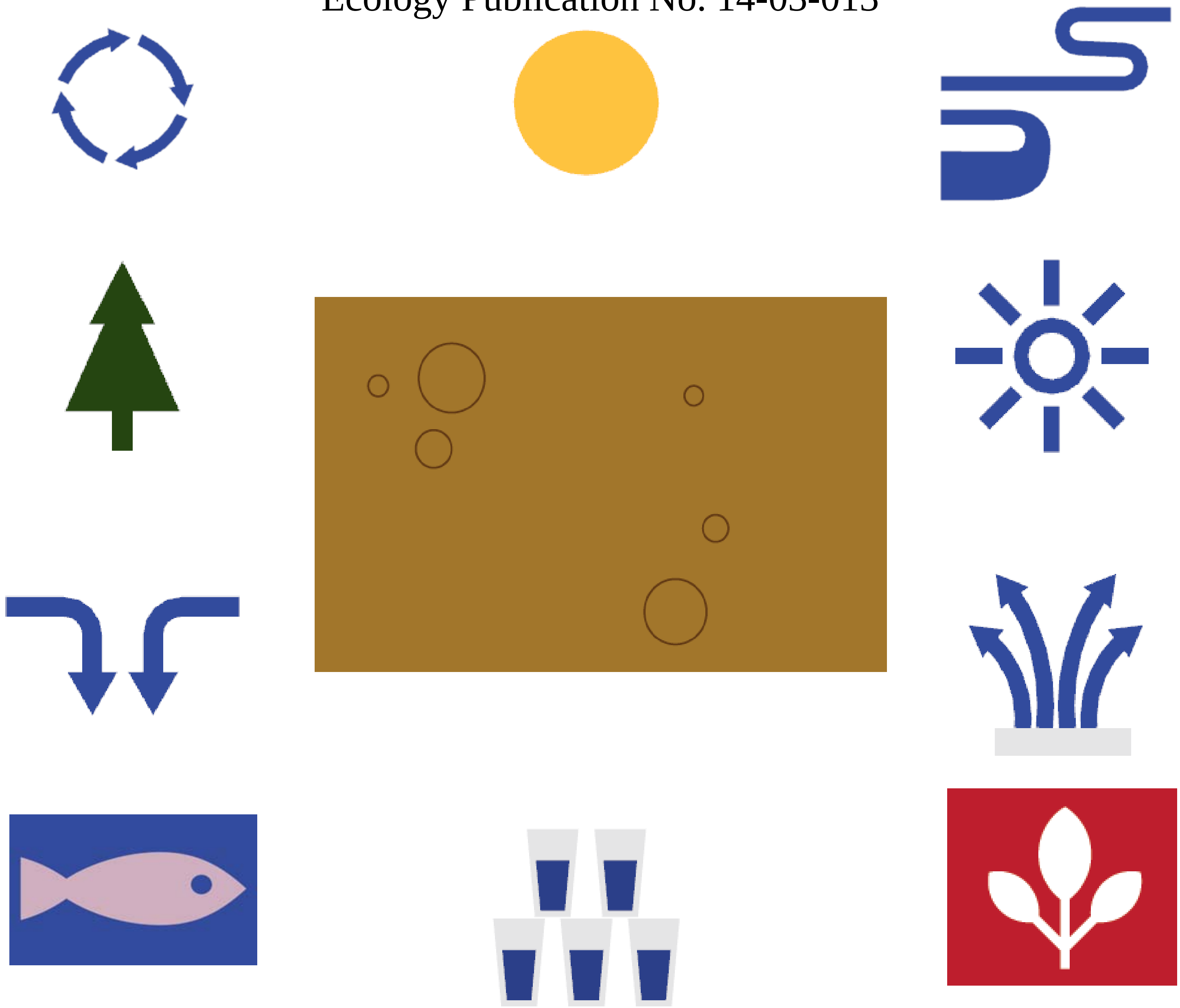
Ecology Publication No. 14-03-013



WRIA 1 Groundwater

Data Assessment

Overview

WRIA 1 Groundwater Assessment
June 2013

An interdisciplinary team of water resource technical specialists worked with the WRIA 1 Joint Board Staff Team to compile existing technical models, studies, and data into an assessment of groundwater in WRIA 1. For a complete list of contributors, see *Chapter 4 - Recommendations for Data Collection and Model Integration* In Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, (eds). WRIA 1 Groundwater Data and Model Assessment, Whatcom County PUD #1, Whatcom County, WA: WRIA 1 Joint Board.

Technical reviewers: Jeremy Freimund, Lummi Nation Natural Resources, Kasey Cykler, State of Washington Dept. of Ecology. See also List of Contributors, *Chapter 4* Section 4.0.

Please cite this Overview as:

Print Citation: Bandaragoda, C., J. Greenberg, C. Lindsay, and M. Dumas (2013). WRIA 1 Groundwater Data Assessment: Overview. *In* Bandaragoda, C., J. Greenberg, C. Lindsay and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board.

Online Citation: Lindsay, C. and C. Bandaragoda, (2013). WRIA 1 Groundwater Data Assessment: Overview. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board. Retrieved [Date], from http://wria1project.whatcomcounty.org/.

This work was funded by the WRIA 1 Joint Board and managed by Whatcom County PUD #1 and funded by Department of Ecology Grant No 1200070 Task 9 Groundwater Study; June 2013.

1. Overview

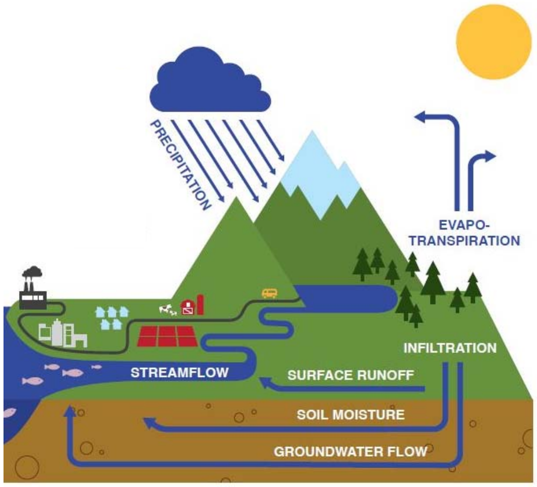


Figure 1. Groundwater is one component of the hydrologic cycle. Groundwater flow begins as infiltration of rain and snow, and then it moves into and through the soil to the aquifer. Some of the groundwater flows laterally and emerges into the surface stream creating baseflow.

The *WRIA 1 Groundwater Assessment (GW Assessment*) assembled and reviewed groundwater reports and other documents and datasets to prepare a searchable catalog of existing groundwater data available to the WRIA 1 Joint Board for use in water resource planning and management in WRIA 1. This review process did not include analysis of the quality of available resources and datasets, nor did the project scope include compilation of groundwater quality information and datasets.

The *GW Assessment* focused on groundwater resources and water source data gaps, specifically

- Identifying the types of groundwater studies and datasets available for each watershed in WRIA 1.
- Compiling groundwater studies and updated datasets into readily accessible formats for use by water resource professionals.
- Identifying future groundwater data collection needed for developing and implementing a groundwater model.
- Identifying data gaps for water source and locations for all water use categories.

This overview introduces the *GW Assessment*, the methods used to conduct the work, and how to access the information presented in the main report and technical appendices, including:

Understanding of WRIA 1 aquifers – A technical description of the WRIA 1 aquifers which outlines available data organized by scale (site specific, drainage, regional) used to conduct groundwater studies of the primary aquifers in WRIA 1: Sumas-Blaine aquifer; discontinuous surficial aquifers; upper valley aquifers; bedrock aquifers; and deep regional aquifers (*Chapter 1*).

Groundwater data and data gaps – A description of the databases previously developed by agencies within WRIA 1 that were compiled to produce locator maps with the number of studies containing specific types of data (e.g., seasonal depth to water) and data gap locations. A summary of data gaps are presented for a range of aquifer properties (*Chapters 2 & 3*).

Understanding of WRIA 1 sources of supply – A description of available knowledge on water supply sources is provided with information presented by type of use: irrigation, dairies, utilities, public water systems, and self-supplied. Options for improving known data gaps are outlined (*Chapter 3 & 4*).

Recommendations for data collection and model integration – Background information and suggestions to support near-term and long-term planning needs related to watershed management and salmon recovery in WRIA 1, including a groundwater model and the types of data required for such a model (*Chapter 4*).

Database of aquifer properties and references (Endnote and Access) – Bibliography of geologic and hydrogeologic data (250+ citations) available for the principal aquifers in WRIA 1, both surficial and deep aquifers, in WRIA 1.

2. What groundwater information is included in this compilation?

The data compilation of aquifer properties, presented in the Endnote and Access databases, catalogues available groundwater resources information based on watershed management units and is searchable by Management Area with cross-referencing based on aquifer, study scale and aquifer properties, shown in Table 1. WRIA 1 Joint Board Watershed Staff Team members provided insight on available studies, technical review, and future planning needs throughout the development of the *GW Assessment.*

The data compilation includes a description of:

1. Current groundwater quantity data available in WRIA 1 and potential uses;
2. Range and spatial extent of groundwater models and parameters available in WRIA 1;
3. Future data collection and model requirements for water resource planning and management in WRIA 1 related to:
   - aquifer characteristics
   - groundwater recharge/discharge areas,
   - groundwater use,
   - surface/groundwater interaction; and
4. Description of Topnet-WM and MODFLOW integration, review of integrated hydrologic models available and recommendations for future modeling efforts in WRIA 1.

Additional analysis of data was beyond the project scope. Readers should note that the database has some repetition, e.g., many studies refer back to a common source such as the USGS Water-Resources Investigations Report 98-4195 (Cox and Kahle, 1999).

In addition to repetition, there are other technical variables to consider when reviewing the resource compilation. In some studies the area to be studied for groundwater analysis was conducted using a topography based approach, while other studies and data rely on a numerical approach which uses a grid framework to represent information.

Table 1. Primary aquifers, scales of data sources, and aquifer properties.

Primary Aquifers		
Sumas-Blaine	Upland	Upper Valley
Deep Regional	Discontinuous	Bedrock
Scales of Data Sources		
Site	Drainage	Regional
Aquifer Properties		
Aquifer Testing	Hydraulic Conductivity	Transmissivity
Aquifer Thickness	Aquifer Storage	Water Level Data
Geophysical Analysis	GW Flow Direction	Seepage Analysis
Hydraulic Gradient	Streambed Conductance	Recharge

A component of previous studies and projects as well as this *GW Assessment*, has been to identify the data and resources needed to expand existing WRIA 1 groundwater information. A complete listing of the available WRIA 1 groundwater resources is compiled and organized into the *WRIA 1 Groundwater Bibliography* (see *Chapter 1* Electronic Appendix).

Water Resource Related Links

WA Department of Ecology

Statewide Water Rights Web Map
http://www.ecy.wa.gov/programs/wr/info/webmap.html

Ecology's Well Log Database
Water Resources website http://www.ecy.wa.gov/programs/wr/wrhome.html

WA Department of Health

http://www.doh.wa.gov/DataandStatisticalReports/EnvironmentalHealth/DrinkingWaterSystemData.aspx

State Department of Health Water System Data
http://www.doh.wa.gov/DataandStatisticalReports/EnvironmentalHealth/DrinkingWaterSystemData.aspx

A central challenge to increasing groundwater knowledge in WRIA 1 is the development and implementation of a modeling system to address ongoing and new questions of concern to the many local communities sharing these water resources. Throughout the development of the *GW Assessment* technical work, the WRIA 1 Joint Board Staff Team provided input on organizing strategies for data resources and identifying the types of issues that will require foremost attention in the future.

The following technical question regarding the need for improved integration between surface and ground water resource information and tools emerged from the review of available resources and technical reviewer input:

"What can we do to allocate water for existing and future uses and how can we best avoid, reduce magnitude, and mitigate impacts while maintaining instream flow and reduce uncertainty in low flow periods?"

To begin to address this question the project team surveyed technical reviewers to gain an understanding of the types of water datasets and resources available, as well as current and longer term management issues that might be addressed (*Appendix B*). Additionally, the team collected information from a range of local and national watershed modeling experts (*Appendix C*) provided insight on options, and incremental steps building on available information. The technical recommendations outlined in *Chapter 4* address WRIA1 water management issues, data collection and model development steps.

It's in the interest of WRIA 1 to be both efficient with the long-term model development plan, as well as improve the quality of the model usefulness by validating it for decision making with each model advancement step. Integrating a surface and ground water model may involve more cost and uncertainty than transitioning existing datasets and parameters to an existing integrated model.

Key Terms for the *WRIA 1 Groundwater Data Assessment*

Conceptual Model: Framework for designing numerical model, layers, extent, and processes represented in the numerical model.

Numerical Model: Mathematical equations and data-based parameters (code) used to represent specified area in a watershed.

Transient Flow Model: Magnitude and direction of flow changes over time, unlike a steady state model.

Drainage: Topographically defined modeled area (WRIA 1 Topnet-WM).

Grid Cell: Square pixel for model area (all groundwater models).

Groundwater Flow: Infiltration, movement from unsaturated to saturated, transport from aquifer to stream.

Baseflow: Ground water contribution of streamflow.

Feet above Mean Sea Level: All elevations presented the report are relative to mean sea level unless otherwise noted.

Depth to Water: The difference between the surface elevation and the static water level

Hydraulic Conductivity or Connectivity: **T**he connection between groundwater and surface water.

At the same time, using uncoupled groundwater model (MODFLOW) or surface water (i.e., rainfall runoff) model (Topnet-WM) have not been used to address core WRIA 1 questions or implemented. This project's recommendations aim to address information needs specific to various scales of surface and ground water resources and their interactions.

3. What do we know about WRIA 1 groundwater resources?

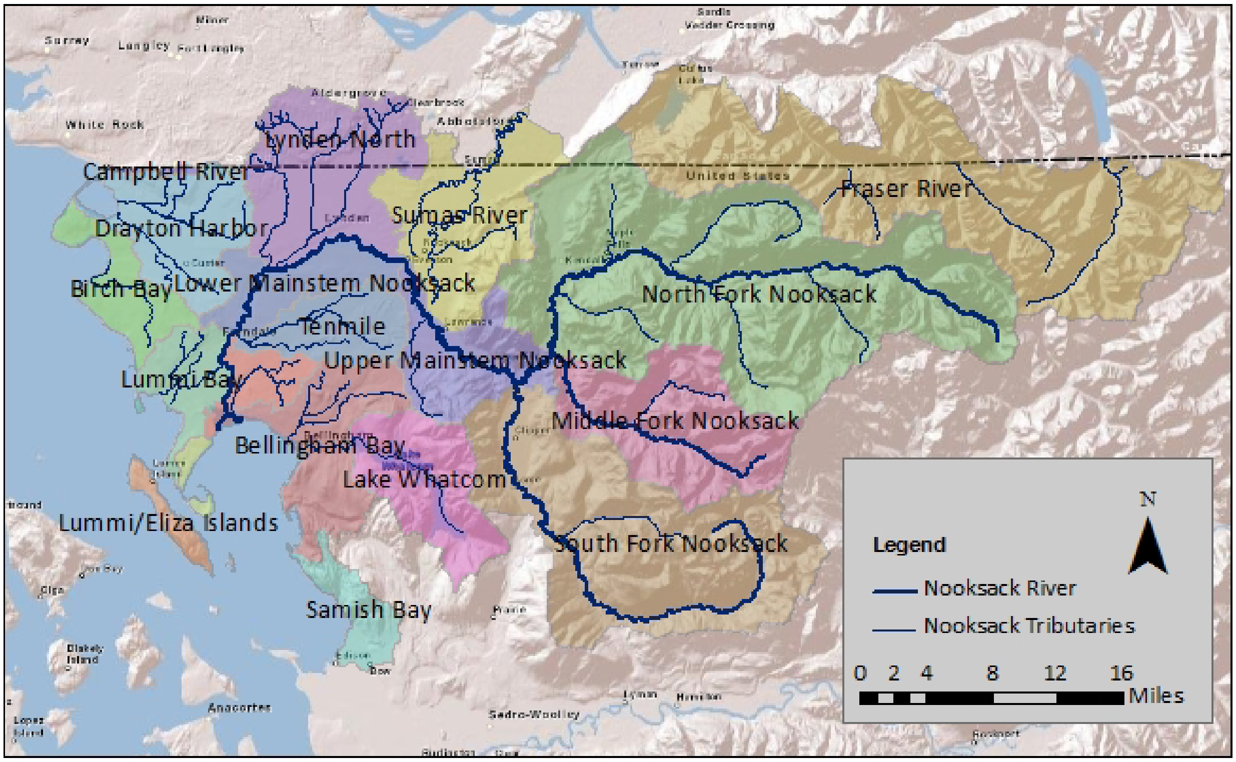


Figure 2. WRIA 1 Management Areas.

WRIA 1 is located in the northwest corner of Washington State and is generally bounded by the Strait of Georgia to the west, British Columbia to the north, the Cascade Range to the east, and the Skagit River Basin to the south. Figure 2 above shows water Management Areas, or aggregated watersheds, located in WRIA 1 that are used to study ground and surface water resources. Within this boundary area are a wide range of geological settings.

There are two primary rivers in WRIA 1. The Nooksack River flows west from the Cascade Range to Bellingham Bay and the Sumas River flows north from the north-central lowlands of WRIA 1 to the Fraser River in British Columbia.

The Nooksack River watershed has a total drainage area of approximately 826 square miles with roughly 49 square miles located in British Columbia, Canada. The mainstem of the Nooksack River is formed by the convergence of the South Fork Nooksack River, which drains roughly 183 square miles, the Middle Fork Nooksack River, which drains approximately 102 square miles, and the North Fork Nooksack River, which has a drainage area of approximately 281 square miles. The North and Middle Forks Nooksack River drainages include the north, west and southwest glaciated slopes of Mt. Baker (10,777 feet) and Mt. Shuksan (9,131 feet).

The Sumas River drainage is approximately 65 square miles and includes much of the area immediately to the south, west and east of the City of Sumas.

Section 3.1 gives an overview of where groundwater data are available within the WRIA 1 watersheds. Section 3.2 provides a snapshot on current primary aquifers in WRIA 1.

.

3.1 Locations where groundwater data are available

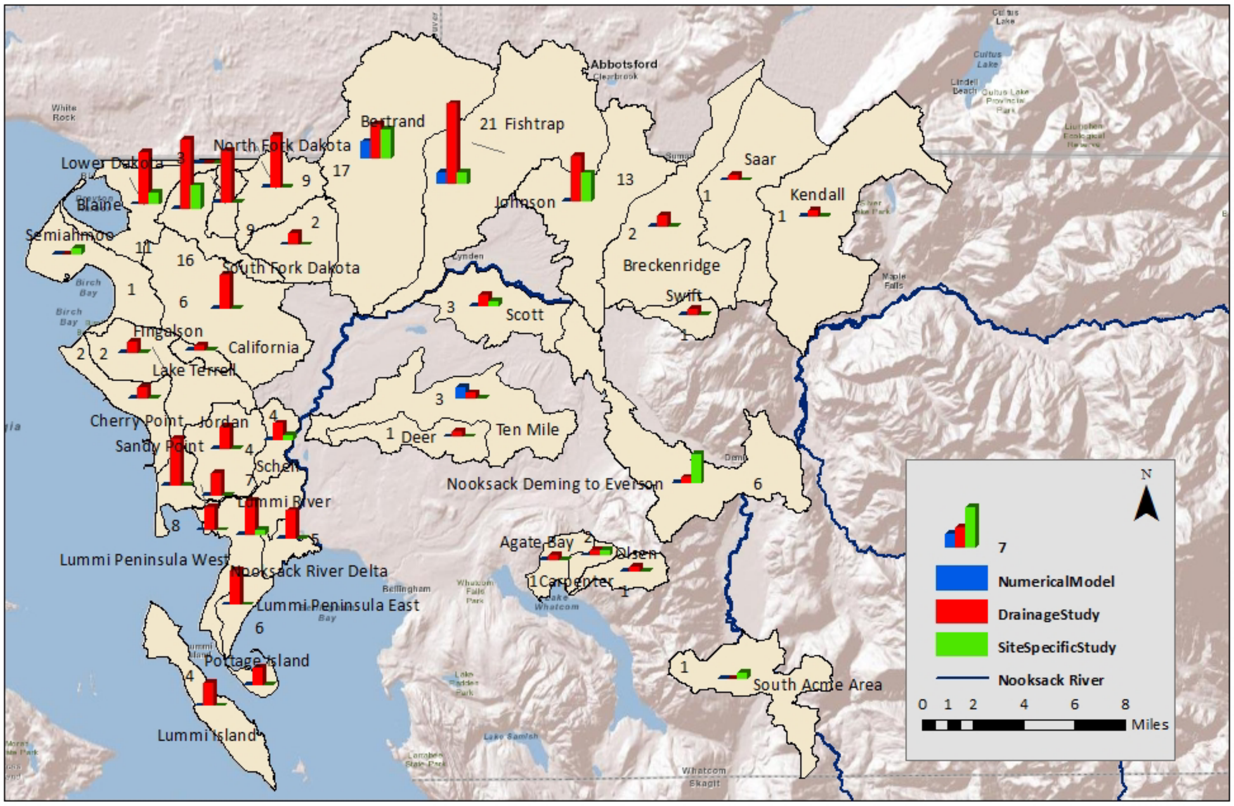


Figure 3. Number of relevant groundwater studies per drainage, with scale showing number of drainage models, drainage studies, and site studies.

Chapter 1, Understanding of Surficial and Deep Aquifers in WRIA 1 provides a general overview of the current knowledge of groundwater in the primary surficial and deep aquifers located in WRIA 1.

Based on the available technical studies and other relevant information, some of the WRIA 1 aquifers are relatively shallow, regionally extensive and fairly well known, such as the Sumas-Blaine Aquifer. While other aquifers, such as the Deer Creek and Lummi Peninsula Aquifers, are generally deeper in nature and more localized in extent.

The range of information varies, across groundwater characteristics and physical locations. For example, a substantial number of publications are available regarding regional or general studies for WRIA 1 that contain data useful for populating a regional groundwater model.

In the case of a drainage scale model, the numbers of studies containing some of the data inputs necessary for constructing a groundwater flow model are available for 20 of the 172 drainages located in WRIA 1 (Figure 3**Figure 3**).

Several of the drainages, Bertrand, Fishtrap, Johnson, Lower Dakota and Nooksack to Deming, and the drainages located on the Lummi Peninsula, have a significant number of technical studies with very useful data. Fewer studies have been completed for the remaining drainages.

The data that are available are, however, insufficient for developing a site specific or sub-drainage model. Additional data collection is required to address water resource planning and management site specific questions.

3.2 Where is groundwater stored?

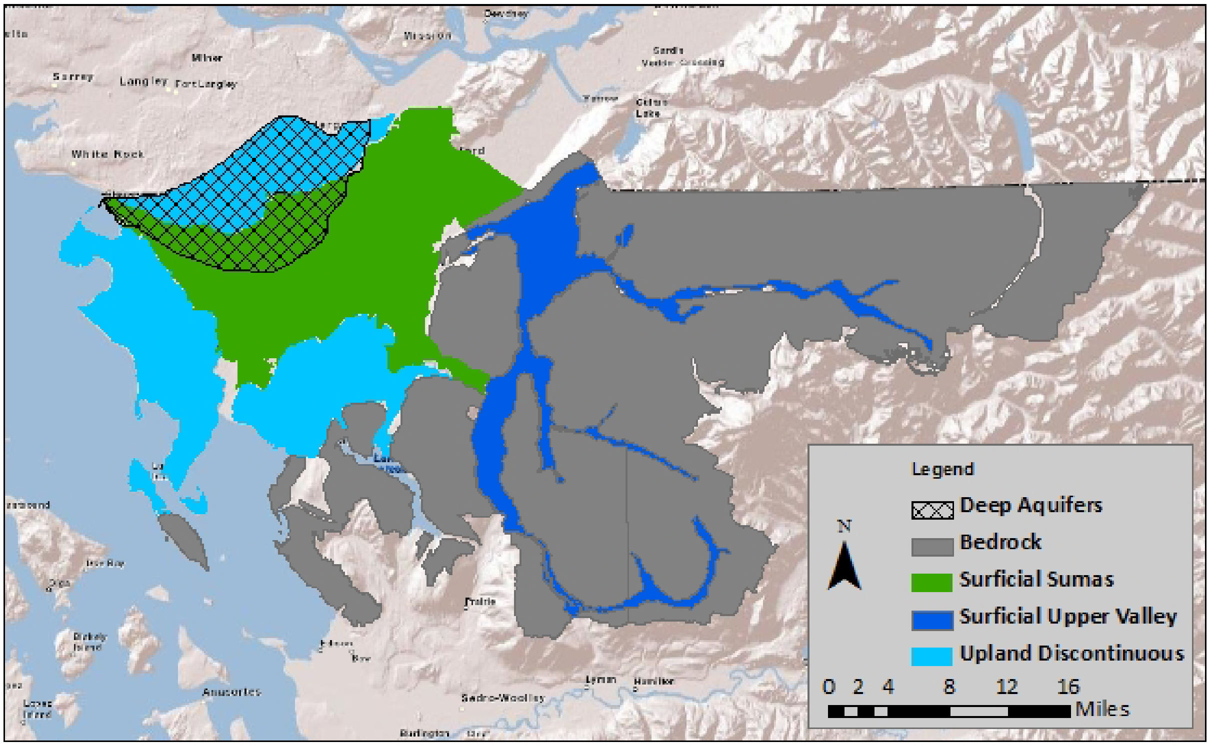


Figure 4. WRIA 1 Primary aquifers in WRIA 1.

3.2.1. Sumas-Blaine Aquifer

The Sumas-Blaine Aquifer is likely the most productive and widely used aquifer in WRIA 1. The aquifer is a common source of irrigation, single-family domestic, and public water systems in the northwestern portion of WRIA 1. The Sumas-Blaine Aquifer generally underlies the flat plain between the towns of Sumas, Blaine, Ferndale, and Everson and the Nooksack River, occupying about 150 square miles.

Groundwater in the aquifer can be at or near the ground surface in the wet winter/spring months and is generally at depths below the ground surface of less than 10 feet throughout the remainder of the year. Regionally, groundwater in the Sumas-Blaine Aquifer tends to flow towards the Nooksack and Sumas Rivers and locally towards the smaller tributary streams, based on studies compiled in this assessment.

Our review of the information compiled for WRIA 1 indicates that a significant volume of groundwater related information is available for the Sumas-Blaine Aquifer including specific information regarding: aquifer parameters (hydraulic conductivity, transmissivity, and storage); surface/ground water interaction potential; and groundwater level monitoring data. An example of how these types of data can be used to help understand groundwater resource conditions is provided in Figure 5. This sample hydrograph of observed water levels shows the estimates for a single well located in the upper reaches of Bertrand Creek drainage which is within the aquifer (Figure 5). The hydrograph illustrates the effects of summer irrigation fluctuations that the Sumas-Blaine Aquifer is likely to typically experience in the upper portion of the Bertrand Creek drainage (roughly five feet of seasonal fluctuation is shown on the graph).

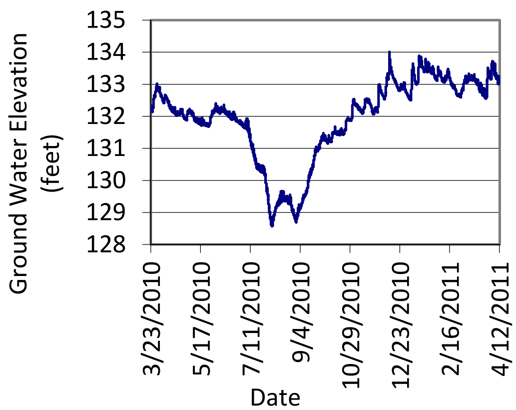


Figure 5. Shallow groundwater hydrograph. Bertrand Creek Subbasin- Well BAE 184. T41N, R2E, Section 36. Ground surface elevation approximately 140 feet.

The hydrograph example above is just one type of data resource useful for management of groundwater and modeling. The following section outlines features of the primary aquifers and the types of information available currently in WRIA 1.

3.2.2. Discontinuous Aquifers

There are numerous discontinuous aquifers located in WRIA 1, most of which are located in the western half of Whatcom County. Surficial and/or deeper (non-surficial) discontinuous aquifers are important sources of potable/nonpotable water and have been identified beneath the Mountain View Upland west of Ferndale, the Boundary Upland just east of Blaine, the Tenmile Management Area (Deer Creek Aquifer), the Lummi Peninsula, and the Birch Point Upland southwest of Blaine. It is also possible that non-surficial discontinuous aquifers are locally present in the Squalicum, Lake Whatcom, and Upper Mainstem Nooksack Management Areas based on the geologic setting and isolated water well report data.

Chapter 1 includes a brief overview of four of the better understood discontinuous aquifers in located in WRIA 1: Mountain View Upland; Boundary Upland; Deer Creek Aquifer; and Lummi Peninsula Aquifer.

All four of these discontinuous aquifers appear to be generally under confined to semi-confined conditions and are typically less than 250 feet in depth. Recharge to these aquifers is primarily from infiltrating precipitation and vertical migration of groundwater from overlying surficial aquifers where present based on available studies.

3.2.3. Upper Valley Aquifers

The upper valley aquifers are located within the narrow valleys of the North, Middle and South Fork Nooksack River Management Areas of WRIA 1. These are significant surficial aquifers in the WRIA and generally consist of interlayered mixtures of gravel, sand, silt, and clay. These aquifers are generally recharged by the direct infiltration of precipitation and flood waters from the adjacent river, and to a lesser extent by lateral flow from surrounding fractured bedrock aquifers.

3.2.4. Deep Regional Aquifers

A deep regionally extensive aquifer (Blaine Aquifer) has been identified in the northwestern portion of WRIA 1 near Blaine and Lynden in a 2008 study by Associated Earth Sciences, Inc (2008b). While bearing a similar name to the surficial Sumas-Blaine aquifer, this deep regional aquifer appears to be located typically at depths greater than 350 feet.

3.2.5. Bedrock Aquifers

Most of the eastern half and southwest portions of WRIA 1 are comprised of a complex mix of sedimentary, igneous, and metamorphic bedrock that is overlain by a thin layer of sediments. Although the bedrock typically has a generally low permeability, it can yield usable quantities of groundwater in localized areas where secondary fractures have increased the overall permeability. Our review of the information compiled for WRIA 1 indicates that a small volume of groundwater related information is available for bedrock aquifers. The data are generally limited to information presented in regional geologic maps, regional geologic/hydrogeologic studies, and on water well reports for wells completed in the fractured bedrock aquifers.

4.0 What do we know about WRIA 1 sources of supply?

4.1. Identification of data gaps for sources of supply

One of the purposes of this project was to provide an overview of the existing information available on water supply sources for the many different types of water use in WRIA 1. Identifying the source water and location(s) from which the water is withdrawn is important for improving water resource management tools. Sources of water in WRIA 1 include surface water (lakes, rivers, and springs) or groundwater (surficial and deep aquifers).

Of the five categories of water use, utilities (municipal and industrial purveyors) have documented their withdrawals, sources of supply, and source locations. For most other water users, the source may be known but the location or service area may be a data gap, especially for public water systems. For irrigation and dairy operations, neither the type of source nor the source locations are known. Table 2 shows the known information and documents in WRIA 1.

Table 2. Water supply sectors and source information.

Type of Water User	Source Known?	Location Known?	Where Documented?	Known Issues with Dataset
Utilities	Yes	Yes	Utility records of water use available from purveyor.	None.
Public Water Systems	Mostly yes; some no	Most no; some known	WA Dept. of Health database; water rights documents; well log database.	Whether place of use on water right documents and service areas are the same.
Irrigation	No	No; Only by rights	Water right documents; three studies completed in the Lower Nooksack Subbasin; well log database.	Non-permitted uses; some permitted users may have switched sources without proper documentation.
Dairy	No	No	Water right documents; public water systems supply water; Locations known by Whatcom Conservation District. 2003 shapefile available but not current.	Analysis of dairy locations; overlay with rights and well logs; need information from public water systems that supply water.
Self-Supplied	Yes	No	Well logs and water right documents.	Locations unknown for most exempt wells unless well logs were filed.

4.2 Irrigation data gaps

Irrigation is the largest use of water in WRIA 1 and even though the demand takes place during limited times of the year, this use coincides with periods of the year when precipitation and streamflows are at their lowest in the annual water cycle for WRIA 1. In the case of irrigation use, the sources of water (ground and/or surface) are not readily known; nor are the locations for which it is withdrawn and where it is spread or applied to the land. In previous technical work in WRIA 1, an estimated proportion for irrigation use was allocated as coming from ground and surface water as derived from water rights. This estimated proportion was used in place of the missing data.

An analysis conducted as part of the *Bertrand Comprehensive Irrigation District Management Plan* (CIDMP) (2004) provides a case study or template of how additional data on water source might be collected in the future to better represent irrigation use when modeling tools are advanced (groundwater integrated, model updated, recalibrated).

Source water proportions from ground and surface water in Bertrand Creek drainage illustrate an example of the potential difference when the estimated proportion is based on water right documents versus information provided by farmers with knowledge of "on the ground" locations and source types as shown in Figures 7 and 8 on the following page. The actual use data were taken from the *Bertrand CIDMP* (2004).

Table 3 shows the results from using each method. The 13 % difference can be attributed to several reasons including the difference between actual water use versus permitted use, overlapping or duplicative water rights, inaccurate information on water right documents etc. As a result, reliance on water rights in WRIA 1 to identify the water source location is not considered a reliable method for determining the proportion of irrigation water derived from ground and surface water.

Actual water use, source type and locations can be better identified working with irrigators and available public information, e.g. aerial photos, parcel maps.

Table 3. Source water identification, Bertrand Creek.

Data Source	Proportion of Source Water	
	Ground water	Surface Water
2004 CIDMP Irrigation water use	87%	13%
CIDMP 2004Water rights annual volume analyzed for overlap	74%	26%

4.3. Dairy farm data gaps

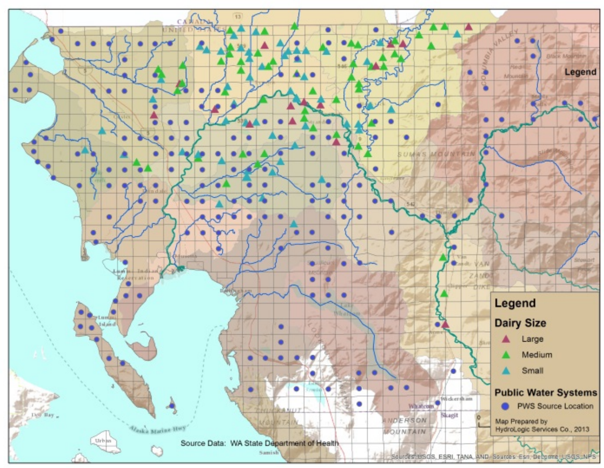
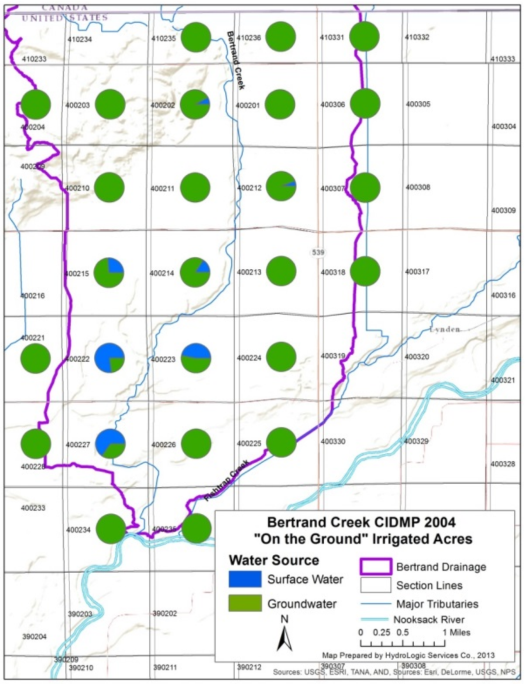


Figure 6. Dairy farms and source locations of public water systems by section.

Little is known about water source locations for dairy farms except that many are purveyed water via public water systems. A recently updated Washington Dept. of Ecology geospatial file of dairy farm locations became available with the data as of 2010. Figure 6 shows the 2010 dairy farm locations by size (small, medium, and large) and public water system sources to the nearest section. This information can help determine which public water systems to contact to fill data gaps for dairy farms.



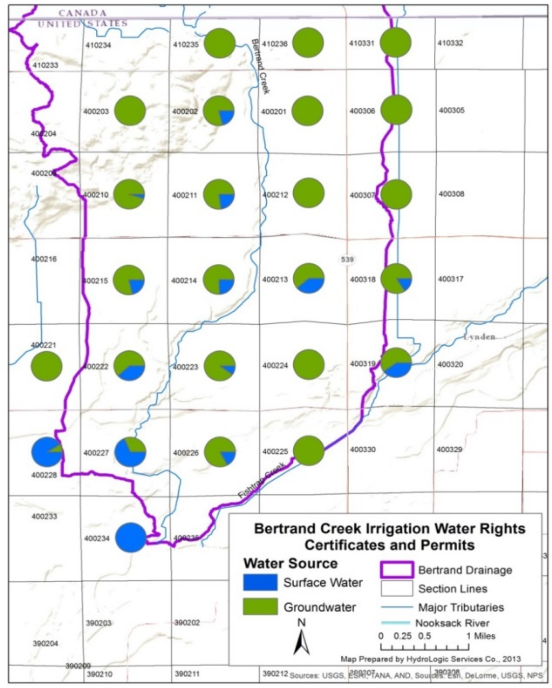


Figure 7. Proportion of irrigation source water in each section, field data collected during Bertrand CIDMP (Greenberg 2004).

Figure 8. Proportion of source water for irrigation water rights, analyzed during Bertrand CIDMP (Greenberg 2004).

4.3 Public Water System data gaps

More than 400 public water systems are active in Whatcom County; 45% are Group A systems and 55% are Group B systems. Group B are very small water systems serving fewer than 15 connections and fewer than 25 people per day. Public water systems in Whatcom County were summarized by water source and type of system (Group A or Group B, see Table 4).

The population served by public water systems can be viewed in Figure 9 on the following page, featuring the section in which the system sources are located. The largest populations are served by sources in only a few sections while most sources serve less than 200 people. The City of Bellingham serves approximately 80,000 people (both the Middle Fork and Lake Whatcom source locations are shown in Figure 9.

Table 4. Public Water Systems by source type.

Type of Source	Group A	Group B
Groundwater	152	210
Surface water	14	5
Intertie – supplied by other PWS	18	5
TOTAL	**184**	**220**

Public water system data from WA Dept of Health (2013 data), Whatcom County Dept. of Health (2000 data), WRIA 1 Project Water Rights Mapping of source locations and service areas (2003) were compared and summarized in this project. Of the 184 Group A water systems, source locations and service areas for 64 need to identified and digitized; some may be found in the 2013 data from Washington Dept. of Health (nearest quarter/quarter section), but the exact location is unknown.

Figures in *Chapter 3* show the number of sources summarized by section for residential and non-residential for public water systems.

Table 5. Public water system data gaps for various points of withdrawal.

Points of Withdrawal	Number of Public Water Systems		
	Group A	Group B	Total
Whatcom County Health, Point of Diversion (PPO)	64	65	129
WA DOH POD by Township/Range/Section	30	33	63
Water Right Place of Use	149	177	326
Parcels served by public water systems (service areas)	64	65	129

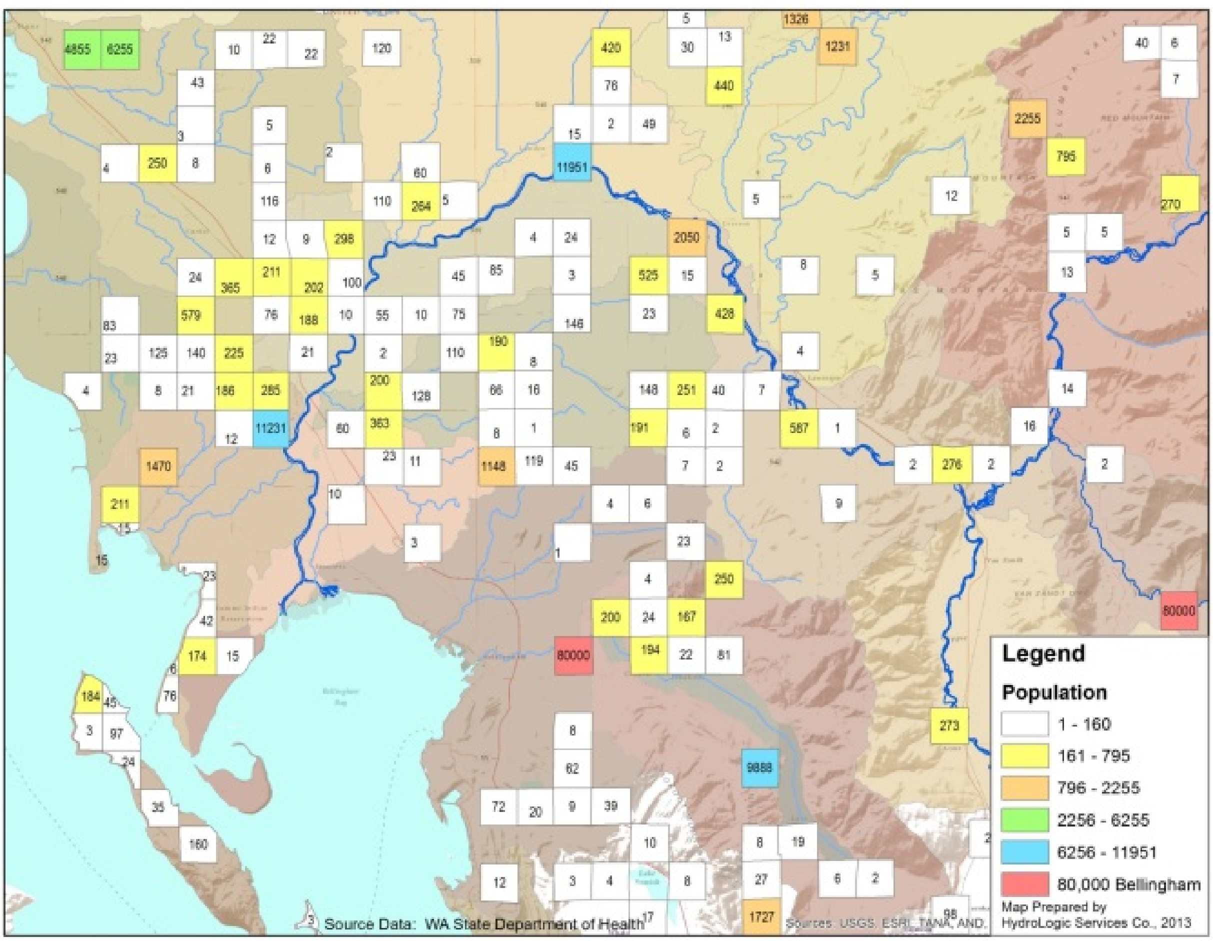


Figure 9. Approximate population served by public water system sources from each section.

4.4 Recommendations to narrow the data gap for water sources

4.4.1. Irrigation

- Develop a set of maps displaying locations of parcel boundaries, well logs and background information including aerial photography and public land survey system.
- Print each section on one page and print a large map of selected area, e.g., Bertrand WID or NLWID, etc.
- Two people from the entity undertaking the effort should meet with farmer representatives, one of whom can take notes.
- Meet with representative farmers of a "district" showing each section and have them identify by parcel: source of supply, location of point of withdrawal, type of crops irrigated, irrigation application (drip, sprinkler, big gun, etc.).
- Request water use data for berry processing from farmers.
- Digitize data collected and confirm irrigated areas using a digital layer of aerial photographs.
- Reconcile discrepancies with well logs, if possible, and water right points of diversion/withdrawal.

4.4.2. Dairy Farms

- Using data from Figure 4, determine public water systems nearby dairies.
- Contact the selected public water associations above to identify whether they supply water to the dairies identified.
- Obtain monthly amounts of water delivered to dairies.
- If not supplied by public water system, identify well logs associated with each dairy to determine source.
- Identify water right associated with dairy. Determine source of supply from water right, if available.

4.4.3. Public Water Systems

- In future modeling efforts, the City of Ferndale's water supply should be changed to 100% from groundwater. For calibration prior to December 2011, the supply will have to remain as surface water but scenario model runs should take into account the change to groundwater for adequately describing the water budget and/or streamflow impacts.
- Request service area databases and geospatial files from the Washington State Dept. of Health and Whatcom County Health Department, if available.
- Obtain and reconcile all data sources to ensure accuracy: Whatcom County Department of Health, Washington State Dept. of Health, WRIA 1 Water Rights CD, and Ecology's well log database.
- As part of the Coordinated Water System Plan Update for Whatcom County, meet with officials from each public water system to obtain points of withdrawals, any water use data available, service areas (all parcels served) for all public water systems.
- Digitize service areas and source locations.
- As part of or subsequent to the Whatcom County Coordinated Water System Plan Update, develop the model inputs required to more adequately represent the public water associations in Topnet-WM. Data required in Topnet-WM include amount of withdrawal, point of diversion, drainage in which water is used, source of supply, return flow amounts and locations for each public water system. Water use data required by MODFLOW groundwater model includes pumping rates from water supply wells.

5.0 Recommendations

Data collection and model recommendations are presented as multiple steps from short-term to long-term based on the data gaps that emerged from this study, including the anticipated model applications derived from WRIA 1 Staff Team input. Model recommendations were developed in part from input obtained from modeling experts familiar with WRIA 1 and/or integrated models available and applied in other watersheds.

Section 5.1 addresses the types of data that are needed to populate and calibrate a groundwater model. Section 5.2 addresses the types of models available, the efficiency of integrating a groundwater with Topnet-WM, and a path forward that appears to be the most cost effective and timely approach to obtaining a modeling tool to assist decision makers in resolving ground and surface water resource issues in WRIA 1.

Currently, a numerical groundwater model for the entire extent of WRIA 1 does not exist. However, models have been developed for the region by Simon Fraser University (SFU, see Allen, Chesnaux, and Simpson references) which includes the northern part of the Lynden Management Area (MODFLOW) and to the Nooksack River and west to the Lummi Peninsula (FEFLOW). Washington State University (WSU) expanded the SFU MODFLOW Model (See Barber and Pruneda references) for the aquifers underlying the Bertrand and Fishtrap Creek drainages with additional improvements to MODFLOW and response functions derived from MODFLOW results were integrated into a visualize display of impact zones from groundwater pumping using different software. This tool was accessible for the non-expert to visualize data and model results.

Generally, there are two approaches to develop integrated model functions appropriate for WRIA 1.

- Integrate models tailored to WRIA 1 with model code based on open source platforms; or
- Use a commercially available integrated model with proprietary components that are serviced and maintained by a provider.

While the latter approach is less customized, ongoing support and maintenance is available. Customizing a product specific to WRIA 1 requires substantial resources to maintain and support.

Chapter 4 provides examples of integrated ground and surface water model data requirements, methods for integrating models using existing WRIA 1 Topnet-WM with a groundwater model, and data collection needed to address key scale and function questions in WRIA 1. *Chapters 1, 2,* and *3* in the full report provide a summary of potential uses of the data (i.e., aquifer characteristics, groundwater recharge/discharge areas, water supply sources and locations, and surface/groundwater interactions).

The model approach selected also requires the WRIA 1 Joint Board Staff Team to develop a clear path forward to address the length of time a model needs to be supported, the organization that will support it: update the data inputs, operate the model, and produce readily accessible information. Developing a vision to address these factors is both critical and cost effective in the long run.

Options for groundwater modeling and integration with surface water modeling are further reviewed in *Chapter 4*.

5.1 Data gap highlights

In this project, a broad range of datasets were reviewed as part of the compilation and recommendation process. These technical recommendations are not an exhaustive list and were prepared using an iterative process, collecting feedback conducted throughout the technical review of draft and final work.

Data gaps were identified by maps in *Chapter 2* which show the number of studies in the various drainages throughout WRIA 1. An example can be found in Figure 10 which shows little to no data in most of WRIA 1 for transmissivity, as an example subsurface property that controls groundwater movement.

While there are sufficient data to build a coarse scale regional model for WRIA 1, insufficient data are available for any high resolution model functions. Therefore, recommendations include collecting more site specific data that can be used to populate and calibrate a groundwater model or the groundwater portion of an integrated model.

It is possible that some questions can be answered using a regional model (coarse scale). The ability to calibrate a model using the existing data will provide information on how well we understand the aquifers at the present time.

For details on water supply gaps and next steps, the reader is referred to Section 4.4, page 14.

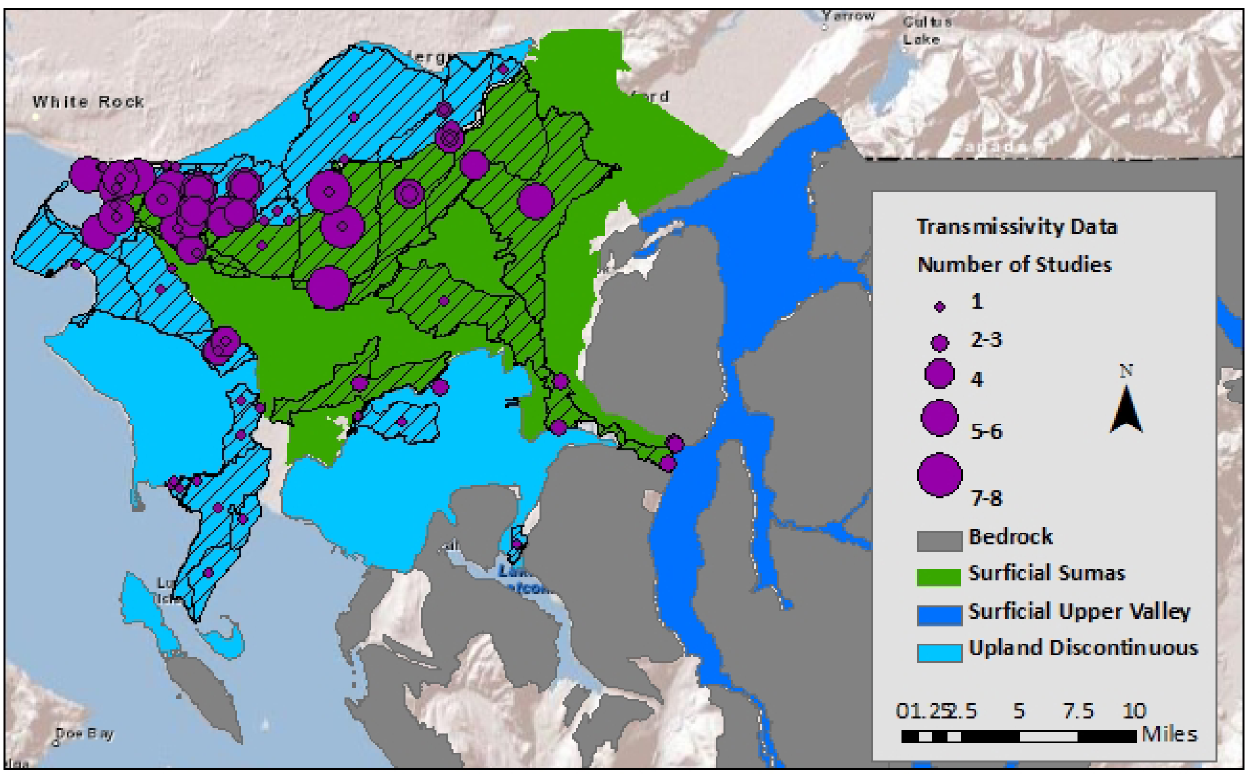


Figure 10. WRIA 1 Locations with aquifer transmissivity data.

5.2 Modeling recommendations

Much of the WRIA 1 below the confluence of the Nooksack River Forks is a groundwater-driven water resource system. Groundwater is plentiful and it is the dominant water source for uses in this area. Thus, a ground water model is required to fully address key locations in WRIA 1 where management issues of concern are present, including locations where ground water and surface water interactions need to be better understood.

At the present time, WRIA 1 has a surface water model with a water management module, Topnet-WM, developed in the early 2000s by Utah State University. Application of the Topnet-WM model in 2012 produced generalized drainage scale results not intended to address sub-drainage or site specific questions. Consequently, the WRIA 1 Joint Board Staff Team requested information on the process to integrate Topnet-WM with a groundwater model.

As part of the *GW Assessment*, several discussions were initiated with technical experts familiar with integrated ground and surface water modeling, some of whom were familiar with the WRIA 1 landscape and available datasets and technical tools. Many different models were considered, however, only a few options emerged as likely scenarios, with one offering apparent cost and time saving recommendations for WRIA 1 Joint Board consideration.

Integrating Topnet-WM with model code of an existing groundwater model is complex and time consuming, with uncertain outcomes. This is not a recommended approach for WRIA 1. Topnet-WM is a research model without ongoing support for the code. Technology changes quickly, which is why we recommend that any model used in the future have the support of a commercial, professional or university organization to maintain and support continuous improvement of the code base.

In discussions with technical experts, we found that a groundwater model for a significant portion of the lower section of WRIA 1 does exist at a regional scale (Figure 11). The FEFLOW groundwater model developed at Simon Fraser University (SFU) covers part of Whatcom County from the International Border to the Nooksack River and west to the Lummi Peninsula. Facilitating and supporting collaborative modeling and data collections with the developers may be in the long-term best interest of WRIA 1. This approach offers both cost effective and time efficiency advantages.

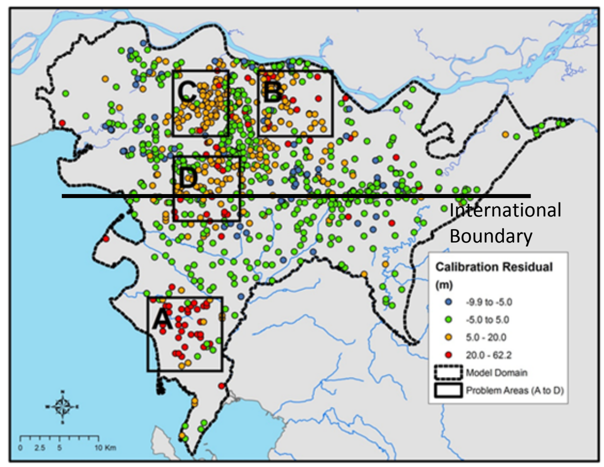


Figure 11. FE Flow groundwater model extent and calibration results (Simpson, 2012).

FEFLOW is a sophisticated groundwater model considered to be the best known for simulating subsurface transient flow. This regional model could be used to establish boundary conditions for smaller scale local models in WRIA 1. We recommend exploring data and model sharing opportunities by promoting an agreement process facilitated by members of the Abbotsford Sumas International Task Force. This approach would rely on collaboration with Simon Fraser University as well as the Danish Hydrologic Institute (DHI) to further develop the existing modeling system, but may prove to be the most cost effective alternative.

Figure 11, sections A-D show where more data may be required to improve the FEFLOW regional model calibration.

Existing U.S. data that were not included in previous FEFLOW work (completed in 2005) could be added to refine the calibration in the WRIA 1 portion. To address site, sub-drainage, or drainage scale issues, additional data collection will be necessary to develop higher resolution sub-models useful for sub-drainage applications.

Collaborative work on a regional groundwater model for WRIA 1 could include the following tasks:

- Extend the SFU FEFLOW model domain to add the mountains and Nooksack River drainages not currently included,
- Use existing surface water and water management model inputs and parameterizations to populate the MIKE suite of model components one of which is a rainfall runoff model similar to Topnet,
- Use coupled MIKE11-FEFLOW regional model to identify areas of concern, and
- Perform a local or sub-drainage scale case study by adapting a sub-model of the regional scale integrated surface-groundwater model.

The recommendations outlined in *Chapter 4* are categorized into the following time frames each of two year durations:

- Short-term (1 – 3 year)
- Mid-term (3-6 years)
- Post Mid-term (5 to 8 years)
- Long-term (10 to 20 years)

Within each time frame are general tasks as follows:

- Conceptual Model Development
- Data Collection
- Numerical Model Development
- Local Use and Applications

Specific recommendations focus on defining dataset, model and geographic areas of concern and prioritizing data collection efforts for each of those. Data collection should include establishing and operating surface and groundwater data collection network in each focus area. Add instrumentation to selected wells at various distances from creek and distances along creek with continuous data recorders (minimum two per priority drainage (five selected drainages) and 12 at intensive 1-2 sites study area). And, conduct seepage runs with 5-15 streamflow measurements in tributaries near selected locations.

Concurrent with data collection, the model inputs and appropriate parameters can be reconfigured to use as inputs into the MIKE suite of integrated models (MIKE-SHE+MIKE 11+FEFLOW), including all of the water management components. Review of the FE Flow calibration, addition of local inputs, and an initial calibration of the integrated model can be concurrent. Refinements to model calibration may occur as new data become available to populate the model. This is an example of the types of step-by-step recommendations included in *Chapter 4,* multiple options are presented for comparison.

INTEGRATED MODEL AND DATA COLLECTION COST ESTIMATES

Short-term:	$470,000-$625,000
Mid-term:	$350,000-$550,000
Post Mid-term:	$270,000 - $325,000
Total Costs:	$1,090,000 - $1,500,000
Maintenance Long-term:	$140,000 - $245,000/year

Chapter 1 Understanding WRIA 1 Aquifers

WRIA 1 Groundwater Assessment
June 2013

An interdisciplinary team of water resource technical specialists worked with the WRIA 1 Joint Board Staff Team to compile existing technical models, studies, and data into an assessment of groundwater in WRIA 1. For a complete list of contributors, see *Chapter 4 - Recommendations for Data Collection and Model Integration* In Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, (eds). WRIA 1 Groundwater Data and Model Assessment, Whatcom County PUD #1, Whatcom County, WA: WRIA 1 Joint Board.

Technical reviewers: Jeremy Freimund, Lummi Nation Natural Resources, Kasey Cykler, State of Washington Dept. of Ecology. See also List of Contributors, *Chapter 4* Section 4.0.

Please cite this Chapter as:
Print Citation: Lindsay, C. and C. Bandaragoda (2013). Understanding WRIA 1 aquifers. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board.

Online Citation: Lindsay, C. and C. Bandaragoda, (2013). Understanding WRIA 1 aquifers. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board. Retrieved [Date], from http://wria1project.whatcomcounty.org/.

This work was funded by the WRIA 1 Joint Board and managed by Whatcom County PUD #1 and funded by Department of Ecology Grant No 1200070 Task 9 Groundwater Study; June 2013.

CHAPTER 1
Understanding WRIA 1 Aquifers

Table of Contents

List of Figures

List of Tables

1.0 OVERVIEW

Significant sources of groundwater are present in glacial outwash and non-glacial alluvial aquifers located beneath the western upland areas and in sediments adjacent to the Nooksack and Sumas Rivers and their tributaries in Water Resources Inventory Area (WRIA) 1. Some of these aquifers are relatively shallow, regionally extensive and fairly well known, such as the Sumas-Blaine Aquifer. While others, such as the Deer Creek and Lummi Peninsula Aquifers, are generally deeper in nature and more localized rather than regional in extent. The purpose of this chapter, *Understanding of WRIA 1 Aquifers,* is to present a general overview of the current understanding of groundwater quantity in the primary surficial and deep aquifers located in WRIA 1 based on the available technical studies and other relevant information. A complete listing of the available WRIA 1 groundwater data resources has been compiled and organized into the *WRIA 1 Groundwater Bibliography* (see Digital Appendix to this report).

Several overviews of the available data regarding groundwater systems in WRIA 1 have been completed in the past by others, including the Washington State Department of Conservation (1960), Tooley and Erickson (1996), the Cascade Environmental Services/Water Resources Consulting Team (Greenberg et al. 1996), the United State Geological Survey (Cox and Kahle 1999), the Nooksack Basin Ground-Water Quantity Study Nooksack Basin Ground Water Quantity Study Group (2000), Utah State University (Kemblowski et al. 2001) and Washington State University (Pruneda 2007, Barber and Wu 2008). Many of these important studies, as well as other resources, are summarized in this chapter.

This chapter is focused on groundwater *quantity* only; compiling and assessing groundwater *quality* data sources is beyond the scope of this project. There are several productive groundwater sources located in WRIA 1 that are significantly limited for use due to natural and/or anthropogenic contamination (Cox and Kahle 1999). For example elevated concentrations of naturally occurring arsenic and natural/anthropogenic elevated concentrations of chloride in relatively shallow groundwater beneath the lower Lummi River drainage and the Lummi Peninsula has resulted in significantly restrictions on the potable and non-potable use of groundwater in this area (Aspect, 2003). Likewise, elevated concentrations of anthropogenic nitrate and ethylene dibromide (EDB) in the Sumas-Blaine Aquifer have limited the potable use of groundwater in the vicinity of Lynden (Mitchell and Babcock 2000).

2.0 WRIA 1 PHYSIOGRAPHIC SETTING

WRIA 1 is located in the northwest corner of Washington State and is generally bounded by the Strait of Georgia to the west, British Columbia to the north, the Cascade Range to the east, and the Skagit River Basin to the south (Figure 1). The primary rivers in WRIA 1 are the Nooksack River which flows west from the Cascade Range to Bellingham Bay and the Sumas River, which begins in the north-central lowlands and flows north into British Columbia, eventually discharging into the Fraser River. The Sumas River drainage is approximately 65 square miles in size and includes much of the area located immediately to the south, west and east of City of Sumas (Figure 1).

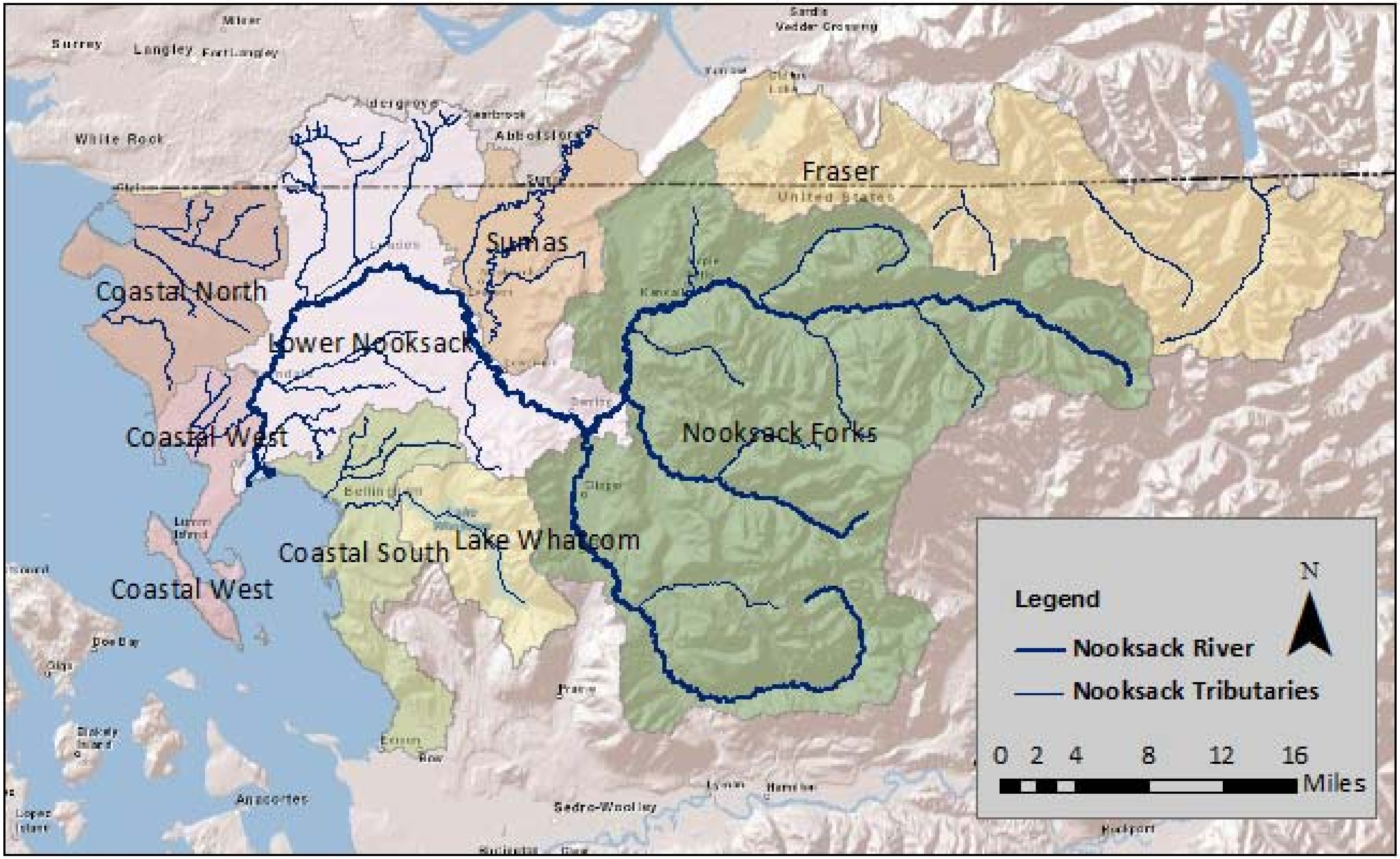


Figure 1. WRIA 1 Aggregated watersheds (Whatcom County PDS, 2011).

The Nooksack River watershed has a total drainage area of approximately 826 square miles with roughly 49 square miles located in Canada. The mainstem of the Nooksack River is formed by the convergence of the South Fork Nooksack River, which drains roughly 183 square miles, the Middle Fork Nooksack River, which drains approximately 102 square miles, and the North Fork Nooksack River, which has a drainage area of approximately 281 square miles. The North and Middle Forks Nooksack River drainages include the north, west and southwest glaciated slopes of Mt. Baker (10,777 feet) and Mt. Shuksan (9,131 feet).

There are likely several hundred drainages and sub-drainages located in WRIA 1. As part of the WRIA 1 Watershed Management Project, 177 individual surface water drainages were delineated in WRIA 1. To simplify watershed characterization, Whatcom County combined the drainages into logical groups based on hydrology and/or socio-economics to form 19 Management Areas (Public Utility District No. 1 of Whatcom County, 2002). Each Management Area is comprised of one or more individual drainages, as described in Table 1 and shown on Figure 1. These Areas are further divided into those that drain to the Fraser River (Fraser), those that drain to the Nooksack River (Nooksack) and those that discharge directly to the coast (Coastal). For example, the Fishtrap drainage is located within the Lynden North Management Area which drains to the Nooksack River, while the North Fork Dakota drainage is located within the Drayton Harbor Management Area which includes individual drainages that drain directly to the coast (Table 1, Table 2, and Table 3; Figure 1).

The 2010 State of Watershed Report prepared for WRIA 1 (Whatcom County Planning and Development Services 2011) combined 17 of the 19 Management Areas into seven "aggregate" watersheds (Coastal North, Coastal South, Coastal West, Lower Nooksack, Lake Whatcom, Sumas, and Nooksack Forks) based on "groupings of watersheds in close proximity of each other." The State of the Watershed Report aggregate watersheds boundaries are shown on Figure 1, the 19 management areas are shown in **Figure 2**. Their aggregated watershed relationship to the various management areas and regional drainage patterns is further described in Table 1, Table 2, and Table 3.

3.0 GENERAL REGIONAL GEOLOGIC SETTING

The surficial geology of WRIA 1 is described on several geologic maps, including those completed by the United States Geological Survey (Newcomb et al. 1949), the Washington State Department of Conservation (1960), Easterbrook (1976), Halstead (1986), (Lapen 2000), and Earth Tech (Canada) Inc. (2001). In a general sense WRIA 1 can be divided into two relatively different regional geologic settings. The eastern, central and southern portions of the WRIA consist of a complex mixture of sedimentary, metamorphic and igneous bedrock (Tooley and Erickson 1996). While the west and northwest portions of the WRIA are generally characterized by several hundred feet of Quaternary glacial and non-glacial sediments overlying a relatively thick sequence of sedimentary bedrock. As discussed in later sections of this report, the primary (i.e., most significant aquifers) are located in the west and northwestern portion of the WRIA, within the Quaternary sediments. The Quaternary sediments were deposited during several glacial and non-glacial intervals that occurred repeatedly during the past roughly 2 million years. A brief discussion of the Quaternary glacial/non-glacial sediments thought to potentially be present in WRIA 1, from oldest to youngest, is presented below. The stratigraphic relationship of these geologic units is shown on **Table 4** and Table 5.

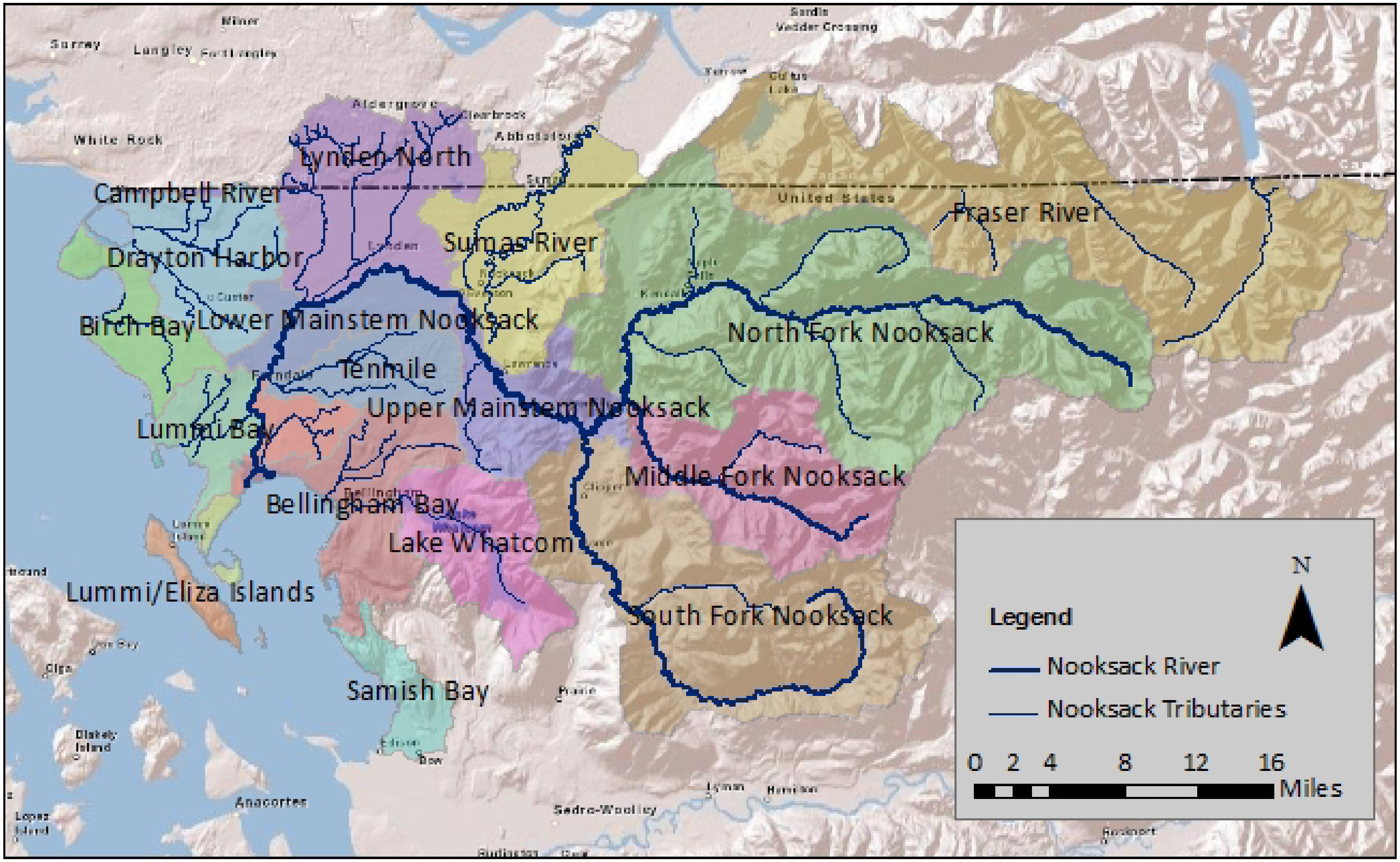


Figure 2. WRIA 1 Management Areas.

3.1 Older Undifferentiated Glacial and Non-Glacial Sediments

For the purposes of this report, we have referred to all glacial and non-glacial sediments older than approximately 60,000 years before present (ybp) as older undifferentiated glacial and non-glacial sediments (**Table 4** and Table 5). This fairly thick sequence of older sediments likely includes marine sediments, glacial deposits of the Double Bluff and Possession glacial events, non-glacial Whidbey Formation sediments, and older glacial/non-glacial sediments.

The older glacial and non-glacial sediments have been encountered at depths generally greater than 300 to 400 feet below the ground surface near the City of Blaine. Where encountered the older sediments appear to generally consist of a relatively thick sequence of fine to medium grained sand with silty sand and silt interbeds and rare lenses of gravel. The currently identified deep regional aquifer in WRIA 1 appears to be located within more permeable sections of these older geologic units.

3.2 Olympia Non-Glacial Sediments

The Olympia non-glacial sediments generally consist of thick deposits of organic silts, clays, silty sands, and fluvial sands and gravels. These sediments are interpreted to have been deposited in a meandering river environment. Beneath the Boundary and Mountain View Upland areas, the upper portion of the Olympia sediments appear to consist of relatively permeable sand and silty sand with some lenses of gravel and silt, while the lower Olympia sediments appear to consist of a relatively thick sequence of low permeability silt, silty sand with lenses of fine sand (AESI, 2008; Aspect, 2003 and 2009). In this area the upper permeable sequence of Olympia non-glacial sediments can contain locally extensive but discontinuous aquifers. The Olympia non-glacial sediments have a variable thickness but where encountered they appear to be regionally extensive and are generally thicker than 100 feet.

3.3 Vashon Glacial Sediments

Approximately 20,000 ybp climatic cooling triggered the growth of the Cordilleran Ice Sheet in British Columbia. The Puget lobe of the ice sheet flowed south through Whatcom County and reached its maximum southern extent near Olympia approximately 14,000 to 15,000 ybp. This glacial advance is referred to as the Vashon Stade. At the maximum Vashon Stade extent, the Puget lobe of the Cordilleran Ice Sheet is interpreted to have reached a thickness of about 4,000 to 5,000 feet near Bellingham and roughly 3,000 feet near Seattle, Washington.

The oldest Vashon sediments in WRIA 1 are outwash sands and gravels that were deposited in high-energy glaciofluvial environments (meltwater streams) that formed in front of the advancing Vashon glacier. The Vashon outwash deposits consist predominantly of highly permeable sand and gravel with various amounts of silt. The Vashon advance outwash deposits are commonly referred to as Esperance Sand in the King and Snohomish Counties and locally as the Mountain View Sand and Gravel in Whatcom County. Discontinuous aquifers appear to be present within the Vashon outwash sediments in WRIA 1.

As the Vashon glacier advanced through Whatcom County, the outwash sediments were overrun and overconsolidated by the approximately 4,000 to 5,000 feet of ice. Lodgement till was deposited at the base of, and subsequently overrun by, the advancing Vashon ice sheet. As a result, this material was glacially consolidated into a dense condition. The Vashon lodgement till generally consists of a complex mixture of low permeability sand, gravel, and silt and generally is not considered an aquifer unit.

3.4 Everson Non-Glacial Sediments

Roughly 13,000 to 14,000 ybp, the Cordilleran Ice Sheet began to melt and retreat to the north. This period of glacial ice retreat is referred to as the Everson Interstade. Shortly after the removal of the ice sheet from the Strait of Juan de Fuca, much of the retreating glacial ice in Skagit, Island, and Whatcom counties floated on the influx of marine waters (Easterbrook 1963, 1992). As the ice floated and/or retreated, it deposited a thick layer of glaciomarine drift over much of Whatcom County. These sediments include the Kulshan (glaciomarine), Deming (fluvial) and Bellingham (glaciomarine) members and are thought to be equivalent to the Fort Langley sediments in southern British Columbia (Kovanen and Slaymaker 2003). The glaciomarine drift is generally non-water bearing, has a very low permeability and is typically an unsorted mixture of blue-gray silt and clay with some lenses of sand and gravel. The Deming member generally consists of a sand with some gravel and silt. The Deming member can form localized aquifers.

3.5 Sumas Glacial Sediments

The Sumas Glacial sediments consist primarily of outwash sand and gravel and some lodgement till. Much of the Sumas, Lynden North, and Drayton Harbor drainages (**Figure 2**) are covered at the ground surface by glacial outwash deposited by high-energy meltwater streams during the most recent advance/retreat of the Sumas ice sheet. The Sumas outwash is generally less than 100 feet thick and consists of loose, moderately to well sorted sand and gravel with some silt (Lapen 2000). The Sumas outwash is the primary geologic unit within which the Sumas-Blaine Aquifer is located.

Sumas lodgement till is typically found at or near the ground surface in the immediate vicinity of the City of Sumas and is described as a dense unit consisting of gravel and sand with some silt and clay. Sumas till generally has a low permeability and does not contain significant aquifers.

3.6 Recent Non-Glacial Sediments

The recent non-glacial sediments include organic peat, alluvial fan and landslide deposits, volcanic mudflow (lahar), and recent fluvial alluvium. The composition of the recent non-glacial sediments is highly variable and can range for highly permeable sand and gravel to low permeability lacustrine silt and clay. The permeable layers of these sediments can form significant aquifers while the lacustrine sediments can form confining units such as in the Sumas River valley

4.0 PRIMARY AQUIFERS

For discussion purposes, various previous authors have divided the primary aquifers located in WRIA 1 into three general classifications referred to as the Sumas-Blaine Aquifer, Discontinuous Surficial Aquifers, and Upper Valley Aquifers. For the purposes of this review, we have expanded this existing aquifer classification system to include Deep Regional Aquifers and Bedrock Aquifers. We have also renamed the Discontinuous Surficial Aquifers classification as simply Discontinuous Aquifers to include deeper discontinuous water-bearing sediments. The following is a brief discussion of each aquifer classification. The approximate geographic locations of the aquifers are shown on **Figure 3**. The aquifer locations shown

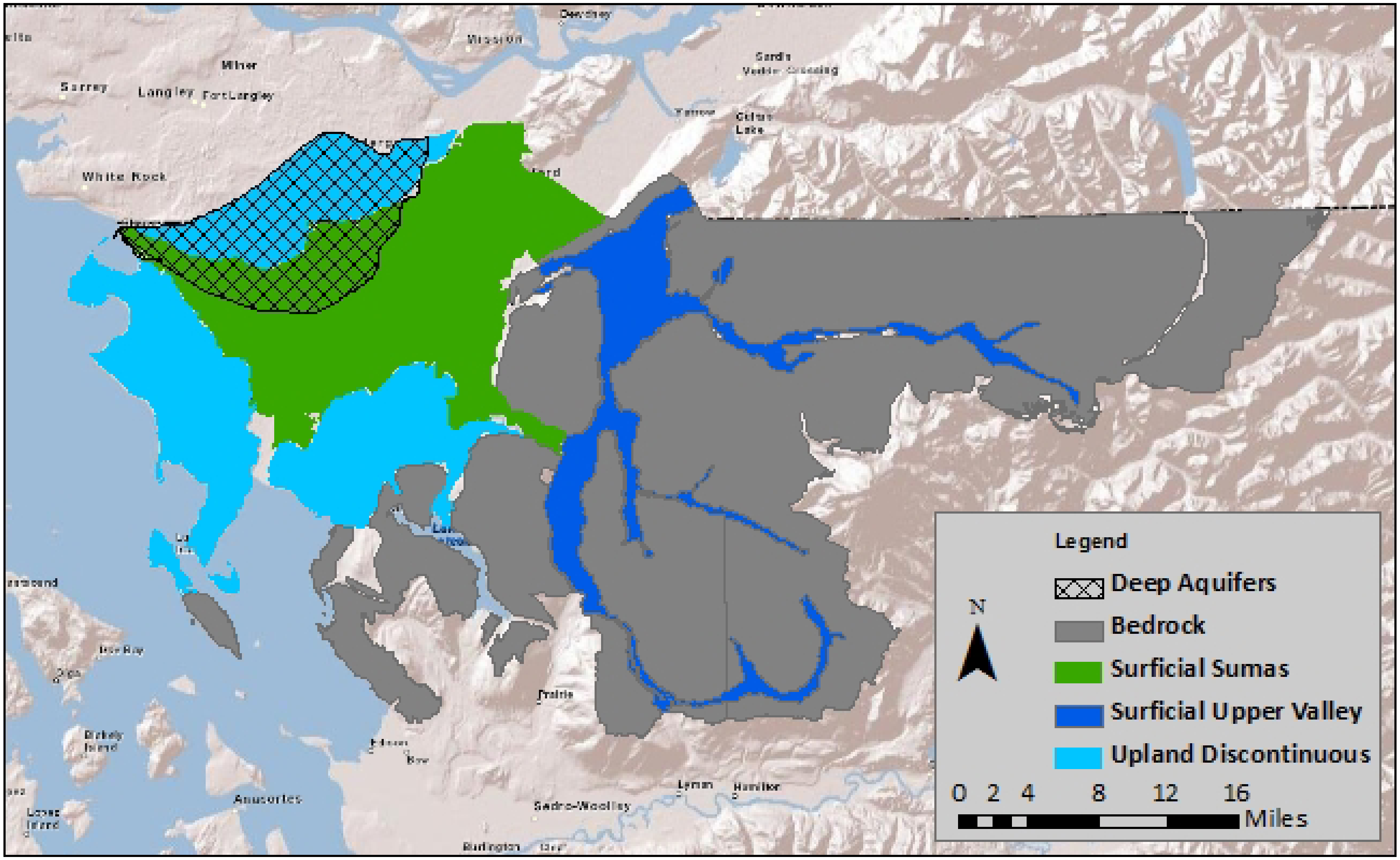


Figure 3. WRIA 1 Primary aquifers.

on Figure 3 are based on specific published information and/or were inferred from the available information reviewed for this project. The locations shown should be considered non-exact and approximate.

4.1 Sumas-Blaine Aquifer

The Sumas-Blaine Aquifer is likely the most productive and widely used aquifer in WRIA 1. The aquifer is a common source of irrigation, single-family domestic, and municipal water in the northwestern portion of the WRIA. The aquifer is primarily comprised of Sumas-age glacial outwash and more recent Nooksack/Sumas River alluvium. The Sumas-Blaine Aquifer is commonly referred to as the Abbotsford Aquifer in Canada and is referred to as the Sumas-Abbotsford, Abbotsford-Sumas, and Sumas Aquifer in other various reports and technical papers. One of the most comprehensive regional overviews of the Sumas-Blaine Aquifer is presented in the United States Geological Survey (USGS) Water-Resources Investigations Report (98-4195) more commonly referred to as the Lynden-Everson-Nooksack-Sumas (LENS)study (Cox and Kahle 1999). Much of the information and data presented in the LENS study are used in later drainage specific and regional studies completed in WRIA 1.

The Sumas-Blaine Aquifer generally underlies the flat glacial outwash plain between the towns of Sumas, Blaine, Ferndale, Everson and the Nooksack River and occupies about 150 square miles (Tooley and Erickson 1996). The aquifer is quite variable in thickness but generally ranges from around 25 feet thick near Blaine to almost 100 feet thick north of Lynden. The aquifer is recharged primarily by the direct infiltration of precipitation and possibly by interflow from other aquifers that underlie surrounding upland areas. The aquifer is generally unconfined in nature except in portions of the Sumas Valley where it is overlain by recent lacustrine silt and clay, and/or ice-contact deposits (Cox and Kahle 1999).

Groundwater in the aquifer can be at or near the ground surface in the wet winter and spring months and is generally at depths below the ground surface of less than 10 feet throughout the remainder of the year. Exceptions occur near Sumas where the depth-to-water exceeds 50 feet and the eastern margin of the aquifer where depths exceed 25 feet (Tooley and Erickson, 1996). All depths presented here are relative to ground surface unless otherwise noted.

Regionally groundwater in the Sumas-Blaine Aquifer tends to flow towards the Nooksack and Sumas Rivers and more locally towards the smaller tributary streams, indicating a relatively high degree of hydraulic connectivity or continuity between the aquifer and surface water. A hydrograph of water levels in a well located in the upper reaches of Bertrand Creek drainage that is completed in the Sumas-Blaine Aquifer is shown on **Figure 4**. The hydrograph shows the effects of summer irrigation and indicates that the Sumas-Blaine Aquifer typically experiences roughly 5 feet of seasonal fluctuations in the upper portion of the Bertrand Creek Drainage.

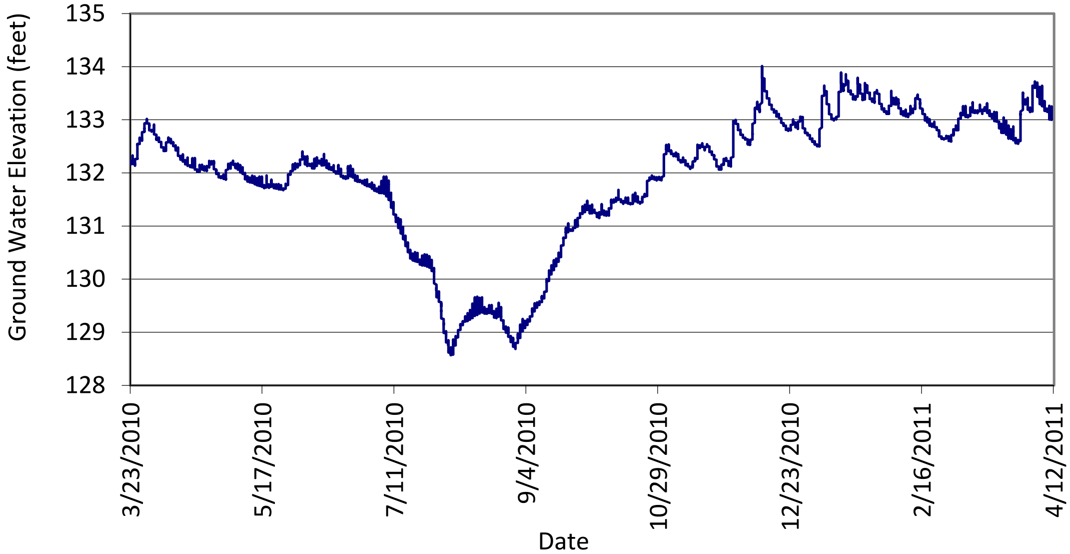


Figure 4. Shallow groundwater elevation time series data. Bertrand Creek Subbasin- Well BAE 184. T41N, R2E, Section 36. Ground surface elevation approximately 140 feet.

Cox and Kahle (1999) reported that the hydraulic conductivity (K) of the Sumas-Blaine Aquifer typically ranges between 7 and 7,800 feet per day (ft/d) and the groundwater flow velocity ranges from less than 1.0 ft/d to over 30 ft/d. Culhane (1993) indicated that the transmissivity (T) of the Sumas-Blaine Aquifer generally ranges between approximately 100 to 30,000 feet squared per day (ft^2/d).

Several detailed studies of various drainages that are located within the surficial Sumas-Blaine Aquifer have been completed in the past (see Digital Appendix to this report). For example, Scibek (2005) developed a regional steady-state MODFLOW numerical groundwater flow model of the “Abbotsford-Sumas Aquifer” to identify the potential impacts of climate change on groundwater resources in southern British Columbia and northwestern Whatcom County. The model is regional in scale and contains insufficient localized data to be useful for addressing many of the more significant water resources issues in WRIA 1. Barber and Wu (2008) later refined and modified the Scibek (2005) regional MODFLOW model to include drainage specific aquifer and streambed conductance data for the Bertrand and Fishtrap drainages in order to use the model to make reasonable evaluations of the potential impacts related to moving surface water diversions to groundwater withdrawals.

Our review of the information compiled for WRIA 1 indicates that a significant volume of groundwater related information is available for the Sumas-Blaine Aquifer including specific information regarding aquifer parameters (hydraulic conductivity, transmissivity, and storage), surface/ground water interaction potential, and groundwater level monitoring data.

4.2 Discontinuous Aquifers

There are numerous discontinuous aquifers located in WRIA 1, most of which are located in the western half of Whatcom County. Tooley and Erickson (1996) indicate that the surficial discontinuous aquifers consist of a variety of geologic deposits including beach (modern and remnant), glaciofluvial terrace deposits, modern alluvial and floodplain deposits, isolated outwash terraces, and marine terrace deposits.

They also indicate that the hydraulic properties of these surficial aquifers are highly variable over short vertical and horizontal distances and that most of these units are not major sources of groundwater. The surficial discontinuous aquifers are typically unconfined in nature, are recharged by the direct infiltration of precipitation and primarily discharge to shallow wells and nearby streams. Groundwater flow direction in these aquifers generally follows the surface topography. Our review of the information compiled for WRIA 1 indicates that there is little available groundwater related information for the surficial discontinuous aquifers. The data are generally limited to information presented on regional geologic maps and on water well reports for wells completed in the aquifers.

Surficial and/or Deeper (non-surficial) discontinuous aquifers have been identified beneath the Mountain View Upland west of Ferndale, the Boundary Upland just east of Blaine, the Tenmile Management Area (Deer Creek Aquifer), the Lummi Peninsula, and the Birch Point Upland southwest of Blaine. It is also possible that non-surficial discontinuous aquifers are locally present in the Squalicum, Lake Whatcom, and Upper Mainstem Nooksack Management Areas based on the area geologic setting and isolated water well report data. The identified deeper discontinuous aquifers appear to be located in Everson-age to Olympia-age deposits consisting of sand with some gravel and silt. The aquifers appear to be generally confined to semi-confined conditions and are typically less than 250 feet in depth. Recharge to these aquifers is primarily from infiltrating precipitation and the vertical migration of groundwater from overlying surficial aquifers where present. A brief overview of four of the better understood discontinuous aquifers located in WRIA 1, is presented in the following sections.

4.2.1 Mountain View Upland

Aspect Consulting (2009) indicates that surficial and deeper discontinuous aquifers are located beneath the Mountain View Upland to the west of Ferndale. The surficial discontinuous aquifers are found on top of or in fine-grained units such as Everson glaciomarine drift. Newcomb et al. (1949) report that wells completed in these relatively shallow discontinuous aquifers tend to go dry during summer months. Aspect concluded that the shallow discontinuous aquifers located on the Mountain View Upland appear to be very localized and generally produce only small volumes of water (Aspect Consulting 2009). Our review of the information compiled for WRIA 1 indicates that there is a minor amount of available groundwater related information for the near surface discontinuous aquifers located on the Mountain View Upland. The data are generally limited to information presented on regional geologic maps, regional geologic/hydrogeologic reports, and on water well reports for wells completed in the aquifers.

Aspect Consulting (2009) also identified a non-surficial discontinuous aquifer located beneath the Mountain View Upland. The aquifer is described as permeable (primarily sand and gravel) Vashon and pre-Vashon sediments and although classified as "discontinuous" for the purposes of this report, the aquifer appears to be locally extensive beneath the upland area. Completion elevations of the wells in the discontinuous aquifer located beneath the Mountain View Upland typically range from about 50 feet above mean sea level to about 200 feet below mean sea level. All elevations presented are relative to mean sea level unless otherwise noted.

The aquifer appears to be generally semi-confined to confined with a potentiometric surface that ranges from near sea level to an elevation of roughly 100-feet. The groundwater flow direction in the discontinuous aquifer identified by Aspect generally flows to the south and/or southwest beneath the southern portion of the Mountain View Upland. A hydrograph of a well that is completed within the discontinuous aquifer hydrograph indicates that the discontinuous aquifer located beneath the Mountain View Upland experiences roughly 300 feet of seasonal fluctuation. Our review of the available information indicates that a significant volume of groundwater related information is available for the non-surficial Mountain View Upland discontinuous aquifer including specific information regarding aquifer parameters (hydraulic conductivity, transmissivity, and storage), groundwater flow direction, and groundwater level monitoring data.

4.2.2 Boundary Upland

The City of Blaine operates several high-capacity production wells completed within a deep discontinuous aquifer located primarily beneath the Boundary Upland (Associated Earth Sciences Inc. (AESI) 2008b). The Boundary Upland discontinuous aquifer appears to be located within Vashon glacial deposits and possibly Olympia nonglacial sediments and is generally separated from the ground surface by several tens of feet of low permeability Everson glaciomarine drift. Although classified as discontinuous for the purposes of this report, the aquifer appears to be locally extensive beneath the Boundary Upland area.

Associated Earth Sciences Inc. (AESI) (2008b) indicates that groundwater in the Boundary Upland discontinuous aquifer appears to be semi-confined to confined and the potentiometric surface of the aquifer ranges in elevation from less than 50 feet to over 250 feet. Groundwater flows radially off the Boundary Upland and the aquifer potentiometric surface has a hydraulic gradient (slope) that ranges from approximately 0.015 (80 feet per mile) to roughly 0.038 (200 feet per mile). The recharge area for the discontinuous aquifer is primarily the Boundary Upland area where the aquifer receives recharge through the vertical infiltration of precipitation and, where present, by vertical leakage of groundwater from overlying surficial aquifers. The aquifer appears to discharge to seawater (Drayton Harbor, Semiahmoo Bay, and Birch Bay), a lesser amount to water supply wells, and possibly to surficial aquifers located in the Lower Dakota drainage (Associated Earth Sciences Inc. (AESI) 2008b).

Exploration and aquifer testing results reported by Associated Earth Sciences Inc. (AESI) (2008b) indicates that the Boundary Upland discontinuous aquifer is as much as 200 feet thick and has an aquifer transmissivity that ranges between 55 ft^2/d to 8,100 ft^2/d. Our review of the information compiled for WRIA 1 indicates that a significant volume of groundwater related information is available for the Boundary Upland discontinuous aquifer including specific information regarding aquifer parameters (hydraulic conductivity, transmissivity, and storage), surface/ground water interaction potential, and groundwater level monitoring data.

4.2.3 Deer Creek Aquifer

The Deer Creek Aquifer is a discontinuous aquifer located in the Tenmile management area (**Figure 2** and Figure 3). The Pacific Groundwater Group (PGG) describes the Deer Creek Aquifer as a locally extensive groundwater system that is commonly encountered at depths of 10 to 200 feet and is typically 100 to 150 feet thick (Pacific Ground Water Group 1995). The aquifer is typically surrounded by low-permeability units that include bedrock and fine grained sediments. PGG also indicates that the aquifer “lacks direct hydraulic continuity with other aquifers and the Nooksack River.”

The Deer Creek Aquifer is highly productive with yields in excess of 400 gpm. The aquifer is the sole source of water for the Deer Creek Water Association, which provides drinking water to over 1,000 customers. Groundwater in the Deer Creek Aquifer appears to flow to the northeast and southwest and has a hydraulic gradient of approximately 0.01 (53 feet per mile) near the water association wells. Recharge to the aquifer is from the local infiltration of precipitation and surface water runoff (PGG, 1995). PGG also reports that the Deer Creek Aquifer transmissivity is 6,020 ft^2/d with a corresponding hydraulic conductivity value of approximately 120 ft/d.

Our review of the information compiled for WRIA 1 indicates that a moderate volume of groundwater related information is available for the Deer Creek Aquifer including specific information regarding the geologic/hydrogeologic setting, aquifer parameters (hydraulic conductivity, transmissivity, and storage) and surface/ground water interaction potential.

4.2.4 Lummi Peninsula Aquifer

The discontinuous aquifer that underlies the Lummi Peninsula is described in detail by Aspect (2003). Aspect indicates that the discontinuous aquifer is a "sequence of sands and gravels that encompasses parts of two or more geologic units or formations. It includes, from shallowest to deepest: Vashon advance glacial outwash, Olympia interglacial (fluvial) deposits and, in some areas, older (pre-Olympia) glacial and interglacial deposits. Because each of these geologic units is comparatively permeable, water is transmitted relatively freely between them, and they combine to form a single aquifer."

Aspect reports that the Lummi Peninsula Aquifer has a mean transmissivity of approximately 2,400 ft^2/d with a corresponding mean hydraulic conductivity of roughly 23 ft/d. The aquifer can be highly productive, however, its productivity with regard to being used for potable water is limited by water quality constraints, specifically elevated chloride concentrations and the potential for seawater intrusion. Our review of the information compiled for WRIA 1 indicates that a significant volume of groundwater related information is available for the Lummi Peninsula Aquifer including specific information regarding the local geologic/hydrogeologic setting, water quality, aquifer parameters, and surface/groundwater interaction potential (Aspect Consulting 2003).

4.3 Upper Valley Aquifers

The Upper Valley Aquifers, as described by (Tooley and Erickson 1996), are associated with the three Forks of the Nooksack River and are significant surficial aquifers in the WRIA. These aquifers generally consist of inter-layered mixtures of gravel, sand, silt, and clay and are located within the river bottoms in the North, Middle and South Fork Nooksack River Management Areas. These aquifers are generally recharged by the direct infiltration of precipitation and flood waters from the adjacent river, and to a lesser extent by lateral flow from surrounding fractured bedrock aquifers. Tooley and Erickson note that in some areas the Upper Valley Aquifers may be hydraulically connected to glaciofluvial terrace and outwash deposits along the valley walls. Our review of the information compiled for WRIA 1 indicates that a small volume of groundwater related information is available for the Upper Valley Aquifers. The data are generally limited to information presented in regional geologic maps, regional geologic/hydrogeologic studies, and on water well reports for wells completed in the aquifers.

4.4 Deep Regional Aquifers

A deep regionally extensive aquifer is identified by (Associated Earth Sciences Inc. (AESI) 2008b) in the northwestern portion of WRIA 1 near Blaine and Lynden (referred to herein as the Blaine Aquifer). The identified deep regional aquifer appears to be located within older pre-Vashon glacial and non-glacial sediments typically at depths greater than 300 feet. The approximate geographical extent of the Blaine Aquifer is shown on **Figure 3**. The following is a brief description of the identified deep regional aquifer.

4.4.1 Blaine Deep Aquifer

The Blaine Deep Aquifer appears to be typically over one hundred feet thick and likely extends into Canada to the north and beneath Drayton Harbor and Birch Bay to the west and southwest where it is eventually truncated by deep channels in the Strait of Georgia (Associated Earth Sciences Inc. (AESI) 2008b). The aquifer appears to be generally located below elevations of approximately -200 to -300 feet within permeable portions of older undifferentiated glacial and nonglacial deposits, and is separated from the ground surface and overlying aquifers by over 100 feet of low permeability Olympia nonglacial sediments.

Subsurface information obtained from oil/gas/coal and water supply exploration wells indicates that near the Nooksack River and the City of Lynden the Blaine Aquifer may be significantly thinner due to the rising elevation of the underlying bedrock surface (GeoEngineers Inc. (GEI) 2001, Associated Earth Sciences Inc. (AESI) 2007a, b, 2008b, 2009a). Several of the City of Blaine production wells are completed in the Blaine Aquifer and several exploration wells completed near the City of Lynden have encountered the deep aquifer (Robinson & Nobel Inc. 1983, Associated Earth Sciences Inc. (AESI) 2007c, 2008a, 2009b). Information presented by GeoEngineers Inc. (GEI) (2001) also indicates that the overlying low permeability Olympia non-glacial sediments may become discontinuous in California, Lower Dakota and Blaine drainages allowing some degree of hydraulic connection between the overlying Sumas-Blaine Aquifer and the deeper Blaine Aquifer.

Groundwater in the Blaine Aquifer is highly confined by the overlying low permeability Olympia nonglacial sediments. Reported aquifer storativity values were generally less than 0.001, indicating confined conditions (Associated Earth Sciences Inc. (AESI) 2008b). Several water supply wells completed in the Blaine Aquifer, located south and southeast of the City of Blaine, are flowing artesian wells. Depths to static water levels in the aquifer typically range from less than 50 feet near Drayton Harbor to over 100 feet near the US/Canadian border. Groundwater in the Blaine Aquifer appears to generally flow toward the southwest in the northwest corner of Whatcom County (Associated Earth Sciences Inc. (AESI) 2008b). The potentiometric surface of the Blaine Aquifer has a relatively consistent hydraulic gradient (slope) of 0.002 (11 feet per mile) in the immediate vicinity of the Boundary Upland area (Associated Earth Sciences Inc. (AESI) 2008b).

Golder (1996) indicates that the primary recharge area for the Blaine Aquifer is likely located in British Columbia. The groundwater flow direction in the Blaine Aquifer also indicates a primary recharge area that is located north of the US/Canadian border. The Blaine Aquifer appears to discharge to seawater (Strait of Georgia) with a lesser amount to deep water supply wells (Associated Earth Sciences Inc. (AESI) 2008b).

Aquifer transmissivity values that were based on relatively long-term aquifer tests in wells completed in the Blaine Aquifer ranged from around 1,000 ft^2/d to roughly 5,000 ft^2/d and are likely most representative of aquifer conditions. Our review of the information compiled for WRIA 1 indicates that a significant volume of groundwater related information is available for the Blaine Aquifer including specific data regarding the regional geologic/hydrogeologic setting of the aquifer, aquifer parameters (hydraulic conductivity, transmissivity, and storage), surface/ground water interaction potential, and groundwater levels.

4.5 Bedrock Aquifers

Most of the eastern half and southwest portions of WRIA 1 is comprised of a complex assemblage of sedimentary, igneous, and metamorphic bedrock that is overlain by a thin layer of sediments. Although the bedrock typically has a generally low permeability, it can yield usable quantities of groundwater in localized areas where secondary fractures have increased the overall permeability of the unit. Our review of the information compiled for WRIA 1 indicates that a small volume of groundwater related information is available for Bedrock Aquifers. The data are generally limited to information presented on regional geologic maps, regional geologic/hydrogeologic studies, and on water well reports for wells completed in the fractured bedrock aquifers.

.

Table 1. WRIA 1 Coastal and Fraser watersheds, aggregated watersheds, management areas, and drainages.

River	2010 Watersheds	Management Area	Drainage			
Coastal	Coastal North	Birch Bay	Cherry Point	Lake Terrell	Fingalson	Semiahmoo
		Drayton Harbor	Blaine	Lower Dakota	North Fork Dakota	South Fork Dakota
			California	Haynie	-	-
	Coastal South	Bellingham Bay	Baker	Fragrance Lake	South Bellingham	Upper Squalicum
			Chuckanut	Lower Squalicum	Spring	Whatcom
			Fort Bellingham	McCormick	Toad	Padden
		Samish Bay	Blanchard	Larrabee	Oyster Creek	Whitehall
			Colony	-	-	-
	Coastal West	Lummi Bay	Jordan	Lummi River Delta	Sandy Point	Schell
			Lummi Peninsula West	Lummi River		
		Lummi Peninsula /Portage Island	Lummi Peninsula East	Portage Island	-	-
		Lummi/Eliza Islands	Lummi Island	Eliza Island	-	-

River	2010 Watersheds	Management Area	Drainage			
Fraser	Sumas	Sumas River	Breckenridge	Johnson	Saar	Swift
			Dale	-	-	-
	Fraser	Fraser River	Chilliwack	Lower Damfino	Upper Silesia	West Fork Liumchen
			Damfino	Lower West Fork Silesia	Upper West Fork Silesia	East Fork Liumchen
			Depot	Middle Fork Silesia	Cultus	-
			East Tributary Silesia	Quartz	Lower Silesia	-
			Ensawkwatch Creek	Tomyhoi	Lower Tomihi	-
		Campbell River	Little Campbell	-	-	-

Table 2. Nooksack Forks watersheds, management areas, and drainages.

River	2010 Watersheds	Management Area	Drainage			
Nooksack River	Nooksack Forks	South Fork Nooksack	Bell	Edfro	Lower Skookum	Upper South Fork Nooksack-East
			Black Slough	Elbow Lake	Lower South Fork Nooksack	Upper South Fork Nooksack-West
			Cavanaugh	Heart Lake Area	Saxon	Wanlick
			Deer, Roaring, & Plumbago	Howard	South Acme Area	-
			Dye	Hutchinson	Upper Skookum Area	-
		Middle Fork Nooksack	Deming Glacier	Heislers	Porter	Sister
			Falls	Lower Clearwater	Rankin	Upper Middle Fork Nooksack
			Galbraith	Lower Middle Fork Nooksack	Ridley	Wallace
			Green	Middle Fork Diversion	Rocky	Warm
		North Fork Nooksack	Anderson/NF Nooksack	Deadhorse	Lower Canyon	Sholes
			Bagley	Dobbs	Lower Deadhorse	Slide Mountain
			Bar	Gallup	Lower Ruth	Swamp
			Barometer	Glacier	Lower Shuksan	Upper Canyon Creek
			Bearpaw Mountain Area	Hamilton	Lower Wells	Upper Glacier
			Bells	Hedrick	Maple	Upper North Fork Nooksack
			Boulder	Jim	Middle North Fork Nooksack	Upper Ruth
			Canyon Lake	Kendall	Price Glacier	Upper Wells
			Clean	Kenny	Racehorse	Whistler
			Coal	Kidney	Roosevelt Glacier	White Salmon
			Cornell	Kulshan	-	-

Table 3. Lake Whatcom and Lower Nooksack watersheds, management areas, and drainages.

River	2010 Watersheds	Management Area	Drainage			
Nooksack River	Lake Whatcom	Lake Whatcom	Academy	Brannian	Geneva	Silver Beach
			Agate Bay	Cable	Hillsdale	Smith/Whatcom
			Anderson/Whatcom	Carpenter	Lake Whatcom (water)	South Bay
			Austin/Beaver	Donavan	North Shore	Strawberry
			Blodel	Eagle Ridge	Olsen	Sudden Valley
			Blue Canyon	Fir	Oriental	Toad
	Lower Nooksack	Lynden North	Bertrand	Fishtrap	Kamm	-
		Lower Mainstem Nooksack	Wiser Lake/Cougar Creek	Nooksack Channel (water)	Schneider	Scott
		Tenmile	Four Mile	Deer	Fazon	-
		Silver/Nooksack Channel & Delta	Nooksack River Delta	Silver	-	-
		Upper Mainstem Nooksack	Lower Anderson	North Fork Anderson	South Fork Anderson	Nooksack Deming to Everson
			Smith	-	-	-

Table 4. Correlation diagram for typical Whatcom County geologic/hydrogeologic units.

Era	Period	Epoch	Geologic Setting	Age[1]	Geologic Units	Hydrostratigraphic Unit	Hydrologic Characteristics
Cenozoic	Quaternary	Holocene	Recent Non-Glacial	<10K	Peat	Surficial Discontinuous and Upper Valley Aquifers	Highly productive unconfined aquifer. Lenses of silt and clay can cause perched groundwater conditions. Lake sediments (lacustrine) that overly the Sumas-Blaine aquifer form a semi-confining unit (aquitard) in the Sumas River Valley.
					Alluvial Fan		
					Landslide		
					Lacustrine	Confining Unit	
					Lahar		
					Alluvium		
		Pleistocene	Sumas Glacial	10K - 11.5K	Glacial Outwash	Sumas-Blaine Aquifer	Highly productive unconfined aquifer. Lenses of silt and clay can cause perched groundwater conditions. The Sumas-Blaine Aquifer is locally confined in much of the Sumas River Valley by overlying lacustrine sediments.
					Lodgement Till	Sumas-Everson Confining Unit	Low permeability glacial till and glaciomarine drift. Contains very little groundwater. Forms an aquitard over older geologic units (Deming Sand and Vashon sediments).
			Everson Non-Glacial	11.5K - 13K	Glaciomarine Drift		
					Submarine Outwash	Discontinuous Aquifers	Localized highly productive aquifer. Referred to as Deming Sand by Easterbrook (1976).
					Glaciomarine Drift	Everson-Vashon Confining Unit	Low permeability glacial till and glaciomarine drift. Contains very little groundwater. Forms an aquitard over older Vashon sediments.
			Vashon Glacial	13K - 18K	Lodgement Till		
					Glacial Outwash	Discontinuous Aquifers	Moderately productive aquifer but generally of limited aerial extent in Whatcom County. Combination of glacial and non-glacial sediments.
			Olympia Non-Glacial	18K - 60K	Coarse-Grained Alluvium		
					Fine-Grained Alluvium	Olympia Confining Unit	Relatively fine-grained non-glacial unit that forms confining layer over older deep regional aquifers.

Table 5. Correlation diagram for typical Whatcom County Geologic/Hydrogeologic Units, continued.

Era	Period	Epoch	Geologic Setting	Age[1]	Geologic Units	Hydrostratigraphic Unit	Hydrologic Characteristics
Cenozoic	Quaternary	Pleistocene	Older Glacial and Non-Glacial Sediments	60K - 2 Million	Till, Glaciomarine Drift, Glaciofluvial and Non-Glacial Deposits	Deep Regional Aquifers	Thick permeable sections of unit form highly productive regional aquifers.
	Tertiary	Pliocene - Paleocene	Bedrock (Huntingdon and Chuckanut Formations)	2 - 65 Million	Sandstone, siltstone, conglomerate and coal	Fractured Bedrock Aquifers and Bedrock Confining Layers	Fracture zones in bedrock form localized relatively low yield aquifers.
Mesozoic - Precambrian	Pre-Tertiary		Bedrock (Multiple Formations)	65 - 570 Million	Sedimentary, Metamorphic and Igneous rocks		

5.0 ELECTRONIC DATA

Electronic Data Tables structure the organization of the *WRIA 1 Groundwater Data Assessment* project deliverables including those containing source data, code, and other intermediary data products and outreach tools to be published on the WRIA 1 Watershed Management Project website.

Electronic Data Table 1. Structure for data organization to be used for online publishing.

Description	Folder & File Name(s)	Spatial Extent	Contract Task
Bibliography by Author last name & by Management Area	WRIA1GW_Chapter1_AppendixA_Bibliography_20130630.docx	WRIA 1	1

6.0 REFERENCES

Aspect Consulting. 2003. Lummi Peninsula Ground Water Investigation.

Aspect Consulting. 2009. Aquifer Study of the Mountain View Upland-Lummi River Area.

Associated Earth Sciences Inc. (AESI). 2007a. Installation and Testing of Production Well PW-5.1, City of Blaine Public Works, Birch Bay Water and Sewer District.

Associated Earth Sciences Inc. (AESI). 2007b. Installation and Testing of Production Well PW-8.1, City of Blaine Public Works, Birch Bay Water and Sewer District.

Associated Earth Sciences Inc. (AESI). 2007c. Irrigation Well Testing DeHaan Property.

Associated Earth Sciences Inc. (AESI). 2008a. Bertrand Creek DeHaan Property and Vicinity.

Associated Earth Sciences Inc. (AESI). 2008b. Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area.

Associated Earth Sciences Inc. (AESI). 2009a. ASR Feasibility Assessment/Installation and Testing of Exploration Well OW-1.

Associated Earth Sciences Inc. (AESI). 2009b. Stream Flow Augmentation Well DeHaan Property.

Barber, M., and J. Wu. 2008. Groundwater Investigations of Bertrand and Tenmile Watersheds.

Cox, S. E., and S. C. Kahle. 1999. Hydrogeology, Ground-Water Quality, and Sources of Nitrate in Low-Land Glacial Aquifers of Whatcom County, Washington and British Columbia, Canada Plate No. 2. U.S. Geological Survey / Whatcom County Planning Department.

Culhane, T. 1993. Whatcom County Hydraulic Continuity Investigtion part 1 Critical Well Stream Separation Distances for Minimizing Stream Depletion. OFTR-93-8.

Earth Tech (Canada) Inc. 2001. Hazelmere Agricultural Servicing Study, City of Blaine.

Easterbrook, D. J. 1963. Late Pleistocene Glacial Events and Relative Sea Level Changes in the Northern Puget Lowland, Washington Geological Society of America.

Easterbrook, D. J. 1976. Geologic Map of Western Whatcom County, Washington. United States Geological Survey

Easterbrook, D. J. 1992. Advance and Retreat of Cordilleran Ice Sheets in Washington. Geographie physique et quarternaire **46**:51-68.

GeoEngineers Inc. (GEI). 2001. Hydrogeologic Services Installation and Testing of Production Well No. 2, Birch Bay, Washington.

Greenberg, J., K. Welch, M. Neuman, P. Willing, and M. Barclay. 1996. Catalogue of Existing Information on Water Resources and Fisheries in the Nooksack Basin, a report to the Nooksack Basin Water Users Steering Committee and the Washington Department of Ecology. Bellingham, WA.

Halstead, E. C. 1986. Groundwater Supply-Fraser Lowland, British Columbia. Inland Waters Directorate, Environmental Canada.

Kemblowski, M., T. Asefa, and S. Haile-Selassje. 2001. Groundwater Quantity Report for WRIA 1, Phase II.

Kovanen, D., and O. Slaymaker. 2003. Lake Terrell Upland Glacial Resurgences and Implications for Late-glacial History, Northwestern Washington State. Canadian Journal of Earth Sciences 40:1767-1772.

Lapen, T. J. 2000. Geologic Map of the Bellingham 1:100,000 quadrangle, Washington. Washington Division of Geology and Earth Resources

Mitchell, D. R., and D. S. Babcock. 2000. Abbotsford-Sumas Aquifer Monitoring Project Final Report. Western Washington University.

Newcomb, Scevan, and Strome. 1949. Groundwater Resources, Western Whatcom County, Washington. Page 134. U.S. Geological Survey

Nooksack Basin Ground Water Quantity Study Group. 2000. Nooksack Basin: Ground-Water Quantity Study Group -Summary- Preliminary Data Review.

Pacific Ground Water Group. 1995. Results of Hydrogeologic Investigations for Deer Creek Water Association, Whatcom County, Washington.

Pruneda, E. B. 2007. Use of Stream Response Functions and Stella Software to Determine Impacts of Replacing Surface Water Diversions with Groundwater Pumping Withdrawals on Instream Flows within the Bertrand Creek and Fishtrap Creek Watersheds, Washington State, USA. Washington State University, Washington State University.

Robinson & Nobel Inc. 1983. City of Lynden Water System Plan, Groundwater Feasibility Study for the City of Lynden.

Scibek, A. 2005. Numerical Groundwater Flow Model of the Abbotsford-Sumas Aquifer, Central Fraser Lowland of BC, Canada and Washington State USA.

Tooley, J., and D. Erickson. 1996. Nooksack Watershed Surficial Aquifer Characterization.*in* Washington State Department of Ecology, editor. Washington State Department of Ecology,.

Washington State Department of Conservation. 1960. Water Resources of the Nooksack River Basin and Certain Adjacent Streams Maps.*in* W. R. Division, editor.

Whatcom County Planning and Development Services. 2011. 2010 State of the Watershed Report.

Chapter 2 Groundwater Data and Data Gaps

WRIA 1 Groundwater Assessment
June 2013

An interdisciplinary team of water resource technical specialists worked with the WRIA 1 Joint Board Staff Team to compile existing technical models, studies, and data into an assessment of groundwater in WRIA 1. For a complete list of contributors, see *Chapter 4 - Recommendations for Data Collection and Model Integration* In Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data and Model Assessment, Whatcom County PUD #1, Whatcom County, WA: WRIA 1 Joint Board.

Technical reviewers: Jeremy Freimund, Lummi Nation Natural Resources, Kasey Cykler, Washington State Dept. of Ecology. See also List of Contributors, *Chapter 4* Section 4.0.

Please cite this Chapter as:
Print Citation: Bandaragoda, C. and C. Lindsay (2013). Groundwater Data and Data Gaps. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board.

Online Citation: Bandaragoda, C. and C. Lindsay (2013). Groundwater Data and Data Gaps. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board. Retrieved [Date], from http://wria1project.whatcomcounty.org/.

This work was funded by the WRIA 1 Joint Board and managed by Whatcom County PUD #1 and funded by Department of Ecology Grant No 1200070 Task 9 Groundwater Study; June 2013.

CHAPTER 2
Groundwater Data and Data Gaps

Table of Contents

List of Figures

List of Tables

1.0 OVERVIEW

The purpose of this chapter is to summarize and describe data, including limitations and gaps. In order to accomplish the technical work necessary to summarize data gaps the project team needed first to compile and catalogue all available groundwater data for WRIA 1 in order to understand what data sets are available regarding groundwater properties, for which locations in WRIA 1, and what specific components were collected. This compilation effort is further described in *Chapter 1 Understanding WRIA 1 Aquifers*. The resulting catalogue of nearly 250 entries, was then used to prepare the description on the spatial distribution of various types of studies including regional, drainage, and site scale studies and numerical model reports using a series of maps to summarize the types of studies and data that are available for the aquifers located in the WRIA 1 drainages.

By mapping the various types of data available in the reference database of more than 250 reference citations, both data types and geographic locations are represented on the maps. Data gaps are illustrated in the absence of data or where there is lower density data. This chapter may best be used as an orientation tool to the citation database (See Bibliography Appendix or Chapter 1 Digital Appendix Table for more information) and updated groundwater databases containing well data collected by various agencies operating in WRIA 1.

Further improvements to groundwater information and integration with other WRIA 1 technical tools requires knowing what kind of data is available and where the data gaps are geographically and what the data gaps are for different types of data.

2.0 DATABASE ORGANIZATION

The available geologic/hydrogeologic information has been compiled into a database that allows citations to be organized based on aquifer type (Sumas-Blaine, Discontinuous, Upper Valley, Deep Regional and Bedrock), citation type (Regional Study, Regional Scale Numerical Model, Drainage Study, Drainage Scale Numerical Model, and Site Specific Study) and by drainage location.

For example, the database can be used to determine what deep regional aquifer data are available in a particular drainage or which specific drainages are covered by regional studies, numerical models and/or site specific studies. The database (See Access database, Digital Appendix Table 1) has also been designed to determine what areas are covered by little to no data thus identifying data gaps.

The first effort to organize WRIA 1 groundwater resources included the Catalogue of Existing Information on Water Resources and Fisheries in the Nooksack Basin, a report to the Nooksack Basin Water Users Steering Committee and the Washington Department of Ecology (Greenberg et al. 1996). The update to this 1996 data assessment effort took place in 2000 by the United States Geological Survey (Pruneda 2007).This project builds on the previous work by using Endnote^{TM} citation database software to catalogue both reference information and datasets, as well as providing a clear link from the ArcGIS and Access databases to the original sources of information. As a result, the existing groundwater databases previously developed by agencies within WRIA 1 are updated into one comprehensive database system.

When building the citation database, five citation types were noted and catalogued by both management area and drainage: Regional Study, Regional Scale Numerical Model, Drainage Study, Drainage Scale Numerical Model, and Site Specific Study. Information regarding 12 datasets that were considered to be critical to the development of a groundwater flow model were also noted, catalogued, and cross referenced by citation type, management area and drainage in the database. These critical datasets included: aquifer testing, hydraulic conductivity, transmissivity, aquifer thickness, aquifer storage, water level monitoring, geophysical, groundwater flow direction, groundwater seepage, hydraulic gradient, streambed conductance, and groundwater recharge/discharge.

The result is a database that can quickly and easily be used to evaluate the relative amount of specific groundwater related information that is available in any single drainage or management area located in WRIA 1. For example, the database can be searched to determine how many site-specific studies have been completed that include aquifer testing information and aquifer transmissivity values for the Sumas-Blaine aquifer in the Kamm Ditch drainage. The database can also be searched to see what regional numerical groundwater flow models have been developed in the WRIA, as displayed on Figure 1. Furthermore, because the database is linked to Endnote™, the searcher can also quickly find the proper citation of each identified reference and in most cases a complete pdf copy of the document. Conversely, the database can be used to identify specific drainages or management areas in WRIA 1 where little or no published information is available (i.e., data gaps) regarding specific aquifer parameters or characteristics, these areas are left blank in **Figure 1**.

The following sections of this chapter were prepared to illustrate the usefulness of the database for indentifying areas with data as well as areas with limited or no data (data gaps) for several of the identified critical groundwater datasets such as aquifer type, aquifer thickness, groundwater level monitoring, and specific aquifer parameters (transmissivity, hydraulic conductivity and storage). Because well logs were not historically required, well counts and maps are not compete data sets for existing wells in WRIA 1.

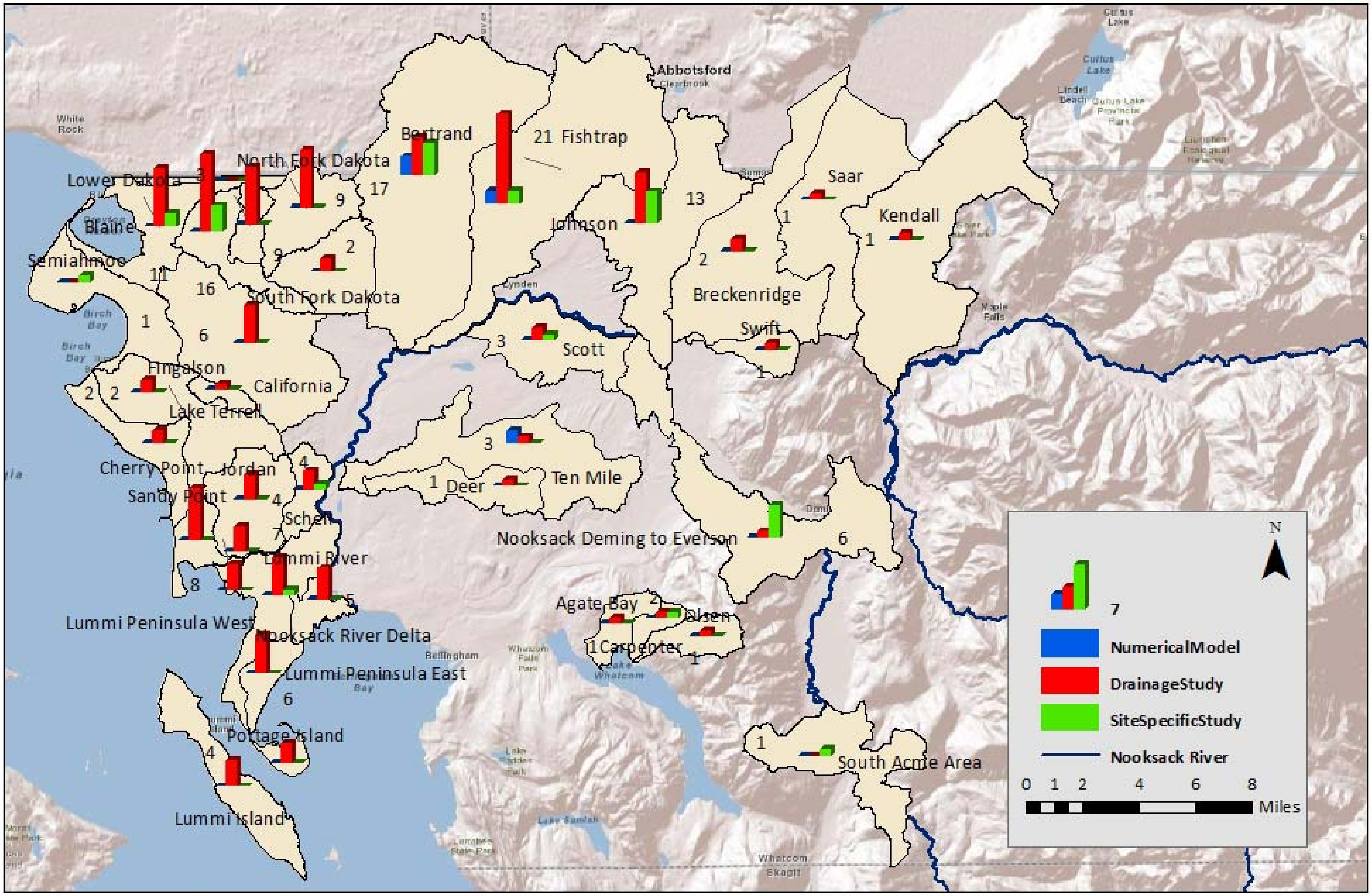


Figure 1. Number of relevant groundwater studies per drainage, with scale showing number of drainage models, drainage studies, and site studies.

3.0 GROUNDWATER DATA SOURCES

3.1 United States Geologic Survey (USGS)

A request was submitted for USGS well data available since 1998 for WRIA 1, which required a customized extraction from the USGS database. This component of the groundwater data compilation work resulted in additional datasets for 2,510 wells with surface elevation data, 278 of which have a depth to water level and corresponding date. Of the wells with water level information, 254 are wells drilled by the USGS and they are the source agency for the data. The remainder of the well information was provided from drillers logs. E-tape was used for 183 of the well measurements, the remainder of the wells used various other method of measurement.

3.2 Washington Department of Ecology

Although water level data are not a component of the reported Washington Department of Ecology (ECY) data[1] there are 20,907 well records from 1937-2013 with well depth and well type information. The complete dataset was downloaded and integrated into the database compiled in this project (See Electronic Appendix). Of the 20,907 well records, 1,757 are missing well completion date. There are three types of wells recorded in this database: Abandonment (wells not in use), Resource Protection, and Water (Table 1). These are shown in Figure 2, where abandoned wells are shown in red, resource protection wells are shown in green, and water wells are shown in blue. Approximately 50% of Ecology wells are for water, the majority of which were completed before 1973. The majority of the nearly 6,000 resource protection wells were installed after 1981 (Figure 3).

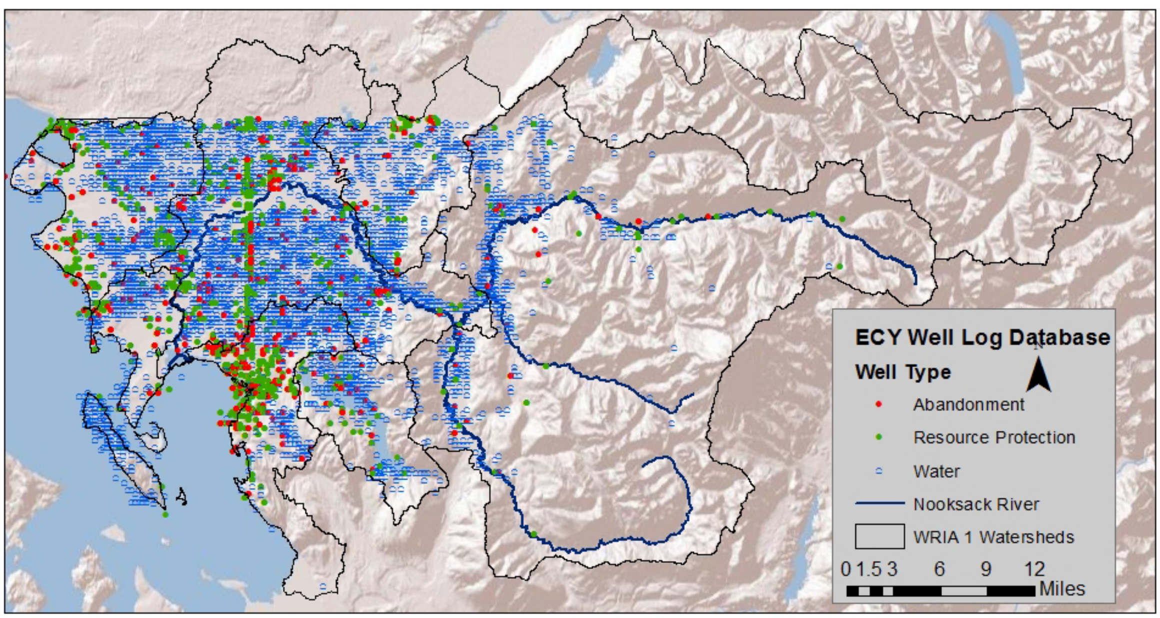


Figure 2. Well type for Department of Ecology well records ranging from 1937-2013.

[1] http://apps.ecy.wa.gov/welllog/ Search criteria used: County: Whatcom, WRIA Name: Nooksack

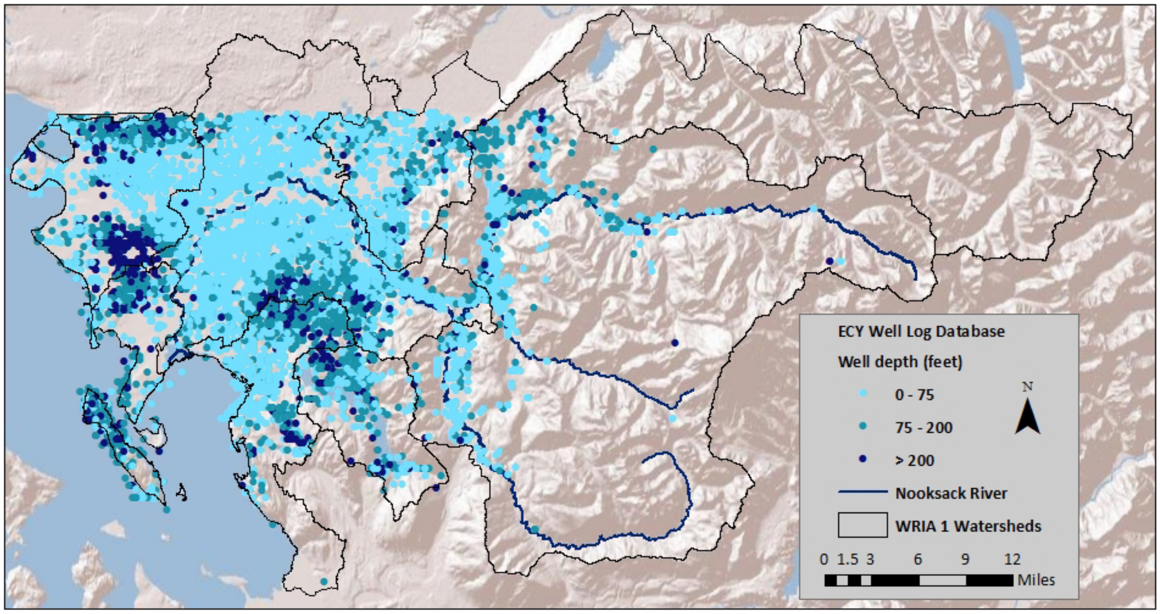


Table 1. Department of Ecology WRIA 1 count of well types.

Well Type	Number of Records	Date Range
Abandonment	4,428	1970-2008
Resource protection	5,892	One in 1938; 1981-2013
Water	10,587	1937-2013

In Figure 3, the approximate depths of the wells obtained from the Ecology database are displayed in shades of blue with light blue corresponding to wells less than 76 feet in depth, blue for wells greater than 75 feet but less than 201 feet in depth and dark blue representing wells greater than 200 feet in depth. The shallow wells are likely completed within surficial aquifers and their distribution (Figure 2) generally corresponds to the boundaries of the surficial Sumas-Blaine and Upper Valley Aquifers shown on Figure 3, *Chapter 1*. Likewise the distribution of the intermediate depth (blue) and deeper wells (dark blue) shown on Figure 3 generally corresponds with the locations of the Discontinuous and Deep Regional Aquifers discussed in Chapter 1.

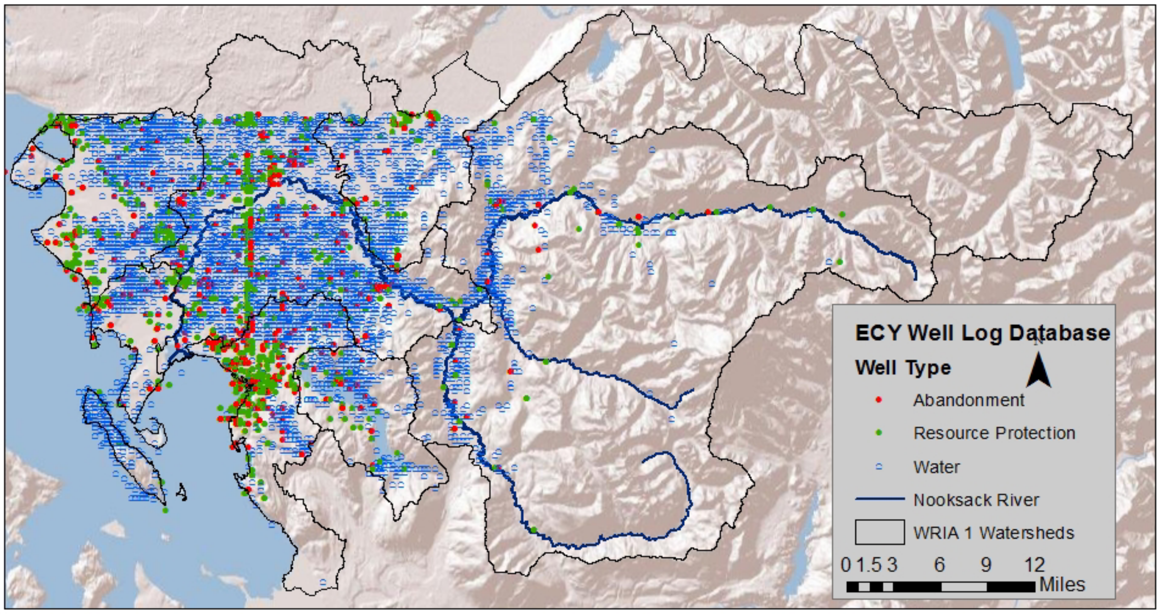


Figure 2. Well type for Department of Ecology well records ranging from 1937-2013.

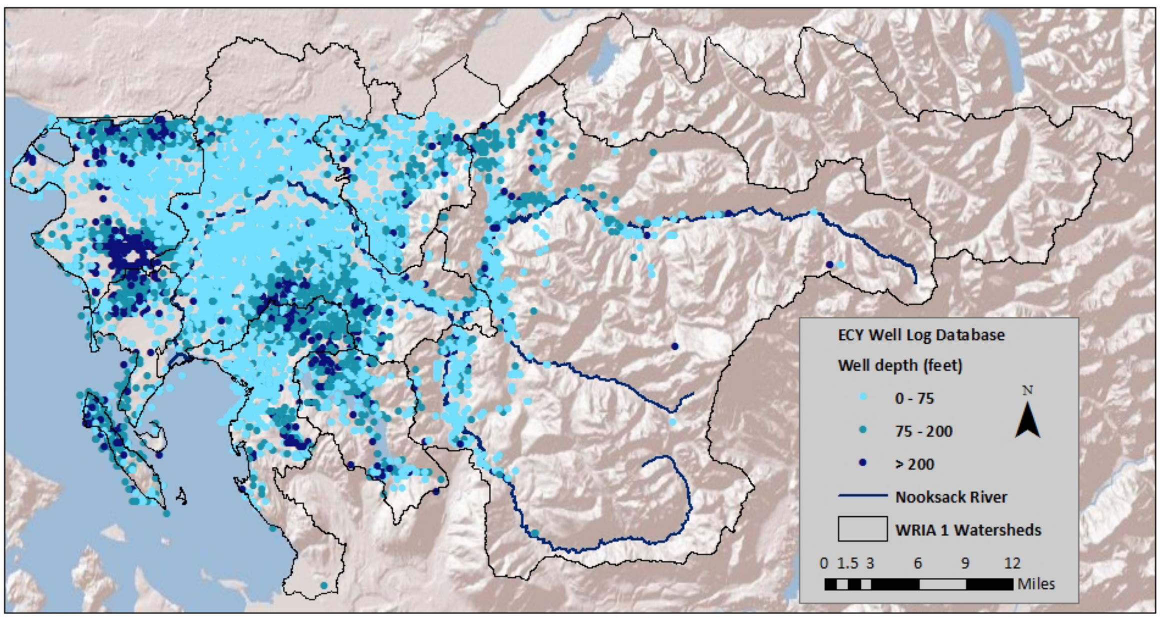


Figure 3. Well depth for Department of Ecology well records ranging from 1937-2013.

3.3 Washington Department of Health

Based on the existing WRIA 1 well log database (ranging in dates from 1954-10/31/2000) of 6,582 well logs with reported static water level, 2,039 are Washington Department of Health (DOH) well locations, 160 of which have ground surface elevation information which allows for the determination of groundwater elevation in the well. It is unknown if the surface elevation data and location were surveyed or mapped by hand, or reported by other means in the individual well reports. Based on personal communications with DOH staff the static water levels for these DOH wells were digitized under contract with Whatcom County in 2000 (Derek Pell, Planning and Engineering manager at Northwest Regional office, derek.pell@doh.wa.gov and Kyle Dodd, Whatcom County Planning and Development Services, kdodd@whatcomcounty.us). Static water level from all wells resulting from the 2000 effort are discussed in Section 4.3 Water Level. Static water level is not a required data input managed by DOH, although individual records could be surveyed, digitized, and integrated into the existing WRIA 1 database in future work. Since 2000, no additional DOH static water level data have been compiled and made availablein WRIA 1.

3.4 Existing Combined Well Log Database 1954-2001

The existing WRIA 1 well log database (1954-2001) was developed in 2000 as described in 3.3 above. The most useful data from this dataset are the 183 wells which include both static water level and ground surface elevation (Table 2). In future work, the surface elevation of wells without surveyed surface elevation data could be estimated using digital elevation models. The difference between the surface elevation and the static water level gives the depth to water, which is potentially useful data, especially in the low flow months Table 3. There are a combined number of well records from USGS, Ecology and Whatcom County (WC) Health for low flow months totaling 1,478 (Table 3, Monthly Totals: August=585; September=432; October=461). Data with both static and surface elevation in the low flow months (Aug-Oct) include only 45 WC Health wells ranging in date from 1977-2000, these are totaled by drainage and shown in Figure 5. Drainages with well data that could be used as point locations and times to verify depth to water table are shown colored by the count of wells within each drainage.

Table 2. Count of well data for various sources for the 1953-2000 database.

	Well (count) Data		
	Static Level	Surface Elevation	Date
Ecology	161	0	161
USGS Historic	3,927	0	3,927
WC Health	2,494	183	2,039
Total	**6,582**	**183**	**6,127**

Table 3. Count of well data by month of completion and source for the 1953-2000 database.

Month	Ecology Scanned	USGS Historic	WC Health	Total
January	6	442	93	541
February	5	230	129	364
March	21	314	187	522
April	13	328	218	559
May	15	354	171	540
June	18	471	238	727
July	17	420	209	646
August	13	381	191	585
September	12	232	188	432
October	22	272	167	461
November	10	221	136	367
December	9	180	112	301

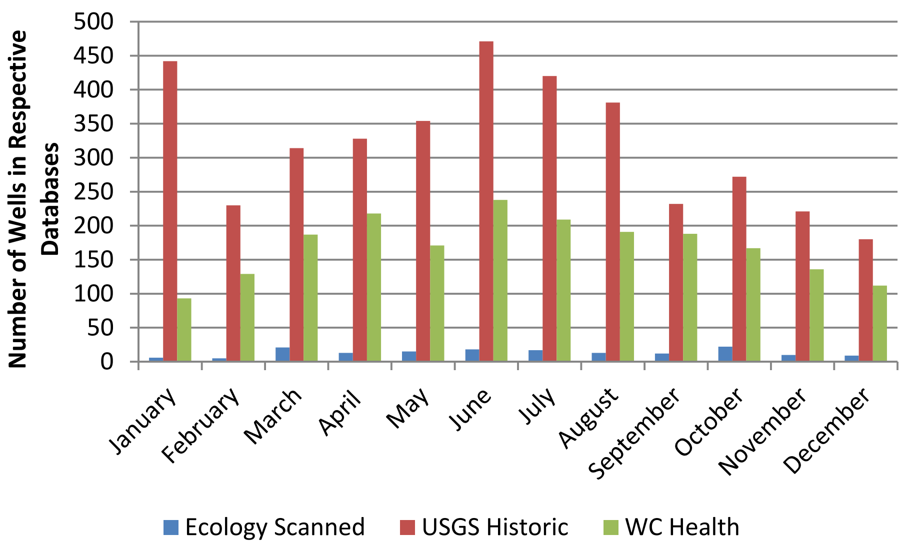


Figure 4. Count of well data based on month of completion for three databases (1953-2000).

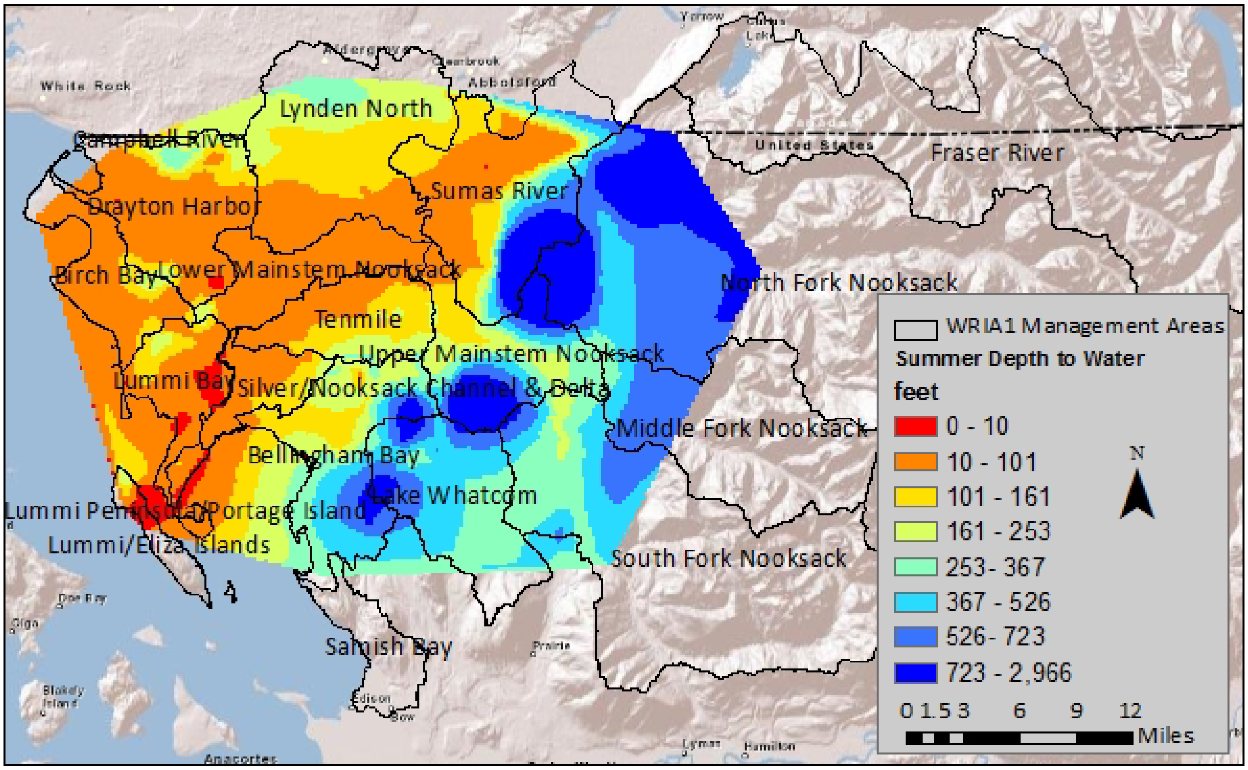


Figure 5. Summer month (July, Aug, Sept) water table elevation measured on well completion date (Ecology wells).

4.0 GROUNDWATER PROPERTIES

4.1 Aquifer Boundaries

As discussed in *Chapter 1*, Tooley and Erickson (1996) divided the surficial groundwater systems located in WRIA 1 into three aquifer units that included the Sumas-Blaine Aquifer, Upper Valley Aquifers, and Discontinuous Surficial Aquifers. It should be noted that several subsequent technical reports have adopted the Tooley and Erickson system when describing surficial aquifers in WRIA 1. Because our evaluation included surficial as well as significant deeper aquifers, we expanded the Tooley and Erickson groupings to include Deep Regional and Bedrock Aquifers, and we re-named the Discontinuous Surficial Aquifer unit as simply Discontinuous Aquifers, which includes the shallow aquifers designated by Tooley and Erickson and deeper non-surficial, discontinuous aquifers. The approximate geographic distribution of the five aquifer units are shown on Figure 6.

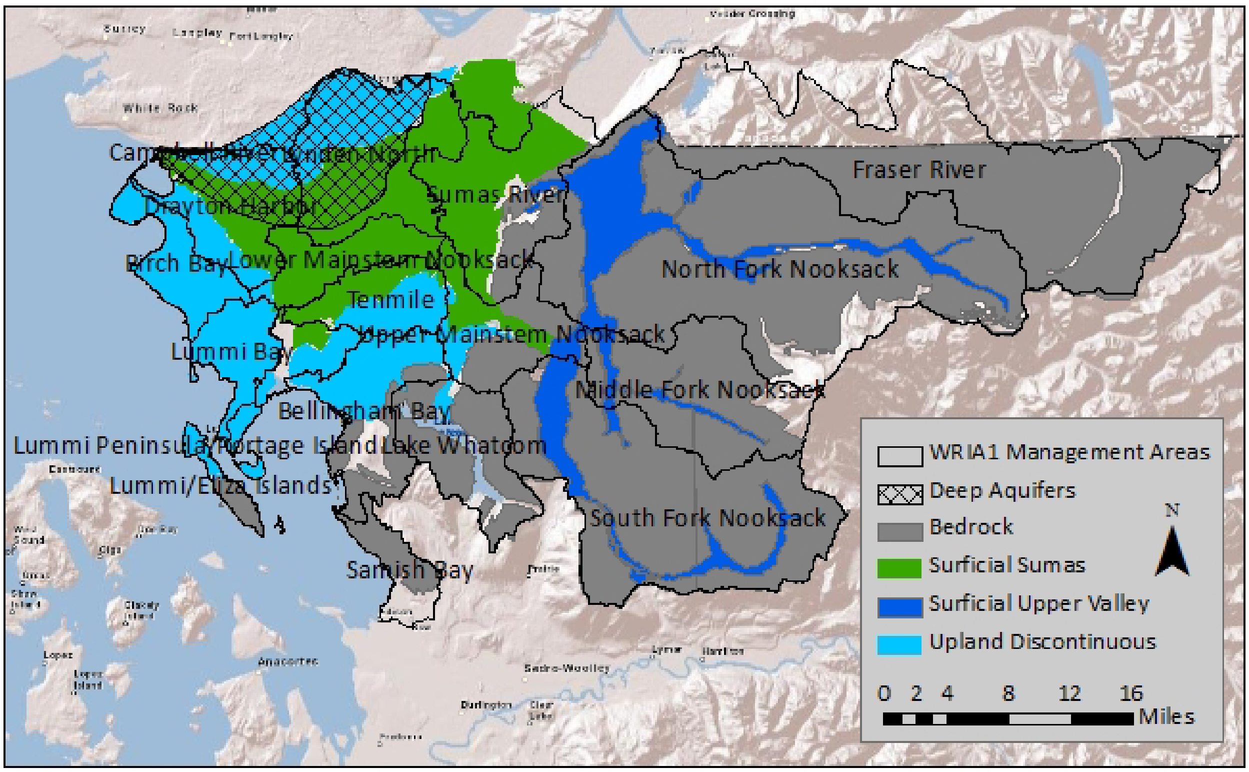


Figure 6. WRIA 1 Primary aquifer approximate boundaries.

4.2 Thickness

Aquifer thickness is a critical input to a groundwater flow model. A search of the citation database indicates that a significant volume of information is available regarding the thickness of aquifers located in the Drayton Harbor, Lynden North, Sumas and LowerMainstem Nooksack Management Areas as shown on Figure 7. Additional information regarding aquifer thickness is also available in several other drainages (Figure 7). However, the citation database also indicates that there are limited to no data regarding aquifer thickness for the majority of the WRIA.

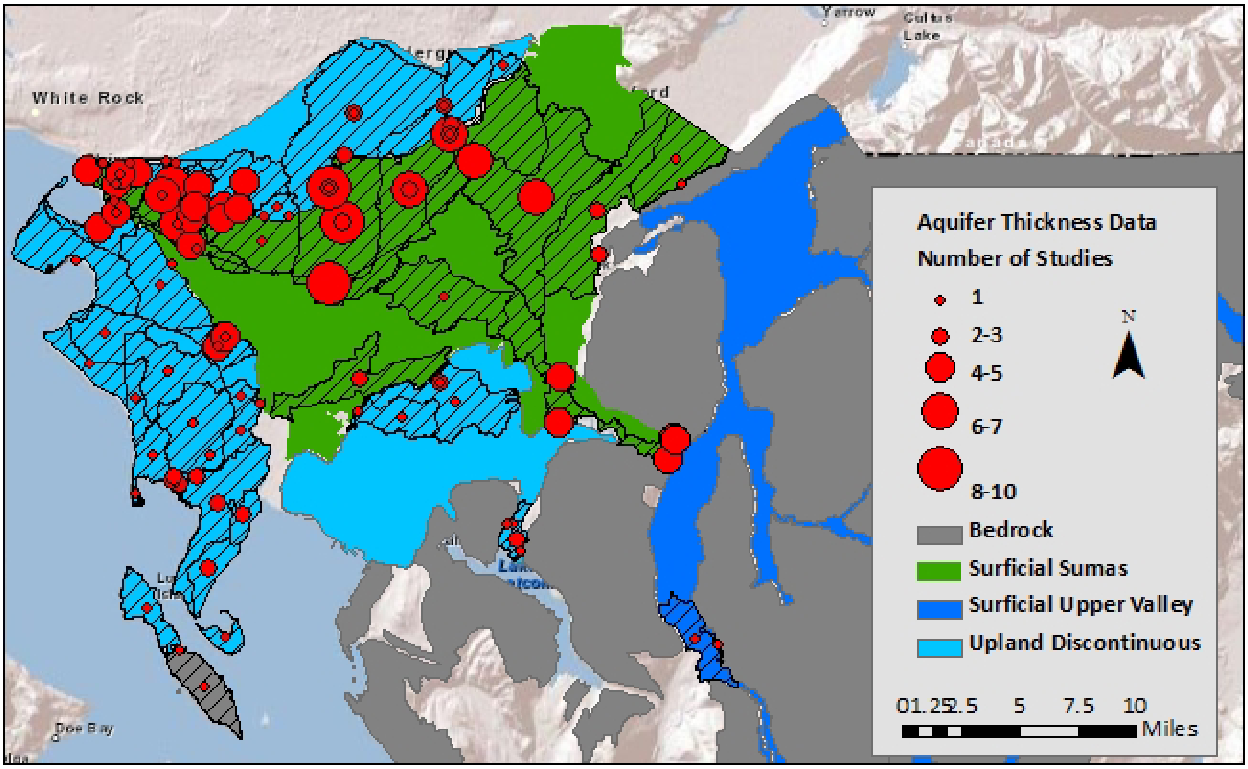


Figure 7. WRIA 1 Areas with aquifer thickness information.

4.3 Groundwater Level

Reliable single-event (synoptic) and time-series groundwater monitoring data are important to the development of a groundwater flow model primarily because they can be used as calibration points for the model. The overall reliability of a groundwater model can be increased if the model is calibrated to a large number of these water level measurements that are geographically distributed across the model domain.

A search of the citation database indicates that there is a significant amount of synoptic and some time-series groundwater level monitoring data available in selected portions of WRIA 1 (Figure 8). However, little water level data appears to be available for most of WRIA 1.

Contour maps of groundwater head values and flow directions have been developed for selected areas and aquifers located in WRIA 1 by various public agencies and private sector groups as shown on Figures 9, 10 and 11 (Cox and Kahle 1999, Associated Earth Sciences Inc. (AESI) 2008, Aspect Consulting 2009b). The information presented in these contour maps can be compared to groundwater head values and flow directions estimated by a regional groundwater model.

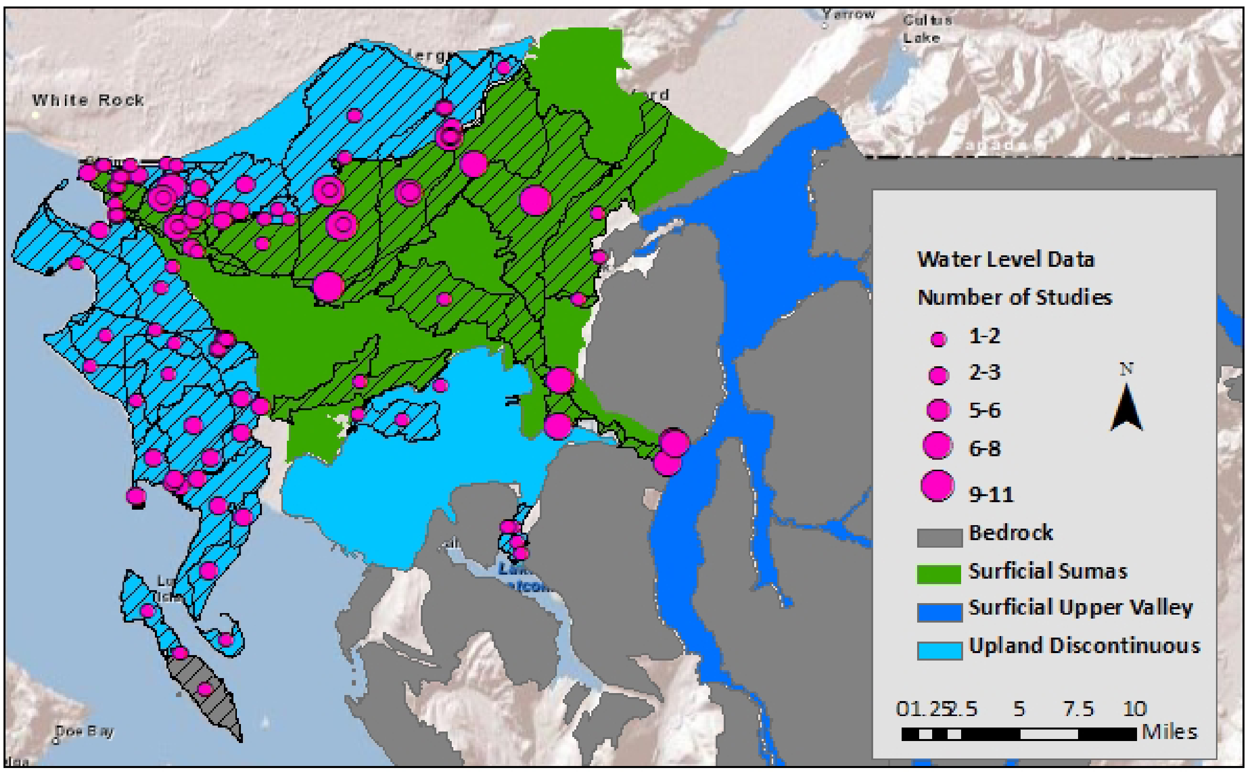


Figure 8. WRIA 1 Areas with water level information.

4.4 Aquifer Transmissivity

Aquifer transmissivity is a measure of the amount of water that can be transmitted horizontally by the full-saturated thickness of the aquifer under a hydraulic gradient (slope) of 1. Aquifer transmissivity can be highly variable over relatively short distances. Aquifer transmissivity is best estimated from site-specific, detailed aquifer tests and is a critical input parameter to a groundwater flow model. Therefore, identifying specific locations where aquifer transmissivity values have been determined is essential to the development of a robust groundwater flow model.

The citation database has been used to develop summary estimates of the number of studies that contain information regarding aquifer transmissivity and the geographic distribution of those studies. The general distribution of the aquifer transmissivity data contained in the database is shown on Figure 9. The distribution of the data clearly indicates that most of the information regarding aquifer transmissivity is in the northwestern portion of the WRIA, generally north of the Nooksack River (Figure 9).

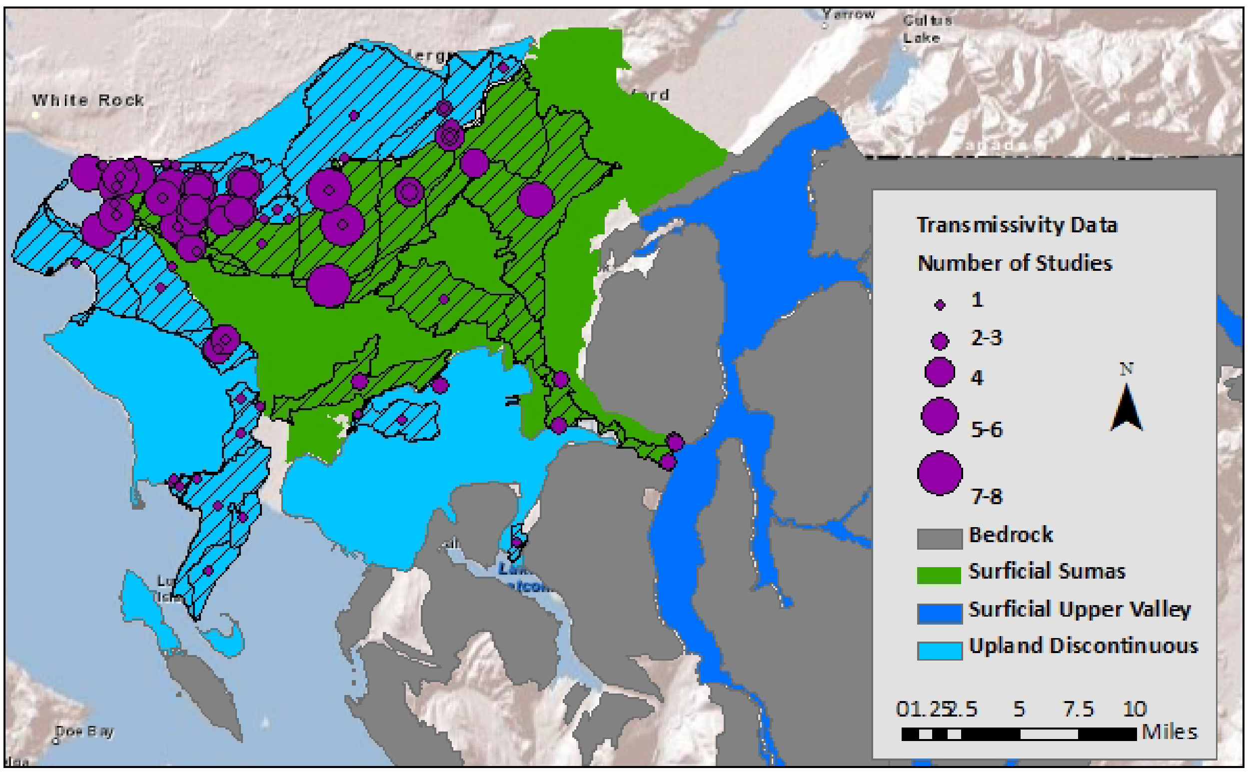


Figure 9. WRIA 1 Locations with aquifer transmissivity data.

4.5 Aquifer Storage

Aquifer storage in a confined aquifer is termed 'specific storage'. Specific storage is the amount of water per unit volume of a saturated formation that is expelled from storage as a result of compression of the confined aquifer and expansion of water when the aquifer is pumped. Specific storage is dimensionless and for confined aquifers generally ranges from highly confined conditions ($<10^{-5}$) to semi-confined conditions ($>10^{-3}$).

Water storage in unconfined aquifers is typically referred to as specific yield. Unconfined aquifers release water from storage by the mechanism of actually draining the pores of the aquifer, which can result in the release of relatively large amounts of water (up to the drainable porosity of the aquifer material, or the minimum volumetric water content).

Aquifer storage is best estimated from site-specific, detailed aquifer tests and is a critical input parameter in transient groundwater flow models. Therefore, identifying specific locations where aquifer storage values have been determined is essential to the development of a groundwater flow model.

The citation database has been used to develop a summary estimate of the number of studies that contain information regarding aquifer storage and the geographic distribution of those studies. A graphical display of the aquifer storage data contained in the database is shown on Figure 13. The distribution of the data clearly indicates that most of the available information regarding aquifer storage is in the northwestern portion of the WRIA, generally north of the Nooksack River (Figure 12).

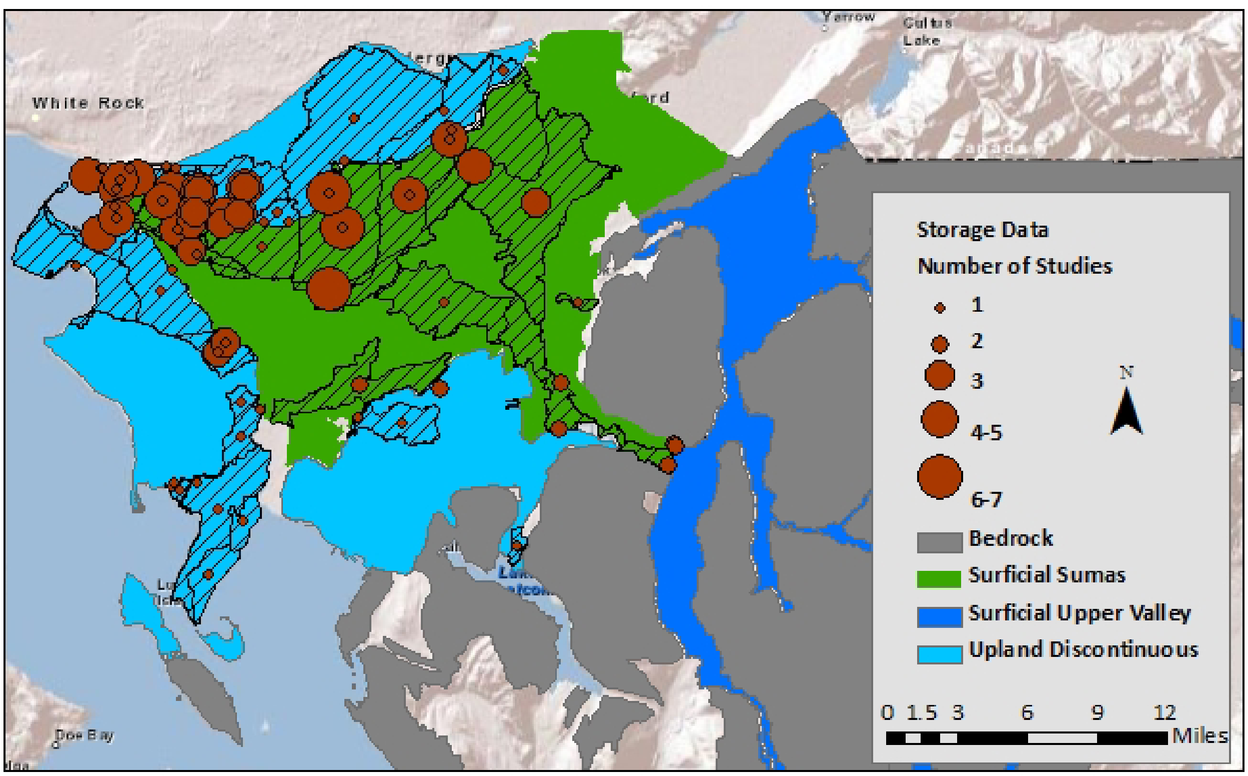


Figure 10. WRIA 1 Areas with aquifer storage data.

4.6 Aquifer Hydraulic Conductivity

Aquifer hydraulic conductivity is a measure of the rate at which water can move through an aquifer and is equal to the transmissivity divided by the saturated thickness of the unit. Aquifer hydraulic conductivity can be highly variable over relatively short distances. Hydraulic conductivity is best estimated from site-specific, detailed aquifer tests and is a critical input parameter to groundwater flow models. Therefore, identifying specific locations where aquifer hydraulic conductivity values have been determined is essential to the development of a groundwater flow model for WRIA 1.

Output from the citation database (Figure 14) shows the geographical distribution of studies that contain hydraulic conductivity values. The studies clearly indicate that most of the data regarding aquifer hydraulic conductivity is in the western portion of the WRIA, along and north of the Nooksack River as well as adjacent to the Canadian Border (Figure 11).

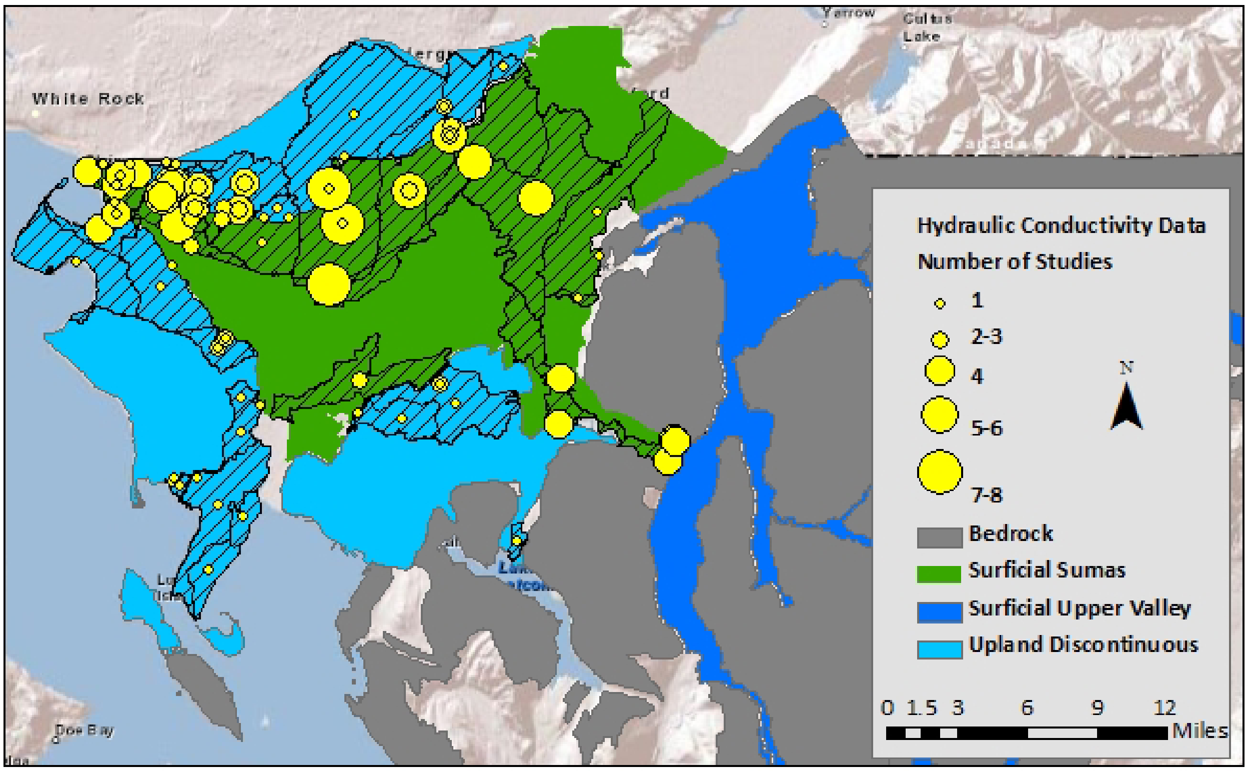


Figure 11. WRIA 1 Areas with hydraulic conductivitiy data (not including SSURGO and STATSGO surface hydraulic conductivity).

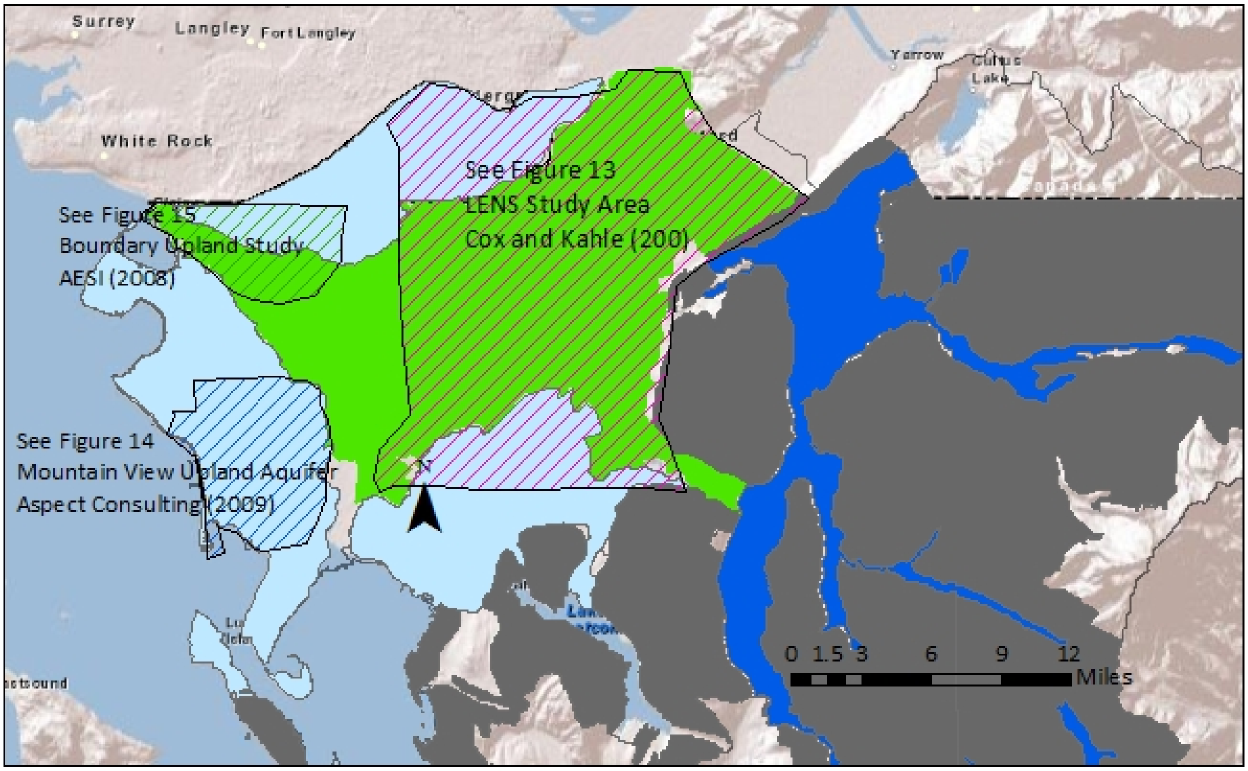


Figure 12. WRIA 1 Water contour study areas (see following three figures for map detail).

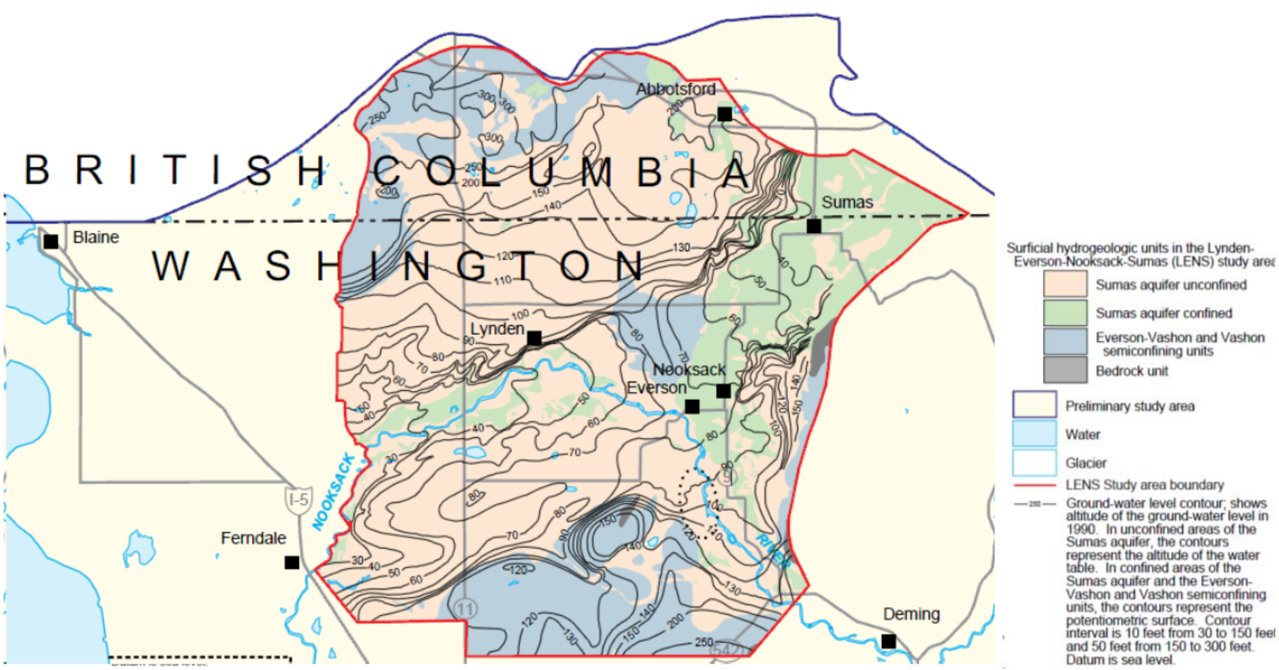


Figure 13. Water level contour map of Sumas-Blaine aquifer taken directly from Cox and Kahle (2000).

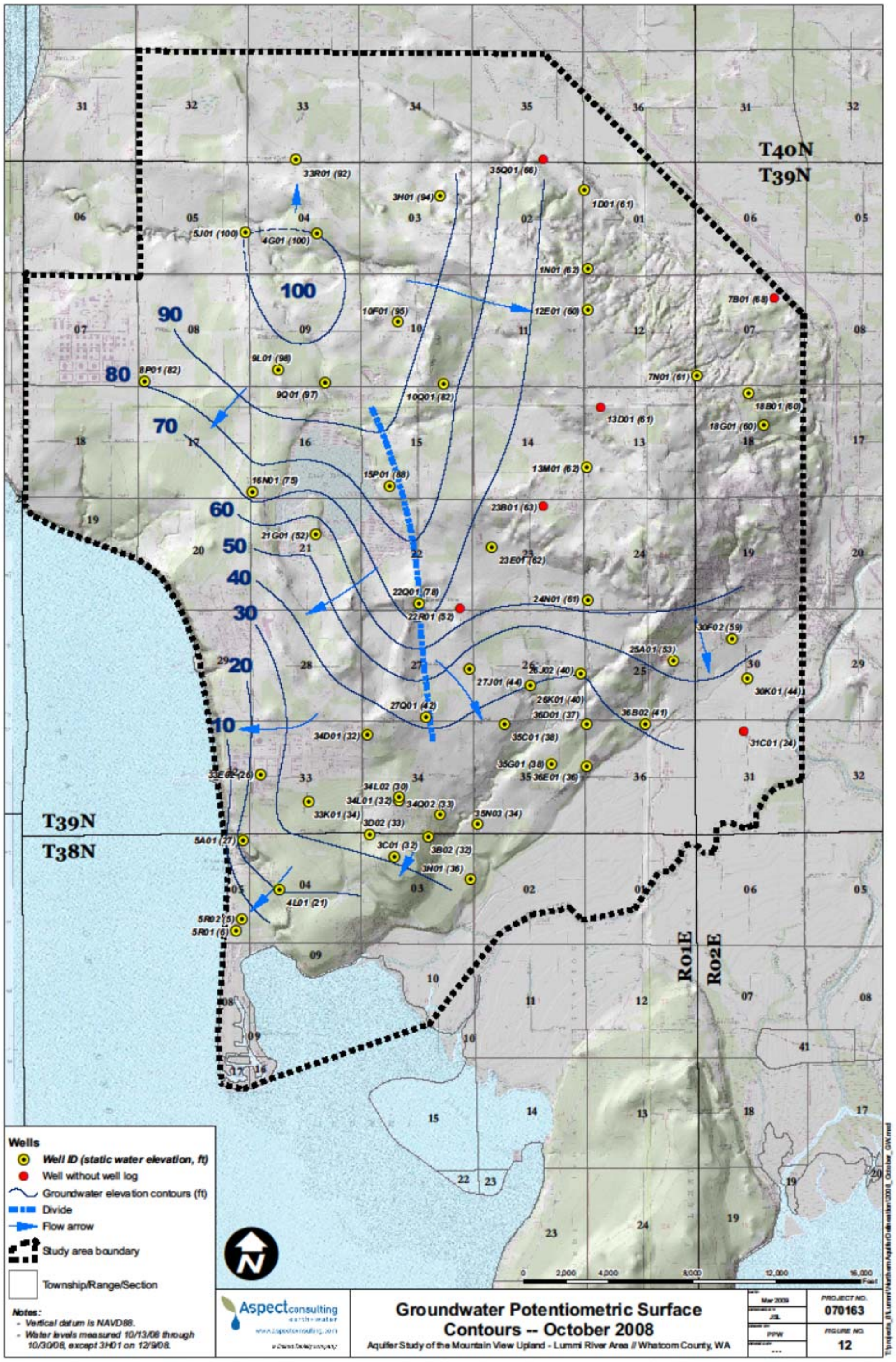


Figure 14. Water level contour map of Mountain View Upland aquifer. Insert taken directly from the Aquifer Study of the Mountain View Upland, Lummi River Area, Whatcom County, WA, Figure 12 (Aspect Consulting 2009a).

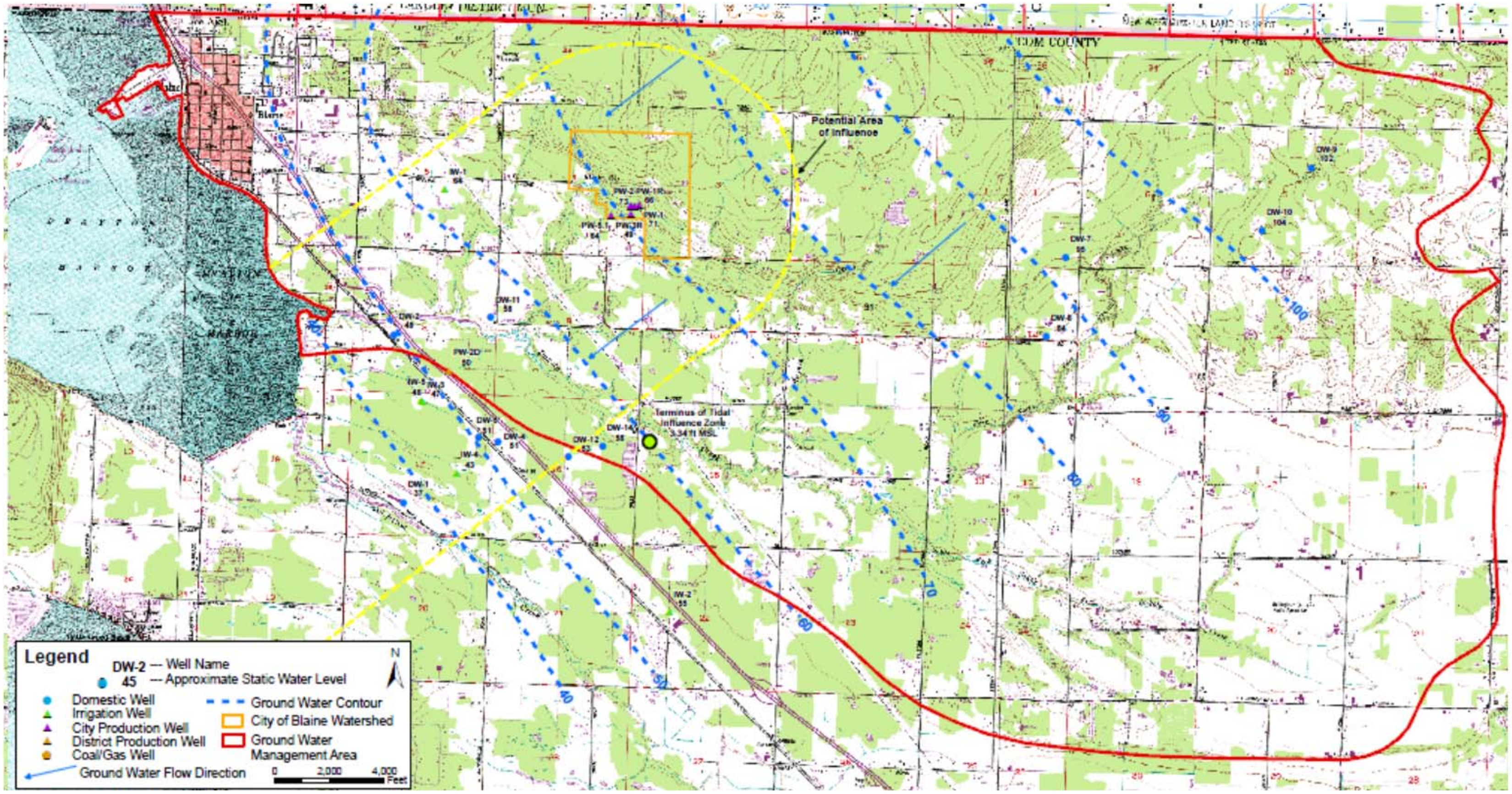


Figure 15. Water level contour map of a deep regional aquifer located beneath the Boundary Upland, taken directly from AESI (2008).

5.0 SUMMARY OF DATA GAPS

Table 4 summarizes the data available from the available studies in the assembled Endnote™ database that can be critical for the development of a groundwater flow model. The number of studies containing the data inputs for a drainage scale model are available for 20 of the 172 drainages located in WRIA 1. Five of the drainages listed in Table 4 (Bertrand, Fishtrap, Johnson, Lower Dakota and Nooksack to Deming) have a significant number of technical studies with very useful data. Fewer studies have been completed for the remaining 15 drainages. A substantial number of publications are available regarding regional or general studies for WRIA 1 that contain data useful for populating a regional groundwater model. (Table 4).

In Table 5, the sample groundwater use statements provide a snapshot of possible future uses of groundwater data and technical modeling information. Table 5 summarizes the relationships between key groundwater resource management questions and the types of data required to inform these issues in WRIA 1 by outlining the data requirements required for both: (a) groundwater model development and (b) the level of reliability required to answer select questions at different scales: site or sub-drainage, drainage, or regional. Data gaps identified by the project team are noted in *Chapter 2* along with a summary of existing sources of groundwater datasets compiled for WRIA 1. Input provided by technical reviewers indicate that improved understanding of the cumulative effects of groundwater pumping on surface water is a priority area for future improvements to groundwater knowledge and technical resources for WRIA 1. This will require a highly reliable model that depends on data collection and model improvements at site or sub-drainage scales, including addressing data gaps for the sources of water used in WRIA 1 (*Chapter 3* describes the data gaps in surface and groundwater use information), which is discussed further in *Chapter 4 Recommendations* along with an explanation of the technical review process used in this project.

Chapter 4 outlines recommendations for integrated ground and surface water modeling and presents options from which to select a path forward working with available resources and tools. Because data collection can be costly and time consuming, a pilot study is recommended as a way to begin to build a groundwater model that will achieve the desired goals. WRIA 1 Joint Board Staff Team will need to select drainage(s) and a sub drainage or site specific location as a starting point. The data collection can ensue for the area upstream and upgradient of the site specific location. A drainage scale groundwater model can begin to be assembled with the current data and refined at the subdrainage scale as data collected becomes available.

Table 4. Summary table of the number of studies containing drainage specific data for populating a groundwater model.

	Aquifer Testing	Hydraulic Conductivity	Transmissivity	Aquifer Thickness	Aquifer Storage	Water Level Data	Geophysical Analysis	GW Flow Direction	Seepage Analysis	Hydraulic Gradient	Streambed Conductance	Recharge
Agate Bay	0	0	0	1	0	1	0	1	0	0	0	1
Bertrand	4	10	10	13	9	13	0	10	4	8	3	8
Blaine	4	9	11	11	9	9	1	8	0	8	0	8
Breckenridge	0	1	0	2	0	1	0	1	0	1	0	0
California	2	4	5	5	4	5	0	5	0	5	0	4
Carpenter	0	1	1	2	1	2	0	2	0	1	0	2
Cherry Point	0	0	0	1	0	2	0	2	0	2	0	1
Deer	1	1	1	1	1	1	0	1	0	1	0	1
Drayton Harbor	0	0	5	5	5	5	5	0	5	0	5	0
Fingalson	0	0	0	0	0	1	0	1	0	1	0	0
Fishtrap	4	10	8	11	6	12	3	14	3	10	3	10
Four Mile	0	1	0	1	0	0	0	1	0	1	0	1
Haynie	2	7	9	9	7	7	0	7	0	7	0	7
Johnson	4	6	6	7	3	10	0	6	3	7	0	2
Jordan	0	0	0	1	0	3	0	4	0	4	0	1
Kendall	0	0	0	0	0	0	0	1	0	1	0	1
Lake Terrell	0	0	0	1	0	2	0	2	0	2	0	1
Little Campbell	0	3	3	3	3	3	0	3	0	3	0	3
Lower Dakota	6	9	13	14	10	14	2	10	0	10	0	9
Lummi Island	0	0	0	2	0	2	0	0	0	0	0	4
Lummi Peninsula East	1	1	1	2	1	4	1	4	0	4	0	3
Lummi Peninsula West	2	1	1	2	1	4	1	4	0	4	0	3
Lummi River	1	1	1	2	1	3	1	3	0	3	0	2
Lummi River Delta	1	1	1	2	1	3	1	3	0	3	0	2
Nooksack Channel	1	0	0	1	0	1	1	0	0	0	0	0

Table 4 continued.

	Aquifer Testing	Hydraulic Conductivity	Transmissivity	Aquifer Thickness	Aquifer Storage	Water Level Data	Geophysical Analysis	GW Flow Direction	Seepage Analysis	Hydraulic Gradient	Streambed Conductance	Recharge
Nooksack Deming to Everson	1	4	2	5	2	6	0	5	0	4	0	2
Nooksack River Delta	1	1	1	2	1	3	1	3	0	3	0	3
North Fork Dakota	2	7	9	9	7	7	0	7	0	7	0	7
Olsen	0	0	0	1	0	1	0	1	0	0	0	1
Portage Island	0	0	0	1	0	3	0	2	0	2	0	2
Saar	0	0	0	1	0	0	0	0	0	0	0	0
Sandy Point	0	0	0	1	0	3	0	4	0	4	0	1
Schell	1	1	1	1	1	3	0	3	0	3	0	0
Scott	1	0	1	1	1	1	0	3	0	1	0	0
Semiahmoo	1	1	1	1	1	1	0	0	0	0	0	0
South Acme Area	0	0	0	1	0	0	0	0	0	0	0	1
South Fork Dakota	2	2	2	2	2	2	0	2	0	2	0	2
Swift	0	1	0	0	1	1	0	1	0	1	0	1
Tenmile	1	4	3	4	3	3	0	4	2	4	2	4

Table 5. Summary of data gaps using a Use-Data-Model Matrix.

	Use	Data		Model
Model Reliability on Site Scale & Data Density	**Priority Uses of Groundwater Information**	**Gaps (2013)**	**Groundwater Data Source**	**Groundwater (GW)**
Low	Ability to evaluate relative down-gradient impacts from changes in land use.	Sufficient data to parameterize a regional model for the complete extent of WRIA 1.	Past regional and drainage studies.	1 layer surficial aquifer GW model; **provides regional** estimates of parameters.
Moderate	Determines the effect of changing water use from self-supplied to municipally supplied water sources.	Insufficient data everywhere with the exception of Bertrand and Fishtrap Creeks, possibly Drayton Harbor, and Lummi Peninsula*.	Past drainage studies and gaps filled by coarser resolution regional studies.	Multiple layer (i.e., 2-5) surficial aquifer GW model; provides **drainage** estimate of parameters.
High	Determine accuracy of model predictions needed to determine the benefit of moving a surface water withdrawal to a groundwater withdrawal, i.e. accurate to justify water right decisions.	Insufficient data everywhere, with the exception of limited areas in Bertrand and Fishtrap Creek drainages.	Site/sub-drainage specific studies with gaps filled by coarser rsolution drainage studies.	Complex (> 5 layers) surficial and deep aquifer model; provides **site specific** estimates of parameters.
	Because the Lummi Peninsula has special water quality issues, it may require specialized modeling.			

6.0 REFERENCES

Aspect Consulting. 2009a. Aquifer Study of the Mountain View Upland-Lummi River Area.

Aspect Consulting. 2009b. Lummi Peninsula Ground Water Investigation.

Associated Earth Sciences Inc. (AESI). 2008. Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area.

Cox, S. E., and S. C. Kahle. 1999. Hydrogeology, Ground-Water Quality, and Sources of Nitrate in Low-Land Glacial Aquifers of Whatcom County, Washington and British Columbia, Canada Plate No. 2. U.S. Geological Survey / Whatcom County Planning Department.

Greenberg, J., K. Welch, M. Neuman, P. Willing, and M. Barclay. 1996. Catalogue of Existing Information on Water Resources and Fisheries in the Nooksack Basin, a report to the Nooksack Basin Water Users Steering Committee and the Washington Department of Ecology. Bellingham, WA.

Pruneda, E. B. 2007. Use of Stream Response Functions and Stella Software to Determine Impacts of Replacing Surface Water Diversions with Groundwater Pumping Withdrawals on Instream Flows within the Bertrand Creek and Fishtrap Creek Watersheds, Washington State, USA. Washington State University, Washington State University.

7.0 ELECTRONIC DATA

Electronic Data Tables structure the organization of the *WRIA 1 Groundwater Data Assessment* project deliverables including those containing source data, code, and other intermediary data products and outreach tools to be published on the WRIA 1 Watershed Management Project website.

Electronic Data Table 1. Structure for data organization to be used for online publishing.

Geodatabase GIS Shapefiles: Filename <WRIA1_Groundwater2013.gdb>			
Description	Folder & File Name(s)	Spatial Extent	Contract Task
Shapefiles of aquifers, USGS hydrogeology, and linked citations by aquifer and drainage	WRIA 1_Groundwater2013.gdb	WRIA 1	2
WA Dept. of Ecology Data download for 20709 wells; DOH wells; USGS wells; combined well dataset sorted by deep, surficial, winter and summer	WRIA1_welldata2013.gdb	WRIA 1	2

Electronic Data Table 2. Structure for Access database.

Access database Tables: Filename <WRIA1_Groundwater2013.accdb>			
Description	Folder & File Name(s)	**Spatial Extent**	**Contract Task**
WA Dept. of Ecology Data download for 20709 wells	Table: Ecology20907Wells	WRIA 1	2
WA Dept. of Ecology Well Type Code Description	Table: Ecology Well Type Code	N/A	2
Primary summary table linking citations to aquifer location and data	Table: Aquifer Characteristics	N/A	2

Primary list of aquifer data present in each citation	Table: Aquifer Data	N/A	2
List of site specific citations and summary of aquifer data and location	Table: Aquifer Site Specific	Various Sites in WRIA 1	2
List of citations with water level data	Table: Water level Summary	Various Sites in WRIA 1	2
Endnote Citations exported from Endnote database	Table: Endnote Citations	N/A	2
Geographic lookup table for Watersheds, management areas, and drainages	Table: DrainageGroupDependency	WRIA 1	2
Lookup Table linking drainage name and Drainage ID	Table: DrainageNameID	WRIA 1	2

Electronic Data Table 3. Structure for ArcGIS database.

ArcGIS database Queries:	Filename <WRIA1_Groundwater2013. accdb >		
Description	**Folder & File Name(s)**	**Spatial Extent**	**Contract Task**
Table linking citation to aquifer location and transmissivity data availability	Query: Transmissivity Data Summary	WRIA 1	2
Table linking citations to aquifer location	Query: Aquifer citations	WRIA 1	2
Table listing citations by type of citation based on scale of study extent	Query: Citation Type	WRIA 1	2
Table linking citations and aquifer type to each drainage	Query: Drainage Aquifers	WRIA 1	2
Table linking citations to each drainage	Query: Drainage Citations	WRIA 1	2
Table linking aquifers to management areas	Query: Management Area Aquifers	WRIA 1	2
Table linking citations to management areas	Query: Management Area Citations	WRIA 1	2
Table selecting Surficial Sumas Aquifer citations and linking to aquifer data availability	Query: Surficial Sumas Citations	WRIA 1	2

Electronic Appendix Table 4 gives the structure for data organization for the electronic appendix of source and intermediate and final products generated during the technical development and review cycles.

Electronic Data Table 4. Archived *WRIA 1 Groundwater Data Assessment* data.

Description	Folder & File Name(s)	Spatial Extent	Contract Task
Disclaimer for WA Dept. of Ecology Data download for 20709 well download	Supporting documents/DISCLAIMER.pdf	N/A	2
Fields Description WA Dept. of Ecology Data download for 20709 well download	well_log_datadictionary.pdf	WRIA1	2
Exports from Access Database in Excel formats and Master Data Table with Citation information	WRIAGroundwaterAccessDBexports/*.xls	N/A	2

Electronic Data Table 5. Projection for Department of Ecology well data.

```
NAD_1983_HARN_StatePlane_Washington_South_FIPS_4602_Feet
WKID: 2927 Authority: EPSG

Projection: Lambert_Conformal_Conic
False_Easting: 1640416.666666667
False_Northing: 0.0
Central_Meridian: -120.5
Standard_Parallel_1: 45.83333333333334
Standard_Parallel_2: 47.33333333333334
Latitude_Of_Origin: 45.33333333333334
Linear Unit: Foot_US (0.3048006096012192)

Geographic Coordinate System: GCS_North_American_1983_HARN
Angular Unit: Degree (0.0174532925199433)
Prime Meridian: Greenwich (0.0)
Datum: D_North_American_1983_HARN
  Spheroid: GRS_1980
    Semimajor Axis: 6378137.0
    Semiminor Axis: 6356752.314140356
    Inverse Flattening: 298.257222101
```

Chapter 3 Sources of Supply for Water Use in WRIA 1

WRIA 1 Groundwater Assessment
June 2013

An interdisciplinary team of water resource technical specialists worked with the WRIA 1 Joint Board Staff Team to compile existing technical models, studies, and data into an assessment of groundwater in WRIA 1. For a complete list of contributors, see *Chapter 4 - Recommendations for Data Collection and Model Integration* In Bandaragoda, C., C. Lindsay, and J. Greenberg. WRIA 1 Groundwater Data and Model Assessment, Whatcom County PUD #1, Whatcom County, WA: WRIA 1 Joint Board.

Technical reviewers: Jeremy Friemund, Lummi Nation Natural Resources; Peter Gill, Whatcom County; Kasey Cykler, Washington State Dept. of Ecology; Christina Bandaragoda, Silver Tip Solutions, Inc.; Charles Lindsay, AESI. See also List of Contributors, *Chapter 4* Section 4.0.

Please cite this Chapter as:
Print Citation: Greenberg, J. (2013). Sources of Water Supply in WRIA 1. *In* Bandaragoda, C., C. Lindsay, and J. Greenberg, editors. WRIA 1 Groundwater Data and Model Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board.

Online Citation: Greenberg, J. and C. Bandaragoda (2013). Sources of Water Supply in WRIA 1. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data and Model Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board. Retrieved [Date], from http://wria1project.whatcomcounty.org/.

This work was funded by the WRIA 1 Joint Board and managed by Whatcom County PUD #1 and funded by Department of Ecology Grant No 1200070 Task 9 Groundwater Study; June 2013.

CHAPTER 3
Sources of Supply for Water Use in WRIA 1

Table of Contents

List of Figures

List of Tables

1.0 OVERVIEW

The purpose of this chapter is to provide an overview of the existing data sources for water supply in WRIA 1 and recommendations for future information collection to fill the existing water supply source (surface and groundwater) point of withdrawal and place of use data gaps needed to address ongoing water resource issues in Whatcom County.

Sources of water in WRIA 1 include surface water (lakes, rivers, springs) and groundwater (surficial and deep aquifers). In the State of Washington, the Department of Ecology is the lead agency for enforcing water use regulations, which are based on the prior appropriation system of water rights (i.e., "first in time is first in right"). Typically, in states where water rights are strictly administered, water use records are required to be submitted by water users on at least an annual basis. However, water rights regulations are generally not enforced in many parts of Washington State for various reasons and as a result, information on actual water use is only collected in certain areas or when certain conditions are met (e.g., municipal purveyor).

In WRIA 1, water sources for the different types of water users are documented with varying levels of accuracy. Irrigation is the largest sector in which water sources and actual water use from the sources are generally unknown. As noted from the *Lower Nooksack Water Budget* (Bandaragoda, et.al. 2012), estimates of total irrigation water use exceed all other sectors by an order of magnitude, therefore it is important to understand the rates of withdrawal from each source (groundwater or surface water). Also, little is known about the source of supply for dairies and berry processing; public water systems are known to purvey water to some dairies. Table 1 summarizes the sources for different types of water users, whether the source type and locations are known, where the water is used, and where these data are documented.

From a WRIA 1 perspective, limited information has been collected on irrigation water use. Three studies have been conducted in the Lower Nooksack Subbasin in which different levels of information were made available by local farmers. As part of the *Bertrand Comprehensive Irrigation District Management Plan* (CIDMP] (Greenberg 2004), detailed drainage information was collected and analyzed on crops irrigated, application of irrigation water (e.g., drip, sprinkler, big gun) and source water; water rights were analyzed from Gill and Atkenson (2003) geodatabases. In 2005, similar data were collected for the Tenmile Creek Watershed resulting in a report *Estimates of Current Irrigation Water Use,* however, source water was not readily identified during the data collection effort (Greenberg 2005). The *North Lynden Watershed Improvement District's Water Management Plan* (Greenberg 2009) included collecting information for Fishtrap Creek drainage. Farmers indicated most of the water sources were groundwater; surface water sources were not specifically identified.

For public water systems and municipal/industrial supplies, source water is identified in the Washington State's Department of Health database as well as on the water right documents for those systems. The water rights places of use and points of diversion were mapped first by Gill and Atkenson (2003) and again by the Department of Ecology (2009). The Whatcom County Department of Health has digitized source locations for public water systems through year 2000; no updates have been done since that time. The Department of Ecology mapped water rights directly from the documents on file but did not perform any analysis of the data which is known to contain inconsistencies; individual water rights can be viewed through the Ecology website.[1] The mapping done by Gill and Atkeson included filtering for data consistency; consequently the WRIA 1 Staff Team agreed that it was most appropriate to use this database rather than Ecology's database for the analysis in this work.

In all of WRIA 1, most of the detailed irrigation source information is found in the Bertrand Creek drainage, which is discussed in this chapter as a "case study" and a potential template for future data collection efforts. The data gaps regarding irrigation water supply sources in Lower Nooksack drainages were identified in the *Lower Nooksack Water Budget Report, Chapter 7* (Greenberg 2012a) and collecting these data would improve model results in future WRIA 1 watershed modeling efforts.

Table 1. Water Source data gaps.

Type of Water User	Source Known?	Location Known	Where Documented	Issues
Utilities	Yes	Yes	Municipal/industrial records of water use.	None.
Public Water Systems	Mostly yes, some no	Mostly no; Some known	WA Dept of Health database; WRIA 1 water rights CD; State Dept of Health.	Whether service areas and place of use on water right documents are the same.
Irrigation	No	No	Water right documents; three studies completed.	Non-permitted uses; some permitted users may have switched sources without proper documentation.
Dairy	No	No	Water right documents; public water systems supply water.	Need detailed analysis of dairy source locations; overlay with rights; need information from public water systems who supply water.
Self-Supplied	Yes, mostly exempt wells	No	Well logs and water right documents.	Not all will have well logs and exempt wells are not documented.

[1] https://fortress.wa.gov/ecy/waterresources/map/WaterResourcesExplorer.aspx

2.0 INFORMATION ON IRRIGATION WATER SOURCES

2.1 Previous Water Source Assumptions

In the 2007 version of WRIA 1 watershed model, Topnet-WM, (Tarboton 2007) a WRIA-wide assumption was made to represent sources as 70% served by groundwater wells and 30% supplied by a surface water source. In addition, 20% of the water sources for dairies were assumed to be derived from groundwater and 80% were derived from surface water. In *Chapter 7* of the *Lower Nooksack Water Budget* (Greenberg 2012a), the relative proportion of withdrawal rates from ground and surface water for each drainage, as identified on water rights documents (i.e., water rights certificates, claims, and permits), was used as model inputs for source mixing (Gill and Atkenson 2003). The proportion of withdrawal/diversion rates from ground/surface water on water right documents was used as a surrogate since source water was unknown. In drainages where gage records (observed flow measurements) were available (Bertrand, Fishtrap, and Tenmile), the distribution was adjusted so that simulated streamflow better matched observed streamflow at the 90% exceedence level (See *Model Calibration* (Bandaragoda 2012)). This adjusted distribution of water source between surface and ground water replaced the drainage-average distribution of withdrawal/diversion rates noted on water rights that was developed for model input. Further refinements of these data were recommended in the *Lower Nooksack Water Budget (Bandaragoda et al. 2012, Greenberg 2012a)*.

Table 2. Topnet-WM 2012 irrigation source mixing parameters based on irrigation water rights used in the *Lower Nooksack Water Budget, Chapter 7* (Greenberg 2012a).

Drainage Name	Groundwater Source	Surface Water Source
Bertrand [1]	71%	29%
Deer	98%	2%
Fishtrap[1]	80%	20%
Fourmile	74%	26%
Kamm	86%	14%
Lower Anderson	13%	87%
Nooksack Deming to Everson	76%	24%
North Fork Anderson	0%	100%
Schneider	61%	39%
Scott	61%	39%
Silver	87%	13%
Smith	29%	71%
South Fork Anderson	3%	97%
Tenmile[1]	56%	44%
Wiser Lake/Cougar Creek	85%	15%

*Fazon is not listed in the water rights review tables. The percentages for Deer Creek were used since Fazon has no known surface water outlet. [1] Adjusted so simulated flows better matched observed flows for the 90% exceedence levels.

2.2 Water Sources Based on Water Rights

Points of withdrawal identified on water rights documents can only be used as a starting point for understanding actual water sources. Without a detailed analysis accompanied by field observations, the proportion of water withdrawn from either groundwater or surface water can be skewed by a number of factors, for example, actual water use versus permitted use, overlapping or duplicative water rights, etc. In addition, the relative percentages of groundwater versus surface water sources for non-permitted irrigation may not be the same as permitted. As a result, reliance on water rights documents in WRIA 1 to estimate the quantity of water use, the water source, and the place of use is not considered to be reliable for irrigation (Gill and Atkenson 2003, Greenberg 2004, 2005, 2009). It should be noted that the rates presented do not represent *actual* water use; rather they illustrate *reported* rates based on Ecology's water rights documents.

Inconsistencies or incomplete information were common with the water right claims documents. WRIA 1 Staff Team was in agreement to not use this dataset for the purposes of understanding the proportion of water from different sources. An example of this problem can be found in the Birch Bay, Drayton Harbor, and Lummi Bay watersheds shown in Figure 1. This claim documented to irrigate 20 acres with 20 acre feet of water and a withdrawal rate of 105 cfs. It is highly likely that the rate of withdrawal is in error, since the magnitude is too high for irrigating such a small number of acres. In this case, the single 105 cfs stock and irrigation water right claim skews the data such that 66% of the water supply in the three drainages noted above comes from surface water and 34% from groundwater in this area; without this water right claim, 29% of the water supply would come from surface water, rather than 66%, and 71% of the water supply would come from groundwater rather than 34%. This can have a significant impact on estimating contributions of surface and groundwater sources to overall water supplies in WRIA 1. There are several ground water points of withdrawals shown in Figure 1 where either the aquifer cannot produce the yields identified in the water rights documents or the groundwater in the aquifer is not potable due to elevated salinity levels.

Despite these limitations, the water rights database and spatial datasets are the best available information in most drainages in WRIA 1. The sources from which water uses are derived are necessary to obtain a better understanding of water management in WRIA 1. Additional effort should be focused on field observations, if possible, by way of conversations with farmers to better understand and document water sources used in WRIA 1.

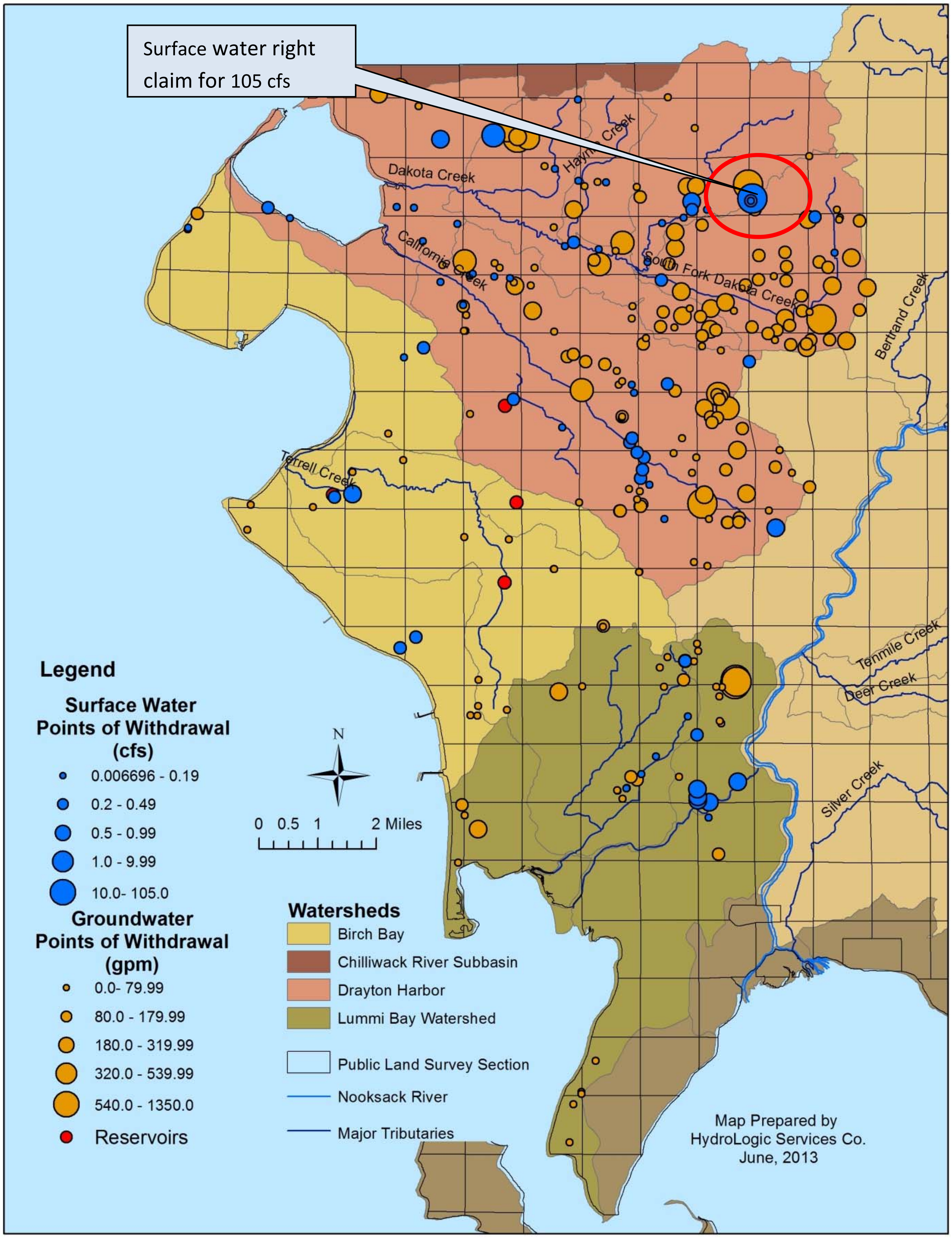


Figure 1. Water rights in the Birch Bay, Drayton Harbor, and Lummi Bay watersheds.

2.3 Bertrand Creek Drainage as a Case Study

The Bertrand Creek water use analysis completed for the *Bertrand Comprehensive Irrigation District Management Plan* (CIDMP) (2004) is an example of data collection efforts to identify source water other than that represented on water right documents. As part of the CIDMP (2004) development effort, water rights and actual water use for irrigation were extensively analyzed. Informal representatives of the local farmers were assembled to provide information for crop type, irrigation application method, and water source. The total irrigated land at that time was estimated to be 7,418 acres, of which 87% was irrigated by groundwater and 13% by surface water (Greenberg 2004). And, coincidentally, during the maximum irrigation month (July), groundwater supplied 87% and surface water 13% similar to the distribution of acres irrigated.

Overlapping water rights in the Bertrand drainage were considered in the CIDMP (Greenberg 2004) analysis as well as claims that had been mapped by Gill and Atkenson (2003). The total irrigated acres associated with the water rights were noted in addition to the actual "on the ground" irrigated acreage discussed above. Figure 2 and Figure 3 can be compared to illustrate the differences between the source water identified by the farmers and the source water noted on irrigation water rights. Table 3 shows the difference between the information obtained from farmers in the drainage and the water rights documents. Source water from wells is 13% higher than the water rights documents show and correspondingly surface water sources 13% less. Based on this difference, our conclusion is that the water right documents are not a reliable foundation for estimating the sources of water used in WRIA 1.

Table 3. Source water proportion from different sources – Bertrand Creek drainage.

Data Source	Proportion of Source Water	
	Groundwater Source	Surface Water Source
2004 CIDMP irrigation water use	87%	13%
Water rights annual volume analyzed for overlap (CIDMP 2004)	74%	26%

Estimated 2004 irrigated acres by source for each section (township, range, and section) are summarized in Table 4 and displayed in Figure 2 since water use was not calculated at this level of detail. Table 5 is a summary by township, range, and section of irrigated acres possible under water rights and by water source (ground or surface) for the Bertrand Creek drainage area. The water rights acreage totals 6,763 with 74% supplied by groundwater and 26% from surface water. In the case of Bertrand Creek drainage, the proportion attributed to each water source from the actual water use data (Greenberg 2004) may be more accurate than the water rights documents. The actual use source data were collected from a handful of farmers and not from each individual irrigator.

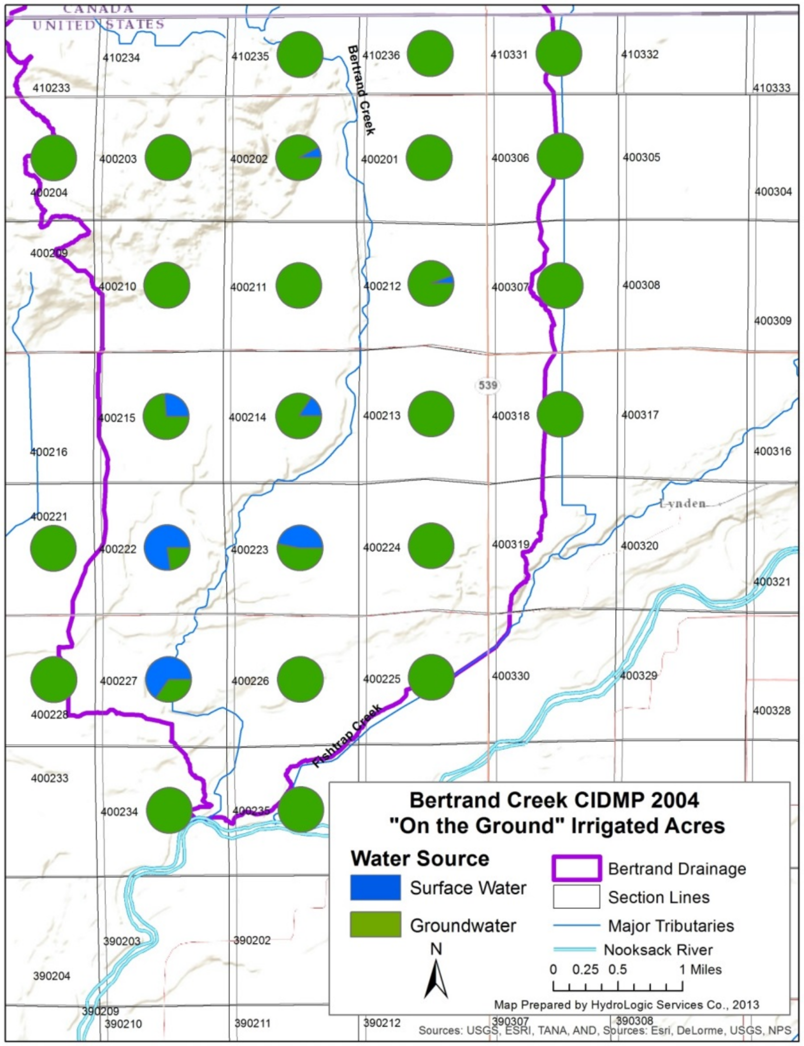


Figure 2. Proportion of irrigation source water in each section, field data collected during Bertrand CIDMP (Greenberg 2004).

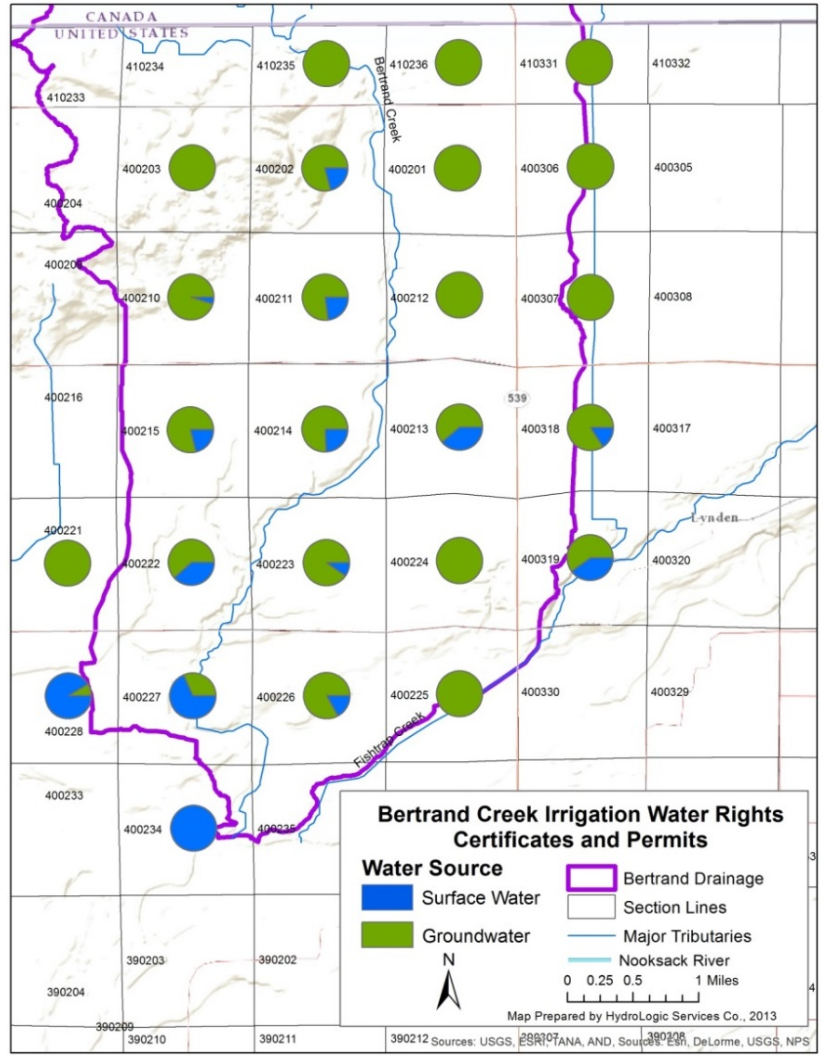


Figure 3. Proportion of source water for irrigation water rights, analyzed during Bertrand CIDMP (Greenberg 2004).

Table 4. Source of supply for actual irrigated acres in Bertrand Creek drainage during Bertrand CIDMP (Greenberg 2004).

Township/ Range/Section	Irrigation by Groundwater (acres)	Irrigation by Surface Water (acres)
400201	541	0
400202	201	17
400203	31	0
400204	194	0
400210	323	0
400211	531	0
400212	446	27
400213	591	0
400214	305	56
400215	398	142
400221	57	0
400222	101	339
400223	226	200
400224	338	0
400225	98	0
400226	353	0
400227	98	184
400228	37	0
400234	85	0
400235	135	0
400306	283	0
400307	307	0
400318	262	0
410235	39	0
410236	303	0
410331	170	0
Total	**6453**	**965**
Percent of Total	**87%**	**13%**

Table 5. Summary of acres irrigated under rights/claims for Bertrand Creek drainage.

Township/ Range/ Section	Acres Noted on Rights for Irrigation			
	Groundwater Certificates and Permits	Groundwater Claims	Surface Water Certificates and Permits	Surface Water Claims
400201	359			44
400202	94		25	
400203	30			
400204				
400209				
400210	240		12	10
400211	219	100	65	
400212	366			104
400213	158		100	
400214	125	1	40	7
400215	361		96	
400221	34	29		
400222	289	7	180	
400223	235	62.5	25	
400224	231	145		
400225	82			
400226	189	100	39	
400227	116		250	
400228	50		520	
400234			7	
400235				
400306	187			
400307	141			
400318	427		80	
400319	30		20	
410233				
410235	95	25		25
410236	348			120
410331	118			
TOTAL	4524	469.5	1459	310
Percent of Total	67%	7%	22%	4%
Grand Total for each source	**74%**	**↔Ground-water**	**26%**	**↔Surface Water**

2.4 Dairy Farms

At the time the *Lower Nooksack Water Budget (Greenberg 2012b)* was completed*,* the number of dairy cows in each drainage had been provided by Whatcom Count. The locations of the current dairies were not available at that time. Recently, the Washington State Dept. of Ecology updated and posted the <dairy2010.shp> GIS file. Last year their website still posted the 2003 version of the same file. The 2010 dairy location GIS file is the only new information available at this time. The water source for each dairy is not known though many are provided water through public water systems. **Figure 4** shows the locations of the dairy farms and the sources of water for all public water systems. The source of water for the public water system situated closest to each dairy farm could be consulted to determine whether the dairy is served by that system.

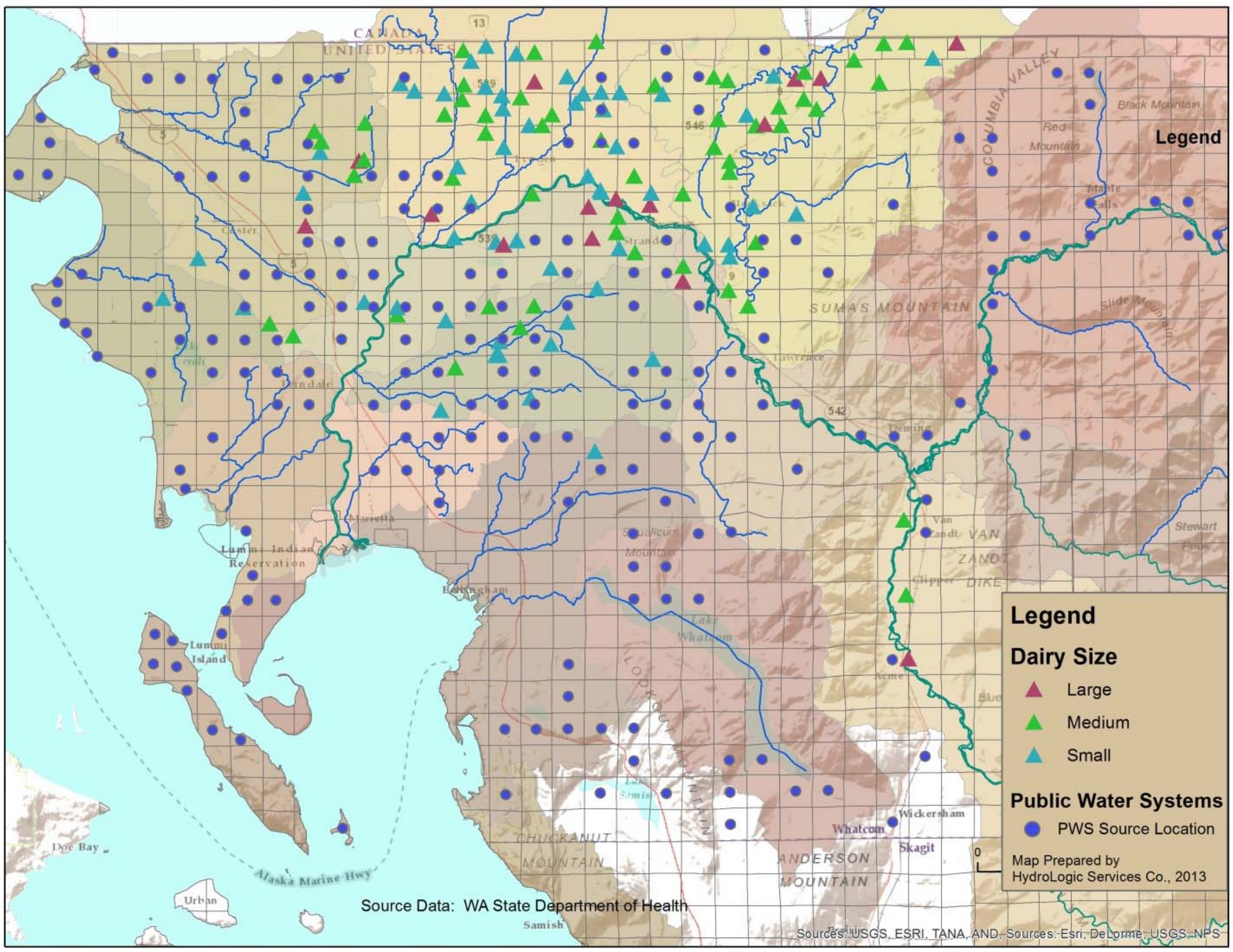


Figure 4. Dairy farms and source locations of public water systems by section.

2.5 Irrigation and Dairy Source Recommendations

The following list identifies recommendations specific to using the Bertrand Creek drainage case study as a model for future data collection for irrigation water sources, in chronological order of tasks:

- Develop a set of maps displaying locations of parcel boundaries, well logs and background information including aerial photography and public land survey system.
- Print each section on one page and print a large map of selected area, e.g., Bertrand WID or NLWID, etc.
- Two people from the entity undertaking the effort should meet with farmer representatives, one of whom can take notes.
- Meet with representative farmers of a "district" showing each section and have them identify by parcel: source of supply, location of point of withdrawal, type of crops irrigated, irrigation application (drip, sprinkler, big gun, etc.).
- Request water use data for berry processing from farmers.
- Digitize data collected and confirm irrigated areas using a digital layer of aerial photographs.
- Reconcile discrepancies with well logs, if possible, and water right points of diversion/withdrawal.

The following list identifies recommendations specific to collecting source data of water supply for dairies:

- Using the data from **Figure 4**, determine most likely public water systems to be serving nearby dairies.
- Contact the selected public water associations above to identify whether they supply water to the dairies identified.
- Obtain monthly amounts of water delivered to dairies.
- If not supplied by public water system, identify well logs associated with each dairy to determine source.
- Identify water right associated with dairy. Determine source of supply from water right, if available.

3.0 INFORMATION ON MUNICIPAL, INDUSTRIAL, RESIDENTIAL, AND COMMERCIAL WATER SOURCES

3.1 Previous Assumptions

In the 2007 version of Topnet-WM (Tarboton 2007), the City of Ferndale was assigned 50% to groundwater and 50% to surface water for source mixing. This was changed to 100% surface water in the *Lower Nooksack Water Budget ((Greenberg 2012b)* since the period of record modeled ended in 2011 which is prior to when Ferndale transferred to wells. The City of Lynden, PUD #1 of Whatcom County, and the City of Bellingham were designated 100% surface water sources in both versions. Self-supplied commercial/industrial was assigned 20% to surface water and 80% to groundwater in 2007 (Tarboton 2007); residential units located outside the boundaries of areas served by municipalities or small public water systems were assumed to be served 100% from groundwater. In *Lower Nooksack Water Budget (Greenberg 2012b)*, the self-supplied water users (residential, commercial, industrial) were assigned groundwater as their only source of supply.

3.2 Public Water System Information

Public water systems were not analyzed in the *Lower Nooksack Water Budget* with the exception of the largest water purveyors: the PUD#1 of Whatcom County, and the Cities of Lynden, Ferndale, and Everson. Through December 2011, all but Everson were dependent on surface water sources. The City of Ferndale constructed wells and began withdrawal for the city's water supply at the beginning of 2012.

Currently, there are four resources containing locations of points of withdrawal/diversion and places of use or service areas: 1) A geospatial database of points of withdrawal/diversion assembled by the Whatcom County Health Department but not updated since 2000; 2) A geospatial spatial database of parcels served by public water systems compiled Gill and Atkeson (2003); 3) Places of use digitized into a spatial geodatabase as part of the water rights mapping effort (Gill and Atkeson 2001); 4) Location of points of withdrawal/diversion by township, range, section, and quarter quarter section found on the State of WA Department of Health website[2].

In the Whatcom County Department of Health's geodatabase 185 Group A systems with 353 sources and 189 Group B systems with 205 sources were found. Using the current Washington State Department of Health's data, there are total of 404 active public water systems in Whatcom County and 131 inactive systems. Of the active systems, 184 are designated as Group A and 220 as Group B. The majority of public water systems are served by groundwater as indicate in Table 6 and Table 7. The largest water users in the public water system category, however, divert from surface water (City of Bellingham, PUD #1 of Whatcom County, etc.).

[2] https://fortress.wa.gov/doh/eh/portal/odw/si/DownloadsReports.aspx

Table 6. Data for Group A public water systems.

Type of Source	Group A Public Water Systems (PWS)				
	# PWS	Mapped POD[1]	Mapped POD[2] Township Range Section	Mapped Water Right POU[3]	Parcels Served by PWS[4]
Groundwater	152	101	126	30	10
Surface water	14	10	13	1	-
Intertie – supplied by other PWS	18	9	15	4	-
TOTAL	**184**	**120**	**154**	**35**	**10**

POD= point of diversion; POU = place of use.
[1]From Whatcom County Health Department shapefile on water rights CD <POD_PWS.shapefile>;
[2]From the State of WA Department of Health (2013) database; documented to nearest QtrQtr Section and mapped to the nearest section<SourceGrpByTRSincPUD2.shp>;
[3] From water rights CD <POUpws.shapefile>, these are water rights places of use;
[4]From water rights CD <pws_customer.shapefile>;

Some systems noted as inactive may be active such as PUD #1 of Whatcom County, BP Cherry Point, PSE Whitehorn Generating Facility, etc.; ***PUD #1 and BP Cherry Point were included as active.***

Table 7. Data for Group B public water systems.

Type of Source	Group B Public Water Systems (PWS)				
	# PWS	Mapped POD[1]	Mapped POD[2] Township Range Section	Mapped Water Right POU[3]	Parcels Served by PWS[4]
Groundwater	210	147	179	43	9
Surface water	5	3	3		
Intertie – supplied by other PWS	5	5	5		
TOTAL	**220**	**155**	**187**	**43**	**9**

POD= point of diversion; POU = place of use.
[1]From Whatcom County Health Department shapefile on water rights CD <POD_PWS.shapefile>;
[2]From the State of WA Department of Health (2013) database; documented to nearest QtrQtr Section and mapped to the nearest section <SourceGrpByTRSincPUD2.shp>;
[3] From water rights CD <POUpws.shapefile>, these are water rights places of use;
[4]From water rights CD <pws_customer.shapefile>

Table 8 shows the data gaps for Group A and B public water system for each data source noted in **Table 6** and **Table 7**. From a hydrologic modeling standpoint, it would be important to identify the points of diversion and the service areas within the model domain to achieve more robust model results. From the review of compiled public water system information, it appears that 326 public water systems do not have water rights. Identifying the service areas would assist in further determining whether any of the 326 actually does in fact have a water right. While the data gaps are summarized by public water system, within a system there may be more than one source of water that needs to be located and digitized.

Of the 184 Group A public water systems, 270 sources are noted in the Washington State DOH data. Similarly, the Group B systems contained 224 sources for the 220 public water systems. Most Group B systems have one source for their water supply, while Group A systems often have several wells serving their needs. While **Table 8** shows 129 public water systems which need points of diversion/withdrawal located to address known data gaps there are likely more than 129 sources which will need to be addressed since many have more than one source.

Table 8. Public water system data gaps.

	Whatcom County Health POD	WA DOH POD by Township Range Section	Water Right Place of Use	Parcels Served by PWS
Group A	64	30	149	174
Group B	65	33	177	211
TOTAL	**129**	**63**	**326**	**385**

The following three figures display where data are available by source locations using the 2013 WA DOH data. **Figure 5** shows the number of water sources in each section throughout Whatcom County and identified as Group A, Group B, groundwater or surface water. The numbers in black indicate the total number of sources for that section. Public water systems using surface water typically have one point of diversion, with the exception of the PUD #1 of Whatcom County and the City of Bellingham.

Figure 6 shows the population served by sources within each section. If public water systems had sources in more than one section, only one section was used so as not to duplicate population numbers. More than 75% of the 2010 population in Whatcom County is served by a public water system and the remaining 25% have either an individual water right or an exempt well. Based on the Census 2010 population and the tabulation of the WA DOH population served by active public water systems, the estimated population served by exempt wells or a single water right is 50,253. The average of the number of people per connections from the WA DOH data and the Census 2010 average household size 2.48 people per household. The resulting number of exempt wells (or water users with a single domestic water right) is roughly 20,000 (**Table 9**).

Figure 7 shows the non-residential public water systems' sources in each section, with the total number of sources shown in the middle of the circle.

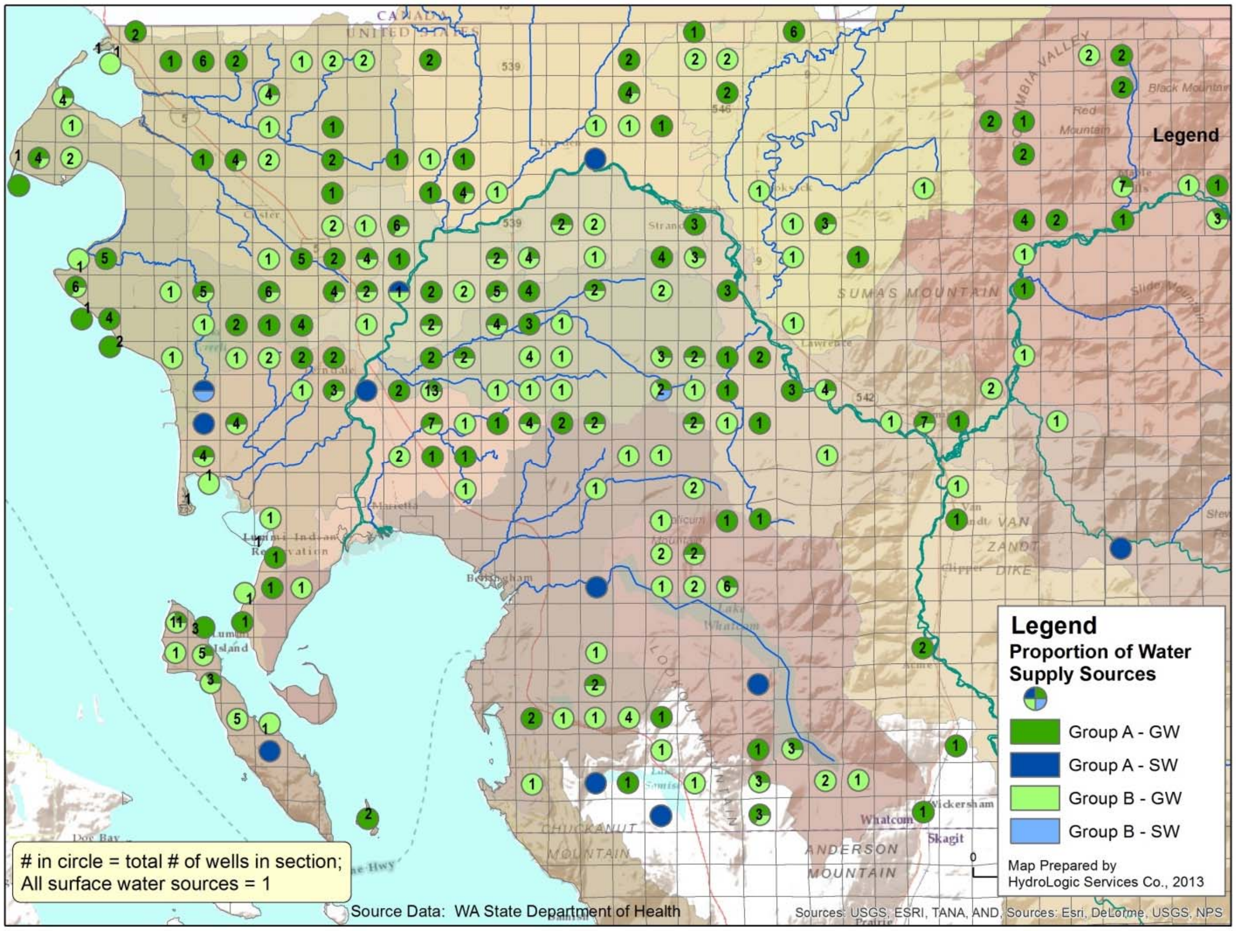


Figure 5. Number of sources for public water systems summarized by section. (GW = groundwater and SW = surface water).

Table 9. Estimate of self-supplied water users in Whatcom County.

	Population	# Connections or Average People Per Household	Estimated of self-supplied households
2010 Census - Whatcom County	201,140	2.43	
Served by Active PWS	150,887	2.53	
Served by single water right or exempt well	50,253		20,282

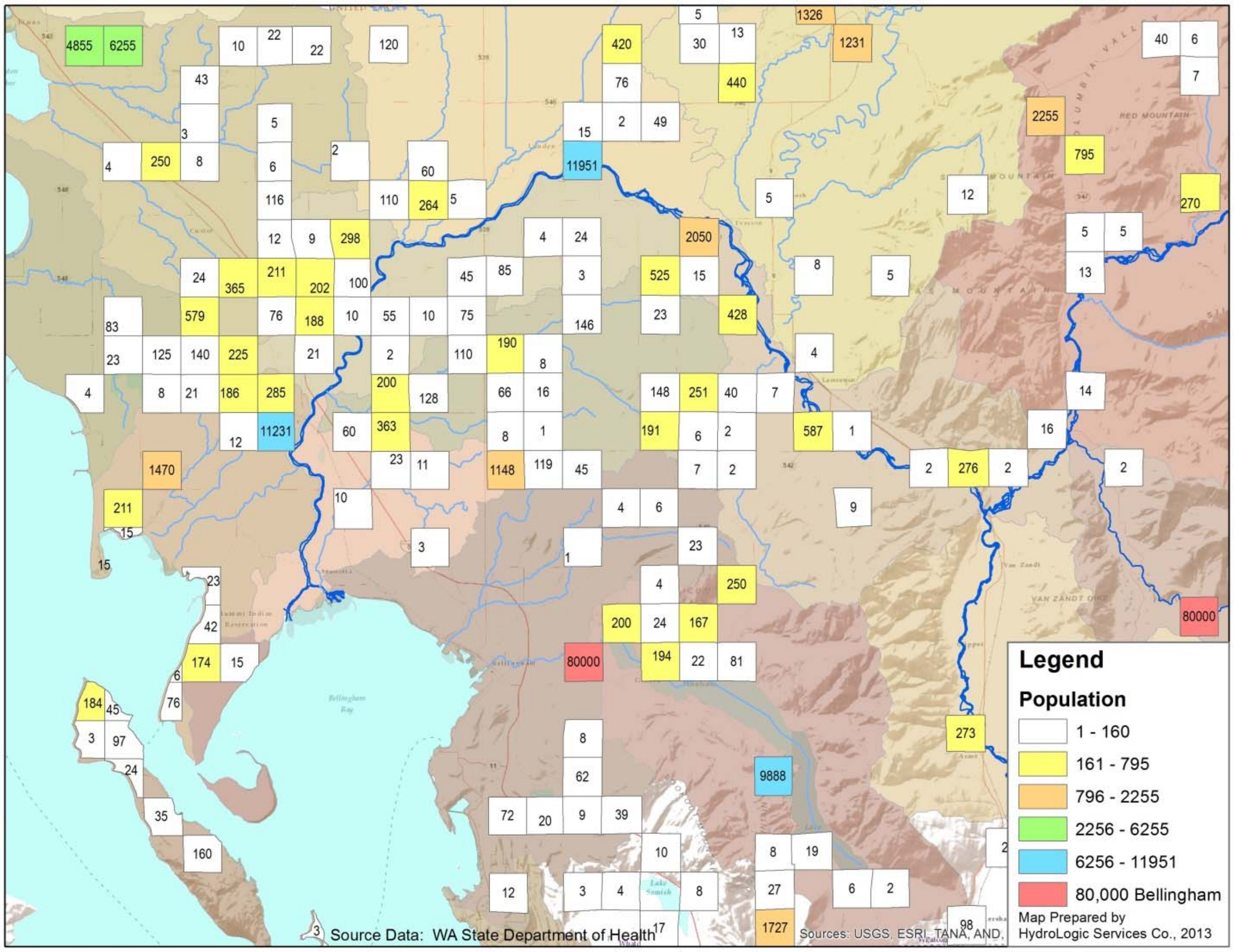


Figure 6. Approximate population served by public water system sources from each section.

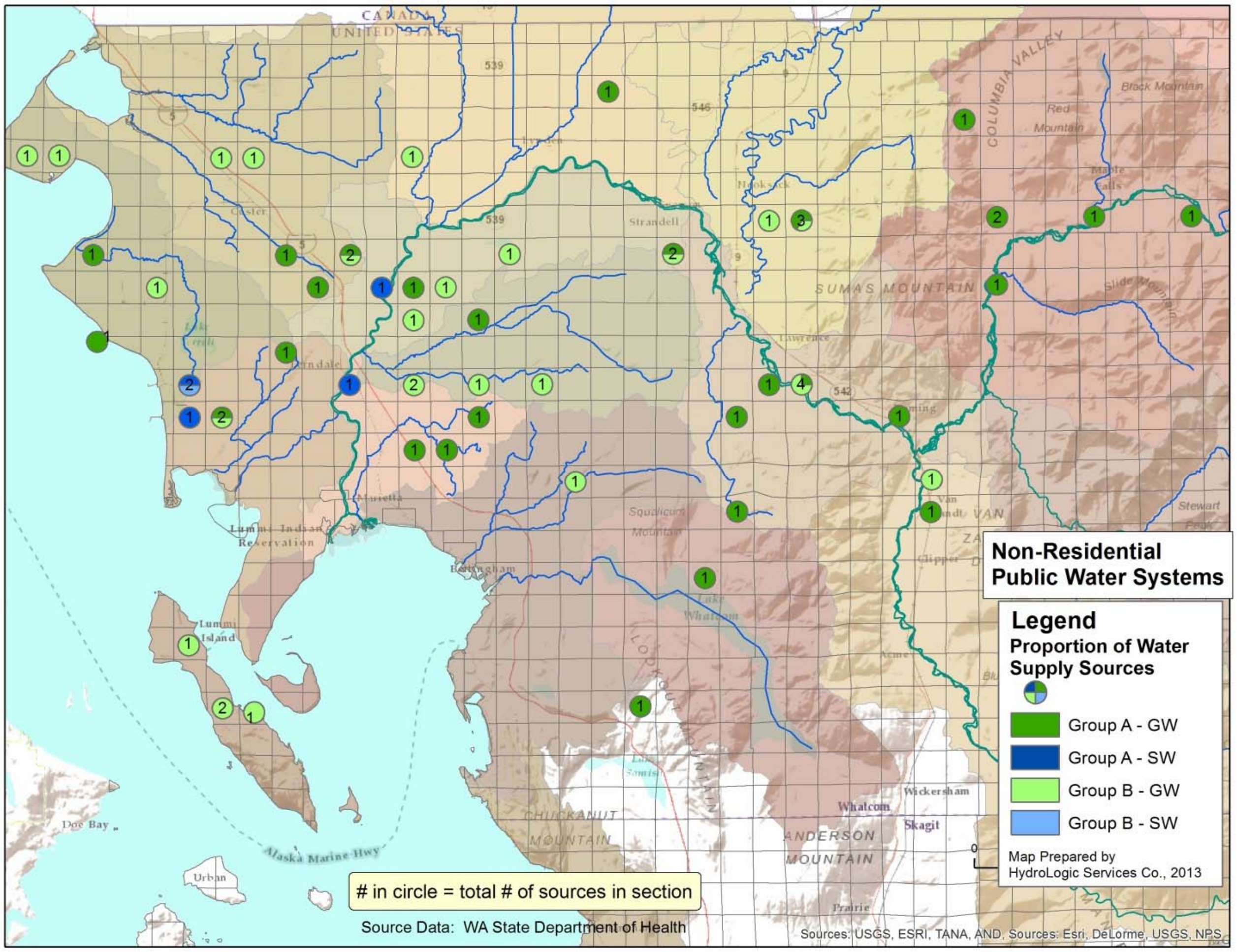


Figure 7. Number of sources in each section for non-residential public water systems in Whatcom County.

3.3 Public Water System Recommendations

The following list identifies recommendations specific to gathering additional water use data from public water systems:

- In future modeling efforts, the City of Ferndale's water supply should be changed to 100% from groundwater. For calibration prior to December 2011, the supply will have to remain as surface water but scenario model runs should take into account the change to groundwater for adequately describing the water budget and/or streamflow impacts.
- Request service area databases and geospatial files from the Washington State Department of Health and Whatcom County Health Department, if available.
- Obtain and reconcile all data sources to ensure accuracy: Whatcom County Department of Health, Washington State Department of Health, WRIA 1 Water Rights CD, and Washington State Department of Ecology's well log database.
- As part of the Coordinated Water System Plan Update, meet with officials from each public water system to obtain points of withdrawals, any water use data available, service areas (all parcels served) for all public water systems.
- Digitize service areas and source locations.
- For the Lower Nooksack Subbasin, the population covered under public water systems can be subtracted from the 2010 population in each drainage to achieve a better estimate of those on exempt wells or using individual water rights.
- Under the Coordinated Water System Plan Update, develop the model inputs required to more adequately represent the public water associations in Topnet-WM. Data required in Topnet-WM include amount of withdrawal, point of diversion, drainage in which water is used, source of supply, return flow amounts and locations for each public water system. Data required by MODFLOW groundwater model includes pumping rates from water supply wells.

4.0 ELECTRONIC DATA

Electronic Data Tables structure the organization of the *WRIA 1 Groundwater Data Assessment* project deliverables including those containing source data, code, and other intermediary data products and outreach tools to be published on the WRIA 1 Watershed Management Project website.

Electronic Data Table 1. Structure for data organization to be used for online publishing.

Description	Folder & File Name(s)	Spatial Extent	Contract Task
2004 irrigated acres in Bertrand Creek drainage by section and source type.	BertrandActIrrArea.shp	Whatcom County	Task 3
Water rights summarized by acres for each section and source type.	PLS_waterrtsSource.shp Derived from WRIA 1 Project Water Rights CD	Whatcom County	Task 3
A compilation of State Dept of Health data from 5 different sources.	WADOH_ActivePWS.xlsx Derived by Ageneral.xlsx; Asource.xlsx; Bgeneral.xlsx; Bsource.xlsx; and PWSSourceReports.pdf from WADOH	Whatcom County	Task 3
File used to develop Tables 4 through 6. This is a compre-hensive table showing data gaps for source locations for each water system.	PWS_A_B_Source_Location.xlsx	Whatcom County	Task 3
Water rights mapped and analyzed through 2003.	WRIA 1 Project Water Rights CD	Whatcom County	Task 3
Shapefile created to map Figure 4.	SourceGrpByTRS.shp	Whatcom County	Task 3
Shapefile created to map Figure 5.	PWS_PopbySec.shp	Whatcom County	Task 3
Shapefile created to map Figure 6.	TRSecPWS_NonResSources.shp	Whatcom County	Task 3

5.0 REFERENCES

Bandaragoda, C. 2012. Model Calibration. Pages pp. 317-344 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Bandaragoda, C., J. Greenberg, D. M., and P. Gill. 2012. Lower Nooksack Water Budget Overview.*in* C. Bandaragoda, J. Greenberg, D. M., and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Gill, P., and A. Atkenson. 2003. WRIA 1 Water Rights CD.*in* PUD #1 of Whatcom County editor. Water Rights Stage 2 Deliverables. PUD #1 of Whatcom County Bellingham, WA.

Greenberg, J. 2004. Water use and water rights.*in* EES Inc., editor. Bertrand Comprehensive Irrigation District Management Plan. WA State Department of Agriculture and the Bertrand Watershed Improvement District, Olympia, WA.

Greenberg, J. 2005. Estimates of Current Irrigation Water Use in Tenmile watershed.

Greenberg, J. 2009. Water Use and Water Rights.*in* J. Greenberg, editor. North Lynden Watershed Improvement District (NLWID) Watershed Management Plan. North Lynden WID, Lynden, WA.

Greenberg, J. 2012a. Water Management: Agricultural Water. Pages pp. 217-246 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Greenberg, J. 2012b. Water Management: Municipal/Industrial, Residential, Commercial Water Use. Pages pp. 247-274 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Tarboton, D. G. 2007. Water Quantity Model Development and Calibration, WRIA 1 Watershed Management Project Phase III, Task 4.1 report. Utah State University, Logan, Utah.

Chapter 4 Recommendations for Data Collection and Model Integration

WRIA 1 Groundwater Assessment
June 2013

An interdisciplinary team of water resource technical specialists worked with WRIA 1 Joint Board Staff Team to compile existing technical models, studies, and data into an assessment of groundwater in WRIA 1. For a complete list of contributors, see *Chapter 4 - Recommendations for Data Collection and Model Integration* In Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, (eds). WRIA 1 Groundwater Data and Model Assessment, Whatcom County PUD #1, Whatcom County, WA: WRIA 1 Joint Board.

Technical Reviewers: Jeremy Freimund, Lummi Natural Resources, Kasey Cykler, Washington State Dept. of Ecology, Rebecca Schlotterback, PUD No. 1 of Whatcom County, Peter Gill, Whatcom County Planning & Development Services, and Clare Fogelsong and Jon Hutchings, City of Bellingham. See also List of Contributors, Section 4.0.

Please cite this Chapter as:
Print Citation: Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas (2013). Recommendations for Data Collection and Model Integration. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board.

Online Citation: Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas (2013). Recommendations for Data Collection and Model Integration. *In* Bandaragoda, C., C. Lindsay, J. Greenberg, and M. Dumas, editors. WRIA 1 Groundwater Data Assessment, Whatcom County PUD #1, Whatcom County, WA. WRIA 1 Joint Board. Retrieved [Date], from http://wria1project.whatcomcounty.org/.

This work was funded by the WRIA 1 Joint Board and managed by Whatcom County PUD #1 and funded by Department of Ecology Grant No 1200070 Task 9 Groundwater Study; June 2013.

CHAPTER 4
Recommendations for Data Collection and Model Integration

Table of Contents

List of Figures

List of Tables

1.0 OVERVIEW

Recommendations for data collection and model integration are based on a limited set of possible future uses of groundwater information tools, a review of existing groundwater data and studies, and a range of conversations with local and national specialists on the development of integrated watershed models. WRIA 1 Joint Board organizations and Watershed Staff Team provided input on recommendations for linking WRIA 1 surface and groundwater modeling applications using a series of technical reviews of compiled groundwater information and input on short and long-term priorities for technical tools to support water resource planning and management in WRIA 1 (see Appendix A for a summary of technical input and questionnaire responses).

The recommendations outlined in this chapter are technical in nature and focus on the type of data that need to be collected and which model improvements/developments are necessary based on the anticipated future uses of groundwater information. For example, in order to better understand surface and ground water interaction, we recommend continuous water-level time series data collection at a network of well locations distributed at multiple distances from streams and along priority tributaries, and streamflow data collection above and below specified study sites. Model recommendations are presented as multiple steps from short-term to long-term using concepts and software that are customized for WRIA 1, but reviewed and validated in other watersheds and informed by technical consultations with specialists familiar with WRIA 1 groundwater resource information and tools (see Appendix B for summary of technical specialist input).

The scope of the recommendations includes exploration of multiple options for linking surface and groundwater models. One option is to couple WRIA 1's existing Topnet-WM with MODFLOW groundwater model using Integration Hydrology Model, IHM, (Geurink and Basso 2012). An alternative to the development of an integrated model (coupling two existing models), is the option of using WRIA 1 model inputs developed for Topnet-WM (Tarboton 2007, Bandaragoda 2008, Bandaragoda et al. 2012a) and MODFLOW (Pruneda 2007, Barber and Wu 2008, Pruneda et al. 2010) or FEFLOW (Simpson 2012) as inputs to an already existing and well supported integrated model (e.g., MIKE-SHE) which does not require additional software development to complete the task. In this approach all components of interest for representing hydrologic and water management processes that are available in Topnet-WM and MODFLOW are also available in MIKE SHE (with use of integrated MIKE 11 and FEFLOW components). An advantage of using MIKE SHE is that groundwater recharge is not specified as a boundary condition as it is in MODFLOW. As with Topnet-WM, recharge is calculated internally and controlled by assigned unsaturated zone hydraulic properties. However, since surface (MIKE 11) and subsurface (FEFLOW) are already dynamically coupled, MIKE SHE allows for free exchanges between surface and groundwater, rather than requiring flow processes to be partitioned between different models (Wobus et al. 2012).

Developing questions and decision-making frameworks with which to put the model to use is a central challenge in the development of a modeling system. In this project, the purpose statement regarding integrated tools was identified by the project team and technical reviewers as follows:

"What can we do* to *allocate water for existing and future uses and how can we best avoid, reduce magnitude, and/or mitigate impacts while maintaining instream flow and reduce uncertainty in low flow periods?"

To begin to address this question in this project, we completed the following tasks: (i) reviewed available groundwater quantity data/references for WRIA 1 (*Chapter 1*), (ii) organized that data into a searchable database that is linked to GIS and can be used to identify data gaps (*Chapter 2*), (iii) assessed the available water source information and data gaps (*Chapter 3*), (iv) surveyed the technical team to gain an understanding of the types of water management issues they would like addressed in the future (Appendix A), and (v) have applied our technical backgrounds, information collected by phone interview with a range of local and national experts (*Appendix C*), and understanding of the available information to develop recommendations for addressing WRIA1 water management issues/questions (*Chapter 4*) including data collection and model development.

It is in the long-term interest of WRIA 1 to be both efficient with the long term model development plan, as well as improve the quality of the model usefulness by validating it for decision making at each step of advancement in knowledge of the physical watershed system. Integrating codes for surface and groundwater model may involve more cost and uncertainty than transitioning existing datasets and parameters to an existing integrated model. The information outlined in this chapter aims to address these information needs across scales: site-specific, drainage, and regional, surface and ground water resources and their interaction.

2.0 INFORMATION

2.1 Need for a Groundwater Model

Based on questionnaire responses from WRIA 1 Joint Board Staff Team members, the highest priority for near term model development is on a site or sub-drainage scale to improve understanding of the effects of pumping groundwater on surface water streams. This question can be answered within a set boundary area, such as a subdrainage area draining to a streamflow reach (i.e., at an instream flow point), and take into account the cumulative effects of groundwater pumping that would affect flow at that location. The magnitude and timing of pumping effects on streamflow are a key area of groundwater knowledge important to water resource managers in WRIA 1. Good representation of the groundwater flow paths, as well as a complete representation of the hydrologic cycle (water budget) including the water movement through the unsaturated zone is required with appropriate scientific rigor to answer this question. Further, the climate and subsurface inputs to the subdrainage area, or boundary conditions are required from a regional scale model in order to more accurately represent the effects of regional hydrology on the local area.

Current and future surface water impacts from groundwater use need to be quantified not only in regard to quantities, but also timing and geographical locations of points of withdrawal and places of use, to a level of reliability that is adequate to satisfy various federal, state, and tribal governments, regulatory agencies, tribes, and other interested parties (farmers, environmental groups, etc.). Achieving the necessary level of reliability regarding potential impacts from **surface water uses** can be accomplished using a surface water model (i.e., Topnet-WM, MIKE 11) that is populated with an appropriate amount of data and properly calibrated. One of the primary challenges with using a surface water model to address these issues in WRIA 1 is the general lack of adequate/ reliable/ accurate data regarding the locations, timing and quantities of surface water uses, both permitted and unpermitted.

Estimating the potential impacts to surface water from **groundwater uses** is possible using a sophisticated numerical transient groundwater model (i.e., MODFLOW, FEFLOW, SEEP/W) that is populated with an appropriate amount of data and properly calibrated to a sufficient amount of time-series groundwater level and streamflow data. The primary challenges associated with developing a reliable groundwater model are related to the degree of understanding of the geologic/hydrogeologic setting of the model domain and the ability to populate the model with enough accurate/reliable data to ensure that the results of the model are relatively accurate and, just as importantly, acceptable to the various interested organizations. Based on our review of the available data there are likely only a few specific areas of WRIA 1 where there may be enough geologic/hydrogeologic and other data necessary to construct a numerical groundwater flow model that would be capable of estimating potential impacts to surface water to the degree of reliability that appears to be necessary for decision-making by participating organizations.

Table **1** outlines the different levels of data and demands of a numerical groundwater flow model, described above, depending on the information needs regarding impacts from groundwater use. Site and sub-drainage specific groundwater use impacts are the scale of model function of most interest for WRIA 1 water resource issue questions in the near-term. The data requirements needed to evaluate these impacts can be intensive, but can be limited to a specific area of interest (pilot or case study), and potentially addressed using a high resolution (high detail) model if a coarse resolution model the extent of the watershed can be used for determining appropriate boundary conditions, or initializing inflow values at the edge of the domain of the study area.

Table 1. Information of groundwater use impacts and model requirements.

Groundwater Use Impacts	Data	Model
Site and sub-drainage specific	Site-specific data; intensive data requirements for a limited area of cumulative impacts upstream of a particular site.	High resolution, small-scale; developed for representing site-specific impacts over a limited extent.
Drainage specific	Drainage averaged site-specific data; moderately intensive data requirements.	Medium resolution; developed for representing and drainage impacts.
Watershed impacts	Average of existing data; longer time frames (seasonal, annual) and impacts averaged over each drainage.	Low resolution; developed for assessment of impacts and relative comparison of scenarios on a watershed scale (drainage average over a multi-drainage extent.

Much of the data input/output of a surface water model is useful in the construction and calibration of a groundwater model. Conversely, the data input/output of a groundwater model can be used as data input to a surface water model. The overall reliability of either model can be significantly increased when it is "coupled" with the other model.

Coupling of the models can be manually accomplished during model construction/calibration by a comparison of data input/output or the models can be physically linked (integrated), although appropriate linking of models that maintains mass balance and a 'balanced water budget' so to speak, is an ongoing area of research and development. MIKE SHE is the best known commercially available integrated model with professionally supported and tested software and user interfaces. All components of interest for representing hydrologic and water management processes available in Topnet-WM and MODFLOW are also available in MIKE SHE (with use of the MIKE 11 and FEFLOW components).

2.2 Current Uses of Groundwater Information

There are three notable recent and ongoing studies using MODFLOW models in WRIA 1. Western Washington University (WWU) has an ongoing study which collected well-log data, water levels, and hydraulic parameter estimates to be used in Groundwater Modeling System software (GMS; user interface for MODFLOW) to develop a three-dimensional conceptual stratigraphic model and determine general groundwater flow patterns in the Squalicum Valley (Lake Whatcom Watershed) (Thane and Mitchell 2013). Washington State University (WSU) developed a steady state regional-scale numerical groundwater model (MODFLOW) to study the impacts of replacing surface-water use with groundwater wells to improve low-flow stream conditions for endangered species within the Bertrand and Fishtrap watersheds (Pruneda 2007, Pruneda et al. 2010). Simon Fraser University (SFU) has recent investigations in the water quality of the trans-national Abbotsford-Sumas aquifer. Vadose zone transport simulations have been undertaken using a 1-D (SEEP/W) and 3D numerical groundwater model (MODFLOW) to investigate the movement of nitrate within the aquifer, both from historical and future perspectives (Scibek 2005, Scibek and Allen 2006, Chesnaux et al. 2007, Chesnaux et al. 2011). After recognizing the SEEP/W and MODFLOW did not sufficiently represent transient flow conditions in the Abbotsford-Sumas aquifer, the FEFLOW model (subsurface component that is coupled to MIKE-SHE) was used to assess the risk to groundwater quality, with a focus on the Langley township but with a model area extending into the US to the Nooksack River (Simpson 2012).

2.3 Models and Integration

Since Topnet-WM was developed with modeling components specifically designed for WRIA1 (2005-2007), significant developments have occurred in the field of integrated modeling, or linking of ground and surface water models. For one example, the Danish Hydrologic Institute (DHI) offers a commercially supported model, MIKE-SHE, which now is available with a finite element integrated groundwater flow component (FEFLOW). For another example, the Tampa Bay Water Authority has spent more than a decade as well as several million dollars and recently completed the development and validation of an Open Source integrated HSPF[1] and MODFLOW model, Integrated Hydrology Model (IHM). Documentation, a user's manual, and training for IHM are now under development.

It is worthwhile for WRIA1 Joint Board Staff Team to consider professionally maintained models, such as MIKE-SHE, compared to the effort required to integrate computer code for a groundwater model to work interactively with Topnet-WM, such as by using IHM model coupling techniques. The latter task can be costly and time consuming and may not be the most efficient way to attain technical tools required to explore solutions to WRIA 1 problems.

2.3.1 MODLOW

MODFLOW (MODular 3D Finite-Difference Ground-Water FLOW Model) is a three dimensional groundwater flow model developed by the United States Geological Survey (USGS) and used extensively in the United States and in many studies in the Sumas-Blaine aquifer (also referred to as the Abbotsford-Sumas aquifer by Canadian colleagues), with examples above given for WRIA 1 (SFU, WSU, and WWU modeling projects(Scibek and Allen 2006, Pruneda 2007, Pruneda et al. 2010, Chesnaux et al. 2011, Thane and Mitchell 2013)). Because the model is modular and open source, many additional functions and packages have been developed along with graphical user interfaces (usually proprietary). Packages for streams, drainage (agricultural water management) and evaporation can be added to MODFLOW, but neither overland flow nor flow simulations in the unsaturated zone can be simulated using MODFLOW. The unsaturated zone, or vadose zone, is the area below the land surface and above the water table. Because the water table is constantly in flux, modeling the movement of infiltrated surface water through the unsaturated zone can be critical to capturing the water table movement in some watersheds and during certain times of year.

An example of a MODFLOW groundwater model was completed for the City of Sumas to evaluate wellhead protection issues; this was not developed to assess surface/ground water interaction (Guzha 2008). Nonetheless, the presentation is useful to understand MODFLOW functionality at its most basic level. Simply stated, the minimum data needed to parameterize MODFLOW is shown in Table 2. On average, the Sumas outwash deposits have horizontal hydraulic conductivities ranging from 7 to 7800 ft/day (Tooley and Erickson, 1996). Pump tests performed in the Strandell well field to the south of the City of Sumas gave values for transmissivity (T), specific yield (Sy), and horizontal hydraulic conductivity (Guzha 2008). A groundwater flow model designed to address surface water/groundwater interaction, such as needed in WRIA 1, would need a significant amount of information regarding nearby surface water bodies including but not limited to the hydrogeologic properties of the sediments immediately underlying the surface water bodies, and streamflow groundwater seepage data.

[1] **H**ydrologic **S**imulation **P**rogram - **F**ortran

Table 2. Example of MODFLOW groundwater hydraulic parameters for the City of Sumas.

Parameter	Average Value
Hydraulic Conductivity	130 ft/day
Transmissivity	2420 sq ft/day
Specific Yield	0.2
Aquifer Thickness	20 ft

The density and types of data needed for any model are a function of the proposed uses of the model and the reliability requirements of the model application. For example a model designed to estimate the potential impact of single or multiple groundwater withdrawals on the flow in a nearby stream for a water right assessment would likely need a significant amount and a high density of site/drainage specific geologic/hydrogeologic information, water use data and streamflow information. However, a model designed to qualitatively evaluate the general impact of a regional change in land-use on groundwater quantity in a basin could likely be completed with a minimal amount of geologic/hydrogeologic and water use data. Any groundwater model developed to address the types of water management issues presented by the WRIA 1 Joint Board Staff Team would likely require a significant density of geologic/hydrogeologic data, including but not limited to time-series groundwater level data, streambed conductance data, seepage data, recharge, water use, aquifer characteristic data, and land use information.

What MODFLOW can do: represent groundwater flow/levels and aquifer-channel seepage.

What MODFLOW can*not* do: storm-event modeling; surface water control structures; or represent full hydrologic cycle water budget since overland flow and unsaturated zone are not simulated.

2.3.2 TOPNET-WM

Topnet-WM refers to the Water Management version of Topnet developed as a work product for the Utah State University (USU) WRIA 1 Watershed Management Project (Tarboton, 2007). This version of the model evolved from the Topnet Model developed in a collaboration between NIWA New Zealand and USU (Bandaragoda et al. 2004, Ibbitt and Woods 2004) that combines TOPMODEL concepts (Beven and Kirkby 1979, Beven et al. 1995) for the simulation of relatively small drainages combined with channel routing. In Topnet-WM, spatial variability is represented by subdividing the watershed domain into model elements at the scale of drainages. Topnet-WM includes many enhancements beyond the original Beven and Kirkby TOPMODEL, such as:

(1) calculation of reference evapotranspiration using the ASCE standardized Penman-Monteith method (e.g., Jensen et al. 1990);
(2) calculation of snowmelt using the Utah Energy Balance Snowmelt model (Tarboton et al. 1995);
(3) the partition of model elements into separate components representing irrigated and non-irrigated areas;
(4) artificial drainage to represent the effect of ditch and tile drained areas on the runoff response;

(5) the partition of the model elements into pervious and impervious areas to allow representation of urbanization;
(6) options for the diversion and storage of water under different management options; and
(7) components to calculate water use and implement water right rules.

What Topnet-WM can do: represent full hydrologic cycle water budget, represent drainage average sub-surface storage of water and water management functions including artificial drainage, water right allocations, and surface and groundwater uses.

What Topnet-WM cann*ot* do: represent groundwater levels of regional aquifers or sub-surface movement of water between drainages (drainage sub-surface water is modeled as draining directly to channels) and aquifer-channel seepage

2.3.3 Integrated Hydrologic Model (IHM) and Northern Tampa Bay (INTB) Model

Development and application of an integrated hydrologic model for the west-central Florida region spans almost 25 years and costs several million dollars, with several generations of dynamically linking HSPF with MODFLOW models used for water resource assessments (USGS 2000c). Throughout the 1990s, the integrated model needed modifications and enhancements (USGS 2000d, b) that took many years to iteratively assess and implement. The current version of the model is the third generation of implementation. In 2004-2007, $1.4 million was spent on model development using consulting firms and contractors. After that investment, significant improvements for satisfactory model outputs remained, and Tampa Bay Water, a public utility, hired and maintains a staff of 3-4 Ph.D. level engineers and modelers who develop and maintain the model (among other work) within their organization.

IHM is a Visual.net code wrapper that controls the HSPF and MODFLOW models. This code and model has been professionally reviewed and approved. Theory and concept documentation, as well as a user manual is currently in production, with IHM training services is anticipated in the future.

What IHM can do: represent full hydrologic cycle water budget, represent groundwater levels of aquifers and aquifer-channel seepage. IHM model wrapper is an open source code that could be used for running individual models such as Topnet-WM and MODFLOW.

What IHM cann*ot* do: water management functions including artificial drainage, water right allocations, and surface and groundwater uses. Instead of HSPF and MODFLOW coupling, for use in WRIA 1, IHM theory could be used and code base modified to couple Topnet-WM and MODFLOW.

2.3.4 MIKE SHE (with MIKE 11 and FEFLOW)

In 1977, a consortium of three Europeans began development of the Système Hydrologique Europèen (SHE), and integrated hydrological modeling system, MIKE-SHE. Since the mid-1980's, MIKE SHE has been further developed by the Danish Hydrologic Institute (DHI) Water and Environment and today is an advanced framework for hydrologic modeling covering the processes of evapotranspiration, overland flow, unsaturated flow, groundwater flow, channel flow and interactions, can represent artificial drainage as well as surface and groundwater uses, as well as limitations on uses (such as priority dates). Different processes can be represented at different levels of spatial distribution and complexity, and there is a user interface to aid in building and describing the numerical model based on the conceptual model of the watershed (DHI 2012).

What MIKE SHE can do: represent full hydrologic cycle water budget, represent groundwater levels of aquifers and aquifer-channel seepage. For use in WRIA 1, many Topnet-WM and MODFLOW parameters and data inputs could be used as MIKE SHE model inputs for MIKE 11 surface and FEFLOW subsurface components.

What MIKE SHE cann*ot* do: MIKE SHE is a proprietary commercial software product. The code base is not available for modification outside of the DHI development.

2.4 Methods for Integrating Models Using Existing Information

Integrating hydrology and water management is generally done by three basic methods shown in Table 3 (USGS 2000a). Model linkage is a method of connecting various traditional or existing models in a basin and passing information between the models. The early work of integrating hydrology models done in WRIA 1 (Guzha and Hardy 2010), between MODFLOW groundwater model and Topnet-WM hydrology model with limited success. It is not known whether the lack of success was due to the calibration of the individual models or the methods used to integrate the models. Another example of model linkage is using climate change scenarios as a one-way input into a hydrology model.

Lumped parameterization is another way to link models, where a single data value or parameter is used to represent a process. For example, in the current Topnet-WM model, the ratio of surface water and groundwater sources used to meet irrigation demand is a lumped parameter that represents the physical process occurring over a drainage. This approach is especially useful when little data are available to represent the hydrologic processes. Finally, physically based model integrations incorporate complex and empirically based algorithms (requiring intensive data inputs) to represent both the physical hydrology and the water management decisions. The existing algorithms representing water rights in the Topnet-WM hydrology model (although they remain untested to date) are an example of physically based model linkage.

In the current state, the WRIA 1 watershed model Topnet-WM (Bandaragoda et al. 2012b) links various elements of the model architecture using a combination of all three methods shown in **Table 3**. The integration of a groundwater model could likewise follow any one of these approaches depending on the data availability and model robustness requirements.

Table 3. Two basic methods for integrating watershed models (USGS 2000a).

Method	Advantages	Disadvantages
Model Linkage	Physically-based hydrology; detailed operations; uses existing models and data such as Topnet-WM (Lower Nooksack Water Budget) and MODFLOW (WSU & Simon Fraser).	Spatial scale mismatch issues Time scale mismatch issues Difficult to calibrate
Physically Based	Most robust hydrology Most robust integration Captures full feedback of watershed processes (IHM linking of HSFP or MIKE-SHE).	Higher computational requirements Higher data requirements Limited domain size

2.5 Model Evaluation by Others

For perspective on the resources required and consideration taken for model development, the project team reviewed the consideration process and outcomes for the model chosen for the Comprehensive Everglades Restoration Project in Florida. For an idea of the scale of effort such a task requires, ten steering committee members and six evaluators developed a study evaluating the costs and benefits of 15 models or combinations of different models (Central and Southern Florida Project 2002) including those listed in Table 4.

Table 4. List of 15 models or combinations of models evaluated for the Everglades Restoration Project (Central and Southern Florida Project 2002).

Integrated Models Evaluated		
adICPR	InHM	MODHMS
BASINS with FEQ	ISGW	MODNET
HSPF	MIKE SHE/MIKE 11	SFRSM including HSE
FEQ	MODBRANCH	EPA SWMM/XP-SWMM 2000
HEC-HMS/HEC-RAS with UNET	MODFLOW	WASH123D

Each model was described and evaluated, with the limitations and advantages listed and the ability of the models to meet each of the following criteria tabulated. Capability criteria included the following:
(1) Simulating groundwater levels around wetlands and groundwater storage facilities;
(2) Simulating rapidly changing groundwater levels and flow and two-way aquifer-channel seepage;
(3) Providing a water budget (pump discharge flows, seepage losses, ET, rainfall, water supply, etc.);
(4) Exchanging data with the 2x2 model in a grid format;
(5) FEMA-approved storm event modeling and continuous modeling for a number of years;
(6) Modeling common type hydraulic control structures with on-off triggers (weirs, gates, pumps, etc.);
(7) Modeling canal geometry versus grid simulation only, exchanging data with DSS;
(8) Graphical user interface with pre- and post-processing capabilities;
(9) Simulate conditions similar to those found in the watershed; and
(10) Model set-up and execution times to meet project schedule.

In the Central and Southern Florida Project (2002), the following three models were selected for further evaluation, listed below. For these criteria, MIKE SHE with MIKE 11 met 9 of the 10 criteria and the other models met 6 of the 10.

- MIKE SHE with MIKE 11
- Combination of HEC-HMS, HEC-RAS with UNET, and MODNET
- Combination of XP-SWMM2000 and MODFLOW

The further model performance capabilities compared to choose between a MIKE SHE with MIKE 11 model or other coupled HEC-MODFLOW or SWMM-MODFLOW models included:

(1) Additional quantity, timing, distribution of water for subsequent projects;
(2) Improvements to water quality (WQ) for natural system;
(3) Water needs for natural system;
(4) Document 2000 level of flood protection;
(5) No loss of quantity, flood protection, water distribution;
(6) Document impacts to wetlands;
(7) Evaluate last-added increments;
(8) Describes regulation schedules, water control and operating criteria;
(9) Describe water fluctuations; and
(10) Distribution of water during droughts.

A final set of criteria included the factors listed in Table 5, where the *GW Assessment* project team applies local knowledge and experience with Topnet-WM and WRIA 1 resources to add information to compare the models evaluated by the Everglades project. In many ways, Topnet-WM coupled with MODFLOW will require similar effort, for example, to parameterize and set up a new MIKE SHE (MIKE 11 and FEFLOW) model. Topnet-WM water management, hydrology modeling and water budget components are comparable to those in MIKE SHE with MIKE 11, and the data input and parameterization of MODFLOW is almost identical to the finite element model using the same governing equations and algorithms in MIKE SHE with FEFLOW to model the groundwater component. The main difference is that MIKE SHE is already a coupled dynamic integrated model with extensive documentation and peer review. While Topnet-WM and MODFLOW are individually well documented and peer reviewed, software integration has not been done successfully before and therefore remains undocumented and unreviewed.

Table 5. Additional factors to consider in model selection (Criteria list and MIKE SHE/MIKE 11 values taken from Table 5 (Central and Southern Florida Project 2002).

Criteria	Topnet-WM with MODFLOW	MIKE SHE with MIKE 11 and FEFLOW
Level of Effort to Set up the Model	High	High
Required Iterations during Scenarios	Low	Low
One Model for WQ/Hydrology/Hydraulics/Structures	No	Yes
Difficulty of Use by agencies after project is done	High	High
Level of Effort to Coordinate WQ/Hydrology/Groundwater/Hydraulics/Structures	High	Low
Extensive Documentation, Peer reviewed	Moderate	High

2.6 Data Improvements Needed to Address WRIA 1 Scale and Function Questions

Input from WRIA 1 Joint Board organizations provided insight on the range and spatial extent of desired future model applications, and *Chapters 1* and *2* have provided a summary of the groundwater data available for model inputs (i.e., aquifer characteristics, groundwater recharge/discharge areas, and surface/groundwater interactions). In Table 6, we outline model requirements for a range of levels of model reliability and model complexity.

Table 6. Model reliability requirements for a range of levels of reliability and applications.

	Groundwater Model Reliability		
	Low	**Moderate**	**High**
Groundwater Model	1 layer vertical GW model; **regional** estimates of parameters.	2-5 layer vertical GW model; **drainage** estimate of parameters.	5-15 vertical layers; **site specific** estimates of parameters; model improvement depends on fit on data and calibration.
Groundwater Data Source	Past regional and drainage studies.	Past drainage studies and gaps filled by regional studies.	Site specific studies with gaps filled by drainage studies.
Climate Data	Monthly averages.	Daily averages.	Sub-daily with continuous data collection.
Seepage Data	Based on estimated stream flow for specific reaches	Some data from seepage runs	Data from multiple seepage runs on numerous streams.
Water Level Data	Minimal based on information presented on water well reports.	Water well report data augmented with some time-series water level data.	Numerous locations and aquifers with time-series water level data.
Streambed Conductance	Estimated based on geology and streambed geomorphology.	Some field measured streambed conductance on selected streams.	Field measured streambed conductance in numerous locations on important streams
Streamflow Data	Sparsely gaged.	Gages at drainage outlet.	Multiple internal gages co-located to GW measurements and climate data.
Aquifer Parameters	Minimal data based on regional studies and specific capacity data on water well reports.	Scattered aquifer testing data supplements with specific capacity data on water well reports.	Aquifer parameters based on numerous long-term aquifer tests.
Example Uses	Ability to evaluate down-gradient impacts of changes in water and land use to support mitigation and natural resource trading.	Determines the effect of changing water use from self-supplied to municipally supplied water sources.	Determine accuracy of model predictions needed for decision making.
Gaps 2013	Sufficient data to parameterize a regional model for the complete extent of WRIA 1.	Insufficient data everywhere with the exception of Bertrand and Fishtrap Creeks, possibly Drayton Harbor, and Lummi Peninsula*.	Insufficient data everywhere.

*Because the Lummi Peninsula has special water quality issues, this would require specialized modeling.

2.7 Integration Options

Generally, there are two approaches to develop integrated model functions appropriate for WRIA 1.

- Integrate models tailored to WRIA 1 with model code based on open source platforms (Option A & C); or
- Use a commercially available integrated model with proprietary components that are serviced and maintained by a provider (Option B).

While the latter approach is less customized, ongoing support and maintenance is available. Customizing a product specific to WRIA 1 requires substantial resources to maintain and support.

In discussions with technical experts, we found that a groundwater model for a significant portion of the lower section of WRIA 1 does exist at a regional scale (Figure 1). The FEFLOW groundwater model developed at Simon Fraser University (SFU) covers part of Whatcom County from the International Border to the Nooksack River and west to the Lummi Peninsula (Simpson 2012). Facilitating and supporting collaborative modeling and data collections with the developers may be in the long-term best interest of WRIA 1. This approach offers both cost effective and time efficiency advantages.

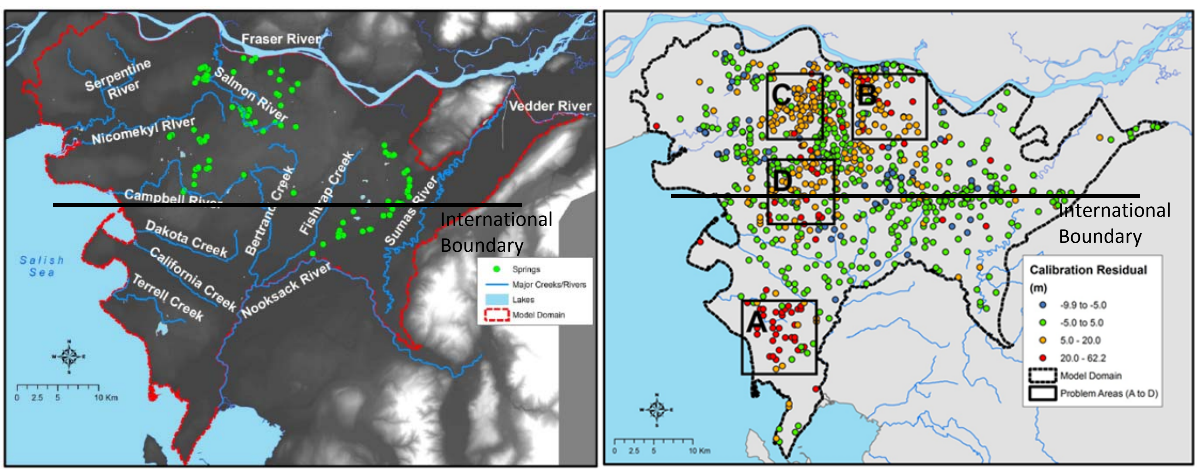


Figure 1. FE Flow groundwater model extent, major creeks (left) and calibration results (right), taken directly from Simpson (2012).

The FEFLOW regional model could be used to establish boundary conditions for smaller scale local models in WRIA 1. We recommend exploring data and model sharing opportunities by promoting an agreement process facilitated by members of the Abbotsford Sumas International Task Force. This approach would rely on collaboration with Simon Fraser University as well as the Danish Hydrologic Institute (DHI) to further develop the existing modeling system, but may prove to be the most cost effective alternative.

Figure 1, sections A-D show where more data may be required to improve the FEFLOW regional model calibration. Existing U.S. data that was not included in previous FEFLOW work (completed in 2012) could be added to refine the calibration in the WRIA 1 portion. To address site, sub-drainage, or drainage scale issues, additional data collection will be necessary to develop higher resolution sub-models useful for sub-drainage applications.

Collaborative work on a regional groundwater model for WRIA 1 could include the following tasks:

- Promote development of a data and model sharing agreement through the Abbotsford Sumas International Task Force.
- Extend the SFU FEFLOW model domain to add the mountains and Nooksack River drainages not currently included,
- Use existing surface water and water management model inputs and parameterizations to populate the MIKE suite of model components one of which is a rainfall runoff model similar to Topnet,
- Use coupled MIKE11-FEFLOW regional model to identify areas of concern, and
- Perform a local or sub-drainage scale case study by adapting a sub-model of the regional scale integrated surface-groundwater model.

3.0 SUMMARY RECOMMENDATIONS TO ADDRESS MODEL GAPS

3.1 Basic Tasks for Data Collection and Compiling a Groundwater Model

The basic tasks for data collection and compiling a groundwater model include:

(1) Compile existing information; [Recommended in *Lower Nooksack Water Budget* and completed for groundwater data with this work]. Select the specific domain of the model. The model domain should be determined based on the types of water management issues the model will be used to address and the amount of pertinent available data needed to construct the model.

(2) Establish groundwater level monitoring networks and conduct seepage runs, as needed within the selected model domain [Seepage analyses have been conducted in Johnson, Tenmile, Bertrand, and Fishtrap drainages]. The data we have are sufficient for building a conceptual model and parameterizing an initial numerical model in those drainages, but further data would need to be collected.

(3) Estimate ground-water recharge [Available from outputs of the *Lower Nooksack Water Budget*]. Topnet-WM would need further calibration to do this step adequately at both high and low flows.

(4) Estimate groundwater and surface water use, source locations, and places of use [Recommended in the *Lower Nooksack Water Budget*]. Data gaps identified in Chapter 3 should be addressed here. Source locations and places of use need to be identified for all data gaps delineated in Chapter 3.

(5) Characterize hydrogeologic framework and develop conceptual model. It has been determined in this work that there is sufficient information to be used for regional characterization, and also in some locations, drainage and site characterizations.

(6) Use the conceptual model to identify critical data gaps or specific areas where a refinement of data is needed.

(7) Determine model(s) to consider using and investigate further which model is most appropriate.

(8) If required, develop code to integrate MODFLOW with TOPNET (not the top recommendation).

(9) Construct and calibrate a groundwater model or use FEFLOW groundwater model and Topnet-WM model inputs with an integrated watershed model.

(10) Identify and simulate management alternatives, process output, present and document results.

Recommendations listed in Table 7, Table 8, Table 9 and Table 10 include a brief description of how the model integration with Topnet-WM could be managed. Option A is to use existing MODFLOW and Topnet-WM code and integrate the models using a code 'wrapper' which would dynamically link the models. Dynamic linking of models is important because the water balance components are communicated between the models for each time step; the surface water model changes when the groundwater model changes and vice versa. The use of this method is described in the section below highlighting the development of an integrated model for Tampa Bay.

The recommended alternative, Option B, is to use Topnet-WM parameters and port them for use in MIKE-SHE integrated model which has the integrated code completed, verified, and supported for continuous development. In this case, Topnet-WM datasets used to develop the *Lower Nooksack Water Budget* and FEFLOW datasets and model parameters from Simpson (2012) could be used to develop a regional scale MIKE-SHE model. The regional scale model can be used to determine regional aquifer and hydrology affects (boundary conditions) on a case study in a smaller sub-drainage study area.

3.2 Recommendations for Short-term Actions

Table 7. Recommendations for short term actions.

Tasks	Short-term 1-3 year Time Frame; 2 year duration; Total Cost Range $470,000-$625,000	Estimated Cost
Conceptual Model Development	Define study area and analyze available well and other hydrogeology data in the study area for parameterization of a groundwater model. Define model inputs for regional WRIA 1- extent and/or of sub-models where intensive data exist and at prospective locations that could be managed in real-time in the future (long-term). Develop and document geologic and hydrogeologic framework to be used as basis for the numerical model.	$45,000 - $75,000
Data Collection	Establish and operate surface and groundwater data collection network in the study area. Add instrumentation to selected wells at various distances from creek and distances along creek with continuous data recorders (minimum 2 per priority drainage (5 selected drainages) and 12 at intensive 1-2 sites study area). Seepage runs with 5-15 streamflow measurements in tributaries near selected locations. Update water management inputs for higher resolution network of Topnet-WM models in Fishtrap and Bertrand Creek. Improve estimates of water use for public water systems, exempt wells, irrigation source water and location for all uses (See Chapter 3 Recommendations). Includes data storage and data management. Collect and analyze additional aquifer testing data in selected locations. It is anticipated that this would involve short-term pump testing of existing wells.	$300,000- $400,000
Numerical Model Development: *Investigate other integrated models that are available and discuss options with developers of those models.*	**Option A:** Characterize the hydrogeologic framework for groundwater model parameterization. Characterize the surface and groundwater use and sources. 'Loosely couple' existing groundwater and surface models by using surface water model recharge as groundwater model input; groundwater model water table level as surface water model adjustment to subsurface storage state variable. Model domain will likely be limited to domain of existing MODFLOW groundwater models and using Topnet-WM in the short term. **Option B:** Characterize the hydrogeologic framework for groundwater model parameterization. Characterize the surface and groundwater use and sources. Set up Integrated Mike-SHE model using parameters and relationships developed in Lower Nooksack Water Budget and earlier work for Topnet-WM. Model domain for complete WRIA 1 extent. **Option C:** Use IHM (HSPF & MODFLOW) and set up MODFLOW as in Option A. Future work would involve adding water management options.	$75,000- $100,000
Local Use and Applications	Explore possible tools and locations for a range of management alternatives, climate, and land use scenarios on regional, drainage, and site scales. Technology transfer for multiple user groups; includes soliciting public opinion on decisions and communicating results in public venue to increase use of existing information and accessible tools.	$50,000 - $60,000

3.3 Recommendations Mid-term Actions

Table 8. Recommendations for mid-term action.

Tasks	Mid-term 3-6 year Time Frame; 2 year duration; Total Cost Range $350,000-$550,000	Estimated Cost
Conceptual Model Development	Update conceptual model based on Short -term project inputs. Develop set of scenarios for model testing.	$15,000 - $30,000
Data Collection	Continue operation of data collection network.	$75,000 - $150,000
Numerical Model Development	**Option A:** Use Integrated Hydrology Model (IHM) code wrappers to dynamically link surface and groundwater models (Topnet-WM & MODFLOW). Parameterize and calibrate model over WRIA 1 extent with objectives at sub-model site locations. Run scenarios, analyze outputs, and present results. **Option B:** Use integrated WRIA 1 model with Mike-SHE algorithms (with inputs ported from Topnet-WM) as boundary conditions for higher resolution sub-model in Bertand and Fishtrap Creek basins. **Option C:** Use IHM (HSPF & MODFLOW) and integrate water management options.	$200,000- $250,000
Local Use and Applications	Use the decision making framework to design scenarios. Technology transfer for multiple user groups; includes soliciting public opinion on decisions and communicating results in public venue to increase use of existing information and accessible tools.	$50,000 - $100,000

3.4 Recommendations for Post Mid-term Actions

Table 9. Recommendations for post mid-term actions.

Tasks	Post –Mid-term 5-8 year Time Frame; 2 year duration; Total Cost Range $270,000 - $325,000	Estimated Cost
Conceptual Model Development	Develop recommendations for future development of model.	$20,000-$25,000
Data Collection	Continue operation and limited expansion and adjustment to data collection network.	$100,000-$150,000
Numerical Model Development	Parameterize and calibrate integrated model. Test scenarios.	$100,000
Local Use and Applications	Technology transfer for multiple user groups; includes soliciting public opinion on decisions and communicating results in public venue to increase use of existing information and accessible tools.	$50,000

3.5 Long -term Planning Options

Table 10. Recommendations for long-term planning options.

Tasks	Long-term 10-20 year Time Frame; Ongoing duration; Total Annual Cost Range $140,000 - $245,000	Estimated Cost
Conceptual Model Development	Develop recommendations for future development of model.	$10,000-$20,000
Data Collection	Maintain operation of data collection network; data storage and data management.	$50,000-$75,000
Numerical Model Development	Test updated scenarios and management decisions. Continuously improve understanding about the watershed physical processes and ongoing impacts. **Option A:** Model code maintenance uncertain, but open source and available. **Option B:** Model code maintained by DHI software developers, proprietary code base with annual updates and service packs that address code issues. $16,000 one time license with annual maintenance fees and agreement to run the model. Inputs, outputs and analysis would be publicly available. **Option C:** Model code maintenance by Tampa Bay Water Authority (4 full time modeling staff) and other future model users; Open Source and available.	$50,000-$100,000
Local Use and Applications	Includes soliciting public opinion on decisions and communicating results in public venue to increase use of existing information and accessible tools.	$30,000-$50,000

4.0 LIST OF CONTRIBUTORS

Table 11 provides the list of technical reviewers invited to provide comments on draft and final groundwater information compilation, assessment and presentations of the WRIA 1 Groundwater Data Assessment work. Active technical reviewers and participants in the questionnaires regarding future uses for integrated surface and ground water tools included Jeremy Freimund, Oliver Grah, Kasey Cykler, Rebecca Schlotterback, Peter Gill, Clare Fogelsong, and Jon Hutchings.

Table 11. Technical Review Information and orientation recipients.

Review Orientation & Packet Recipients		
Rebecca Schlotterback PUD No. 1 of Whatcom County	Mark Personius Whatcom Co. Planning Dept.	Kasey Cykler, Washington Dept. of Ecology
Steve Jilk PUD No. 1 of Whatcom County	Jon Hutchings, City of Bellingham	Doug Allen, Washington Dept. of Ecology
Peter Gill, Whatcom Co. Planning Dept.	Clare Fogelsong, City of Bellingham	Becky Peterson, WRIA 1 Joint Board Contract Mang
John Thompson, Whatcom Co. Public Works	Jeremy Freimund, Lummi Nation Natural Resources	Chris Brueske, Whatcom Co. Planning Dept.
Oliver Grah, Nooksack Tribe Natural Resources	Victor Johnson, Lummi Nation Natural Resources	Frank Lawrence III, Lummi Nation Natural Resources

5.0 ELECTRONIC DATA

Electronic Data Tables structure the organization of the *WRIA 1 Groundwater Data Assessment* project deliverables including those containing source data, code, and other intermediary data products and outreach tools to be published on the WRIA 1 Watershed Management Project website.

Electronic Data Table 1. Appendix files.

Description	Folder & File Name(s)	Contract Task
Comments & Responses	WRIA1GW_Chapter4_AppendixB_Comments_20130630.docx	4
Technical consultation phone interviews	WRIA1GW_Chapter4_AppendixC_TechnicalConsultations_20130630.docx	4

5.0 REFERENCES

Bandaragoda, C. 2008. Bertrand Creek Hydrologic Model Update and Assessment.

Bandaragoda, C., J. Greenberg, M. Dumas, and P. Gill. 2012a. Lower Nooksack Water Budget Overview.*in* C. Bandaragoda, J. Greenberg, D. M., and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Bandaragoda, C., J. Greenberg, D. M., and P. Gill. 2012b. Lower Nooksack Water Budget Overview.

Bandaragoda, C., D. G. Tarboton, and R. Woods. 2004. Application of TOPNET in the Distributed Model Intercomparison Project. Journal of Hydrology **298**:178-201.

Barber, M., and J. Wu. 2008. Groundwater Investigations of Bertrand and Tenmile Watersheds.

Beven, K., R. Lamb, P. Quinn, R. Romanowicz, and J. Freer. 1995. TOPMODEL. Pages 627-668 *in* V. P. Singh, editor. Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, Colorado.

Beven, K. J., and M. J. Kirkby. 1979. A Physically Based Variable Contributing Area Model of Basin Hydrology. Hydrological Sciences Bulletin **24**:43-69.

Central and Southern Florida Project. 2002. Comprehensive Everglades Restoration Plan: HYDRAULICS FINAL MODEL EVALUATION REPORT EAA STORAGE RESERVOIRS – PHASE 1.

Chesnaux, R., D. M. Allen, and G. Graham. 2007. Assessment of the Impact of Nutrient Management Practices on Nitrate Contamination in the Abbotsford-Sumas Aquifer. Environmental Science and Technology **41**:7229-7234.

Chesnaux, R., D. M. Allen, and M. W. M. Simpson. 2011. Comparing isotopic groundwater age measurements with simulated groundwater ages: example of the Abbotsford–Sumas Aquifer (USA and Canada) and application. Water and Environment Journal.

DHI. 2012. MIKE SHE User Manual Volume 1.

Geurink, J. S., and R. Basso. 2012. Development, Calibration, and Evaluation of the Integrated Northern Tampa Bay Hydrologic Model Tampa Bay Water and Southwest Florida Water Management District.

Guzha, A. 2008. Integrating Surface and Sub Surface Flow Models of Different Spatial and Temporal Scales Using Potential Coupling Interfaces. Doctoral. Utah State University, Logan, Utah.

Guzha, A. C., and T. B. Hardy. 2010. Simulating streamflow and water table depth with a coupled hydrological model. Water Science and Engineering **3**:241-256.

Ibbitt, R. P., and R. Woods. 2004. Re-scaling the topographic index to improve the representation of physical processes in catchment models. Journal of Hydrology **293**:205-218.

Jensen, M. E., R. D. Burman, and R. G. Allen, editors. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice No. 70, New York.

Pruneda, E., M. Barber, J. Wu, and D. M. Allen. 2010. Use of stream response functions to determine impacts of replacing surface-water use with groundwater withdrawals. Hydrogeology Journal **18**:1077-1092.

Pruneda, E. B. 2007. Use of Stream Response Functions and Stella Software to Determine Impacts of Replacing Surface Water Diversions with Groundwater Pumping Withdrawals on Instream Flows within the Bertrand Creek and Fishtrap Creek Watersheds, Washington State, USA. Washington State University, Washington State University.

Scibek, A. 2005. Numerical Groundwater Flow Model of the Abbotsford-Sumas Aquifer, Central Fraser Lowland of BC, Canada and Washington State USA.

Scibek, J., and D. M. Allen. 2006. Comparing modelled responses of two high-permeability, unconfined aquifers to predicted climate change. Global and planetary change **50**:50-62.

Simpson, M. W. M. 2012. Assessing Risk to Groundwater Quality Using an Integrated Risk Framework. Simon Fraser University, Burnaby, British Columbia, Canada.

Tarboton, D. G. 2007. Water Quantity Model Development and Calibration, WRIA 1 Watershed Management Project Phase III, Task 4.1 report. Utah State University, Logan, Utah.

Tarboton, D. G., T. G. Chowdhury, and T. H. Jackson. 1995. A Spatially Distributed Energy Balance Snowmelt Model. Pages 141-155. IAHS Publ. no. 228, Proceedings of a Boulder Symposium.

Thane, N., and D. R. Mitchell. 2013. A Groundwater Characterization of Squalicum Valley, Lake Whatcom Watershed, Whatcom County, WA. Western Washington University.

USGS. 2000a. Approximate Locations of Aquifer Tests in the WRIA 1 Study Area. USGS.

USGS. 2000b. Generalized Pattern of Ground-Water Movement for the Puget Sound Aquifer System in the WRIA 1 Study Area. USGS.

USGS. 2000c. Surficial Hydrogeologic Units of the Puget Sound Aquifer System in the WRIA 1 Study Area. USGS.

USGS. 2000d. Water-Level Contours in the Uppermost Aquifer of the Lynden-Everson-Nooksack-Sumas (LENS) Study Area. USGS.

Wobus, C., R. Prucha, and D. Albert. 2012. Potential Hydrologic and Water Quality Alteration from Large-scale Mining of the Pebble Deposit in Bristol Bay, Alaska: Results from an Integrated Hydrologic Model of a Preliminary Mine Design. The Nature Conservancy, Anchorage, AK.

Appendix A: WRIA 1 Groundwater Assessment Bibliography

June 2013

Table of Contents

1.0 OVERVIEW

This document lists the 245 Books, Reports, Journal Articles, Government Documents and Maps that reference groundwater resources and physical characteristics of the hydrogeology of WRIA 1. The bibliography lists the references by Author last name. This was generated using the Endnote Library **<WRIA 1 Groundwater2013_EndnoteLibrary.enl>.** The second section lists the references in full detail, including the title of electronic files connected to references (where available).

2.0 INSTRUCTIONS FOR USING ENDNOTE

1. Download Endnote at www.endnote.com. Endnote is a commercial software package with tools for searching, organizing and sharing research, creating bibliographies and writing documents with tools connected to Microsoft Word. [30 day free trial versions are available].
2. Save **< WRIA 1 Groundwater2013_EndnoteLibrary.enl>** and folder **< WRIA 1 Groundwater2013_EndnoteLibrary.data>** to the same folder on your computer.
3. Click on <**WRIA 1 Groundwater 2013.enl>** and sort, search, and view linked electronic documents.

3.0 BIBLIOGRAPHY BY AUTHOR LAST NAME

Acme Water District No 18. 2001. Acme Water District # 18 Wellhead Protection Plan.

Allen, Chesnaux, and McArthur. 2007. Nitrate Transport Modeling within the Abbotsford-Sumas Aquifer, British Columbia, Canada and Washington State, USA. Page 181 *in* D. o. E. a. Sciences, editor. Simon Fraser University.

Aly, A., S. Fleming, A. M. Lavenue, T. Liebert, G. Ruskauff, T. Donigan, T. Jobes, R. Allen, and J. Wilson. 2001. Uncertainty and Sensitivity Analyses for the Central Northern Tampa Bay Area Integrated Hydrologic Model: Phase II. Tampa Bay Water, Clearwater, FL.

Anderson Creek Water Association. 2001. Anderson Creek Water Association Wellhead Protection Area.

Armstrong, J., and W. Brown. 1954. Late Wisconsin Marine Drift and Associated Sediments of the Lower Fraser Valley, British Columbia, Canada. Geological Society of America **65**:349-364.

Armstrong, J. E. 1960. Surficial Geology of the Sumas Map-Area, British Columbia.

Armstrong, J. E. 1976. Surficial Geology Map of Mission, British Columbia. Geological Survey of Canada.

Armstrong, J. E. 1977. Quaternary Stratigraphy of the Fraser Lowland, in Brown, E.H. and Ellis, R.C., eds., Geological Excursions in the Pacific Northwest, Bellingham, Washington, Western Washington.

Armstrong, J. E. 1981. Post-Vashon Wisconsin Glaciation, Fraser Lowland, British Columbia. Geological Survey of Canada: 34.

Armstrong, J. E., D. R. Crandell, D. J. Easterbrook, and J. B. Noble. 1965. Late Pleistocene Stratigraphy and Chronology of Southwestern British Columbia and Northwestern Washington. Pages 321-330, Geological Society of America Bulletin.

Aspect Consulting. 2003. Lummi Peninsula Ground Water Investigation.

Aspect Consulting. 2008. Water Quantity and Quality Report, Foothills Subarea.

Aspect Consulting. 2009. Aquifer Study of the Mountain View Upland-Lummi River Area.

Associated Earth Sciences Inc. (AESI). 1994. Wellhead Protection Plan for the City of Everson, Washington.

Associated Earth Sciences Inc. (AESI). 1996. City of Sumas Wellhead Protection Plan.

Associated Earth Sciences Inc. (AESI). 1996. Pole Road Water Association; Delineation of Wellhead Zones of Contribution; Wellhead Protection Program.

Associated Earth Sciences Inc. (AESI). 1999. Well Rehabilitation Assessment Lummi Tribal Water and Sewer District.

Associated Earth Sciences Inc. (AESI). 2004. Groundwater Feasibility Study Delta Water Association.

Associated Earth Sciences Inc. (AESI). 2007. Installation and Testing of Production Well PW-3 Whatcom County, Washington.

Associated Earth Sciences Inc. (AESI). 2007. Installation and Testing of Production Well PW-5.1, City of Blaine Public Works, Birch Bay Water and Sewer District.

Associated Earth Sciences Inc. (AESI). 2007. Installation and Testing of Production Well PW-8.1, City of Blaine Public Works, Birch Bay Water and Sewer District.

Associated Earth Sciences Inc. (AESI). 2007. Irrigation Well Testing DeHaan Property.

Associated Earth Sciences Inc. (AESI). 2007. Streamflow Augmentation Evaluation.

Associated Earth Sciences Inc. (AESI). 2008. Bertrand Creek DeHaan Property and Vicinity.

Associated Earth Sciences Inc. (AESI). 2008. Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area.

Associated Earth Sciences Inc. (AESI). 2009. ASR Feasibility Assessment/Installation and Testing of Exploration Well OW-1.

Associated Earth Sciences Inc. (AESI). 2009. Stream Flow Augmentation Well DeHaan Property.

Associated Earth Sciences Inc. (AESI). 2013. Swift Creek Draft Environmental Impact Statement.

Bandaragoda, C. 2008. Bertrand Creek Hydrologic Model Update and Assessment.

Bandaragoda, C. 2012. Model Calibration. Pages pp. 317-344 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Bandaragoda, C., L. Doremus, and J. Greenberg. 2012. Streamflow Observed Data. Pages pp. 288-316 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Bandaragoda, C., J. Greenberg, and M. Dumas. 2012. Existing Condition Water Budget Scenario. Pages pp. 345-396 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Bandaragoda, C., J. Greenberg, and M. Dumas. 2012. Historic Conditions. Pages pp. 397-442 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Bandaragoda, C., J. Greenberg, M. Dumas, and P. Gill. 2012. Lower Nooksack Water Budget Overview *in* C. Bandaragoda, J. Greenberg, D. M., and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Barber, M., and J. Wu. 2005. Proposal for Groundwater Investigations of Bertrand and Tenmile Watersheds.

Barber, M., and J. Wu. 2008. Groundwater Investigations of Bertrand and Tenmile Watersheds.

BEK Engineering & Environmental Inc. 2000. Phase I Hydrogeologic Investigation Y-Road Landfills, Whatcom County Washington.

Blunt, J. J., D. J. Easterbrook, and N. W. Rutter. 1987. Chronology of Pleistocene Sediments in the Puget Lowland, Washington. Pages 321-353 *in* Washington State Department of Natural Resources, editor.

Branton, D., and A. Burgess. 1986. City of Lynden Water System Plan, Appendix D, Groundwater Test Explorations.

Brookfield, A. 2013. Integrated Hydrologic Models: Building New Tools for Water Management. Page 50 *in* K. G. Survey, editor. UNL Spring 2013 Water Seminar University of Kansas.

Butts, M., K. Feng, A. Klinting, K. Stewart, A. Nath, A. Potts, T. Hazlett, P. Manning, J. Larsen, and T. Jacobsen. 2010. Real-Time Integrated Watershed Management of the Big Cypress Basin, Florida. Pages pp. 1002-1012 *in* Watershed Management 2010: Innovations in Watershed Management under Land Use and Climate Change. ASCE.

Butts, M. B., and D. N. Graham. 2008. Evolution of an integrated surface water-groundwater hydrological modelling system *in* Proceeding of IAHR International Groundwater Symposium - Flow and Transport in Heterogeneous Subsurface Formations: Theory, Modelling & Applications,

, Istanbul, Turkey.

Callan, D. M. 1971. Results of an Eight Day Field Pumping Test of Two Production Wells at the Fraser Valley Trout Hatchery. B.C. Ministry of the Environment, Groundwater Division.

Cameron, V. J. 1976. The Late Quaternary Geomorphic History of the Sumas Valley Thesis (M.A.)--Simon Fraser University, 1989.

Carmichael, Wei, and Ringham. 1995. Fraser Valley Groundwater Monitoring Program Final Report.

Central and Southern Florida Project. 2002. Comprehensive Everglades Restoration Plan: HYDRAULICS FINAL MODEL EVALUATION REPORT EAA STORAGE RESERVOIRS – PHASE 1.

Chesnaux, R., and D. M. Allen. 2007. Simulating Nitrate Leaching Profiles in a Highly Permeable Vadose Zone. Environ Model Assess.

Chesnaux, R., D. M. Allen, and G. Graham. 2007. Assessment of the Impact of Nutrient Management Practices on Nitrate Contamination in the Abbotsford-Sumas Aquifer. Environmental Science and Technology **41**:7229-7234.

Chesnaux, R., D. M. Allen, and M. W. M. Simpson. 2011. Comparing isotopic groundwater age measurements with simulated groundwater ages: example of the Abbotsford–Sumas Aquifer (USA and Canada) and application. Water and Environment Journal.

Clague, J. J. 1975. Late Quaternary Sea Level Fluctuations, Pacific Coast of Canada and Adjacent Areas. Geological Survey of Canada **75-1C**.

Clague, J. J., and J. L. Luternauer. 1982. Late Quaternary Sedimentary Environments, Southwestern British Columbia.

Clague, J. J., and J. L. Luternauer. 1983. Late Quaternary Geology of Southwestern British Columbia.

Clague, J. J., J. L. Luternauer, P. A. Monahan, K. A. Edwardson, S. R. Dallimore, and J. A. Hunter. 1998. Quaternary Stratigraphy and Evolution of the Fraser Delta; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia. Geological Survey of Canada:57-90.

Clague, J. J., J. L. Luternauer, and D. C. Mosher. 1998. Geological Setting of the Fraser River Delta; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia. Geological Survey of Canada: 7-16.

Cline, D. R. 1974. A Groundwater Investigation of the Lummi Indian Reservation Area, Washington.

Clothier, B. 1997. Construction Report for the City of Sumas Well Field Replacement Well 4.

Converse Consultants. 1994. Hydraulic Testing of Well 1-C, East Pole Road Water Association, Whatcom County, Washington.

Converse Consultants NW. 1993. Hydrological Investigation Strandell Well Field, Everson, Washington.

Cook, K. Date Unknown. Nooksack Watershed Ground Water Issue Paper.

Cosgrove, Johnson, Laney, and Lindgren. 1999. Description of the IDER/UI Snake River Plain Aquifer Model US. Bureau of Reclamation, Moscow, Idaho.

Cox, S. E., and S. C. Kahle. 1999. Hydrogeology, Ground-Water Quality, and Sources of Nitrate in Low-Land Glacial Aquifers of Whatcom County, Washington and British Columbia, Canada; Plate No. 2. U.S. Geological Survey / Whatcom County Planning Department.

Cox, S. E., F. Simonds, L. Doremus, R. Huffman, and R. Defawe. 2005. Groundwater Surface Water Interactions and Quality of Discharging Ground Water *in* Streams of the Lower Nooksack River Basin, Whatcom County, Washington in USGS, editor.

Creahan, K. 1988. Water Table Evaluations and Groundwater Flow in an Unconfined Aquifer in Northern Whatcom County, Washington. Western Washington University.

Culhane, T. 1993. Whatcom County Hydraulic Continuity Investigation part 1 Critical Well Stream Separation Distances for Minimizing Stream Depletion. OFTR-93-8.

Daly, R. A. 1912. Geology of the North American Cordillera at the 49th Parallel.

Delta Water Association. 1991. Delta Water Association Well Pump Test.

Deming Campus Wellhead Protection Area. 2001. Deming Campus Wellhead Protection Area Map - Mt. Baker School District.

Department of Ecology. 1994. Lummi Island Groundwater Study Final Report *in* Centennial Clean Water Fund, editor.

Department of Ecology. 1996. Surficial Aquifer Lateral Boundaries and Well Locations Map. Washington State Department of Ecology.

Dethier, D. P., F. Pessl, R. Keuler, M. Balzarini, and D. Pevear. 1995. Late Wisconsinan Glaciomarine Deposition and Isostatic Rebound, Northern Puget Lowland, Washington. Geological Society of America Bulletin **107**:1288-1303.

DHI. 2012. MIKE SHE User Manual Volume 1.

Didricksen, K. 1997. Hydrogeology and Water Resources of the California Creek Drainage Basin, Whatcom County, Washington. U.S. Bureau of Reclamation.

Dogrul, E., W. Schmidt, R. Hanson, T. Kadir, and F. Chung. 2011. Integrated Water Flow Model and MODFLOW-Farm Process: A Comparison of Theory, Approaches, and Features of Two Integrated Hydrologic Models.

Dragovich, Dunn, and Parkins. 1997. Quaternary Stratigraphy and Cross Sections, Nooksack, Columbia, and Saar Creek Valleys, Kendall and Deming, Whatcom County, Washington. Washington State Department of Natural Resources.

Dragovich, Norman, and Hau. 1997. Geologic Map and Interpreted Geologic History of the Kendall and Deming 7.5-minute Quadrangles, Whatcom County, Washington. Washington State Department of Natural Resources.

Droost, B. 1996. Selected Ground-Water Data for the Lummi Indian Reservation, Whatcom County, Washington 1995. OFR 96-166. USGS/Bureau of Indian Affairs.

Earth Tech (Canada) Inc. 2001. Hazelmere Agricultural Servicing Study, City of Blaine.

East Pole Road Water Association. 1994. East Pole Road Water Association.

Easterbrook