterns of the Qog needs to be completed. Additional studies using existing information and new information from specifically constructed wells should be conducted to refine understanding of Qog discharge. Such studies could include a detailed well inventory of existing wells and direct static water level measurements; drilling new test/ monitoring wells; transducer studies; and pumping tests.

6.1.2 Recharge to Deep Aquifer

Another example or Qog aquifer uncertainty is the volume of water that recharges the aquifer. While Figure 13 presents a depiction of recharge to the groundwater system as a whole, the amount of recharge that works its way downward to the deeper aquifer is not known.

An understanding of the volume of recharge in comparison to the volume of discharge (water balance) is needed to identify the potential safe yield of the aquifer. The concept of safe yield has been used in the past to identify the volume of water available for development.

Complete a water balance for the deep Qog aquifer. Estimates of discharge from the Upper Aquifer are needed, which includes estimates of Upper Aquifer use (well pumpage) and stream baseflow (from stream gauging).

6.1.3 Deep Aquifer Occurrence in Airport Vicinity

The occurrence of the deep aquifer (Qog) beneath the airport is unknown. Its occurrence nearby is based on the existence of one well in Section 17, T31N, R5E. This well, located about 2 miles northwest of the airport, was drilled in 2001, is 572 feet deep, and encounters sand and gravel (Qog) at the bottom. This well is shown in cross-section B-B' (Figure 5).

Use of the deep aquifer is attractive to the City because of its occurrence beneath the clays and silts of the transitional beds (Qtb unit). The low permeability Qtb unit can help protect the deep aquifer from surface activity. This protection is important from both water quality and instream flow standpoints.

The upcoming airport drilling program should include plans to explore for the deep aquifer. The proposed well could be designed with the flexibility to complete a deep well if the Qog if it is encountered at depth.

6.2 AQUIFER TRANSMISSIVITY

Several investigators have attempted to quantify aquifer transmissivity (this study; Kirtland, 2005; Thomas, et al, 1996; and Franz & Kresch, 2004). In general, these estimates are limited by the data source, typically well logs. Better information results from properly conducted, long-term, constant-rate pumping tests such as has occurred for the Airport test well (PGG, 1993) and the Haller Park Replacement Well No. 1 (PGG, 2002). These tests indicated that aquifer transmissivity is much higher than is estimated based on well log information.

A better understanding of aquifer transmissivity is needed to guide future municipal water supply development and future water rights purchases. Such an understanding would identify zones within aquifers that generally are able to supply large quantities of water as well and identify specific areas within an aquifer that are potentially more able to supply needed quantities.

Evaluate aquifer specific transmissivity information by completion of additional constant-rate pumping tests. These tests could be conducted on existing wells (with permission) or on test wells that are drilled to evaluate future potential for water supply sources.

6.3 DEPTH TO BEDROCK

The occurrence of shallow bedrock beneath the Marysville Trough in the southern portion of the study area is indicated in this study. This occurrence is based on one well log, albeit from a reputable well driller, and further assessment may be needed.

This presence (or not) of bedrock in the southern portion of the study area is important to Arlington because it identifies the bottom of explorations. If bedrock in the area is around 100 feet (as indicated in Figure 7) then development of municipal supply would be limited. An additional benefit of this understanding for Arlington is that future water rights purchases can be considered in the context of potential well yield.

Assess the indicated occurrence of shallow bedrock in the southern portion of the study area by confirming the location of well 31/5-33R. Specifically located test wells could be drilled or geophysical studies undertaken to complete this evaluation.

6.4 PORTAGE CREEK

Hydraulic continuity of the groundwater system and Portage Creek is not well understood.

The creek's location near the City and within future development areas suggest that further evaluation is warranted. The closure of groundwater that is hydraulically coupled with Portage Creek suggests a detailed understanding of continuity between the creek and groundwater is needed.

Develop a long-term groundwater monitoring program in the vicinity of Portage Creek. This program should include transducer studies and periodic depth-to-water measurements. Shallow monitoring wells may be needed depending on the availability of existing wells.

6.5 ADDITIONAL ISSUES

In addition to the specific recommendations provided above, future efforts to organize and access City water resources information could be stored in a GIS framework. A database of area wells was generated during completion of this study and this database could be used as a starting point for future accessible data storage.

Other examples of how data generated for this study could be used in the future are shown in Table 4. Some of these efforts could be accomplished using existing data and some others would require information identified in Section 6.0. Table 4 also highlights accomplished tasks that will provide better understanding of the four issues cited above (**bold**) and highlights specific work (*italic*) needed to refine the understanding of the four issues.

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Table 1: Summary of Surface Water Monitoring in Stillaguamish Basin

Station	Type	Northing[1]	Easting[1]	Agency
Armstrong Creek near Arlington	Manaul Stage Height	447037	1322866	Ecology
Boulder River near Mouth	Manaul Stage Height	467461	1409332	Ecology
Canyon Creek near Masonic Park	Flow	410812	1378440	Ecology
Church Creek near Stanwood	Flow	458766	1279539	Ecology
Deer Creek near Oso	Flow	470261	1373992	Ecology
Hatt Slough @ Marine Dr	Automatic Stage Height	445654	1274335	Snohomish County
Jim Creek @ Whites Rd.	Flow	432015	1342812	Ecology
North Fork Stillaguamish River @ Oso	Flow	465875	1383266	Ecology
North Fork Stillaguamish River near Arlington	Flow	462491	1344648	USGS
North Fork Stillaguamish River near Darrington	Manaul Stage Height	468144	1428822	Ecology
Pilchuck @ I-5	Temperature	446238	1303144	Snohomish County
Pilchuck Creek @ Bridge 626	Flow	445667	1302657	Ecology
Pilchuck Creek @ Hwy 9	Temperature	464457	1316190	Snohomish County
South Fork Stillaguamish River @ Jordan Rd. Bridge	Flow	401533	1361203	Ecology
South Fork Stillaguamish River near Granite Falls	Automatic Stage Height	404390	1366812	USGS/Snohomish County
Squire Creek @ Squire Creek Park	Flow	464416	1436019	Ecology
Stillaguamish River @ Arlington	Stage	441740	1324529	Snohomish County
Stillaguamish River @ I-5	Automatic Stage Height	439483	1305104	Snohomish County
Stillaguamish River @ Pioneer Hwy	Automatic Stage Height	444809	1295975	Snohomish County
Stillaguamish River near Silvana	Manaul Stage Height	439651	1304650	Ecology

1 Easting and Northing in State-Plane South Coordinate System

Table 2 - Geologic Unit Correlations

Kirtland, etal, 2005		Thomas, etal, 1996		This Study	
Aquifer	Name/Symbol	Aquifer	Name/Symbol	Aquifer	Name/Symbol
Alluvial	Qal	Alluvium	Qal	Upper Aquifer	Qal
Recessional Outwash	Qvr	Vashon recessional outwash	Qvr	Upper Aquifer	Qvr
Vashon Till	Qvt	Not mapped	Qvt	Not Recognized	Qvt
Advance Outwash	Qva	Vashon advance outwash	Qva	Upper Aquifer	Qva
Upper Coarse-Grained	Q(A)c	undifferentiated sediments	Qu	Deep Aquifer	Qog
Lower Coarse-Grained	Q(B)c	undifferentiated sediments	Qu	Not Recognized	---
Sedimentary Rock	Tb	bedrock	Tb	Not Studied	Br

Table 3: Summary of Aquifer Properties

		This Study		Thomas, et al, 1996			
Unit		Transmissivity (gpd/ft)		Hydraulic Conductivity (ft/day)		Thickness[4]	Transmissivity (gpd/ft)
		Median Value[1]	Measured Value[2]	Median[3]	Maximum	Assumed	
Qal		6,000	700,000	88 (30)		10	6,600
Qal					3200 [5]	10	950,000
Qvr[6]	All Occurrences	7,500		180 (48)		10	13,500
	Marysville Trough	15,000		210 (14)		10	15,700
	Arlington Heights	2,200		280 (11)		10	20,900
Qva	All Occurrences	Not Estimated		40 (215)		10	3,000
	Marysville Trough		50,000				
	Getchell Plateau	Not Estimated		36 (40)		10	2,700
Deep Aquifer (Qog)		3,300		31 (54)		10	2,300

Notes:
1 Based in median value calculated from specific capacity data
2 Transmissivity value for Qal based on the pumping-test results of Arlington's Replacement Well No. 1 (PGG, 2002B)
Transmissivity value for Qva based on pump test at Airport Test Well (PGG, 1993) and may represent combined Qva and overlying Qvr
3 Hydraulic conductivity value is median value presented in Table 4 (Thomas, et al, 1996). Value in parenthesis is number of wells.
4 Thickness is assumed thickness of open interval for wells
5 Hydraulic conductivity value is "maximum" reported in Table 4 (Thomas, et al, 1996)
6 In this study, transmissivity Values for "All Occurrences" are based on all specific capacity data. Values for
Marysville Trough and Arlington Heights are based on pump-test derived specific capacity data.

Table 4: Utility of this Study as a Basis to Address Other Issues

Issue	Completed as part of study	Future Work
Water Rights Water Rights Support	3-Dimensional conceptual model (**aquifer occurrence**); **Aquifer transmissivity evaluation**;	Site-specific impairment analysis; Same "body of public water" evaluation
Identify Water Rights for Future Municipal Development	Arlington area WRATS database developed	Fully develop a well-log database with more detailed well-construction information; Develop coordination between well log database and WRATS; Coordinate with Snohomish County database
Stormwater	Upper Aquifer groundwater elevation map; Depth-to-water input into database; Topography GIS layer	*Develop depth-to-water map for various seasons*
Aquifer Storage and Recovery	**Deep aquifer characterization; Deep aquifer groundwater elevation; Deep aquifer wells (based on elevation of completion)**	Propose promising areas for ASR development; Refine occurrence of deep aquifer (Qog); Depth-to-water mapping; *Refine characterization of Deep Aquifer*
Source analysis (different bodies of groundwater)	Conceptual model defines two aquifers separated by Qtb and one Upper Aquifer that behaves as one body of public water	Develop aquifer testing program with multiple monitoring wells
Wellhead Protection Capture Zone Delineation	**Aquifer transmissivity estimates summarized;** Groundwater flow directions for two aquifer defined	Develop various capture zone scenarios depending of proposed pumping scenarios; Rerun model for each scenario
Critical Aquifer Recharge Areas	**Recharge to groundwater system mapped**; GIS base developed with varying coverages organized on PGG computers	Develop soils map based on NRCS data; Develop linkage between land use and soils data; *Develop recharge map for Qog aquifer*
Water Quality Information	GIS base map completed; Groundwater elevation data input; Geology incorporated into GIS environment	Develop GIS coverages from other sources; Develop susceptibility map
Future Groundwater Development Options	GIS base map completed; Well yield information input into well construction database; Land use and Arlington service area layers in PGG computers; Subsurface defined with cross-sections; **Existence of Qog beneath airport surmised**	Develop map with prioritized development areas based on a variety of input; Develop saturated thickness maps; *Drill exploration well at airport to evaluate occurrence of Qog*
Groundwater/ Surface Water Interaction	Geology layer developed in GIS; Groundwater elevation mapping completed; Topographic layer collected and included in GIS coverages	*Develop depth-to-water map and layer it with surface water features; Develop groundwater monitoring program in vicinity of Portage Creek*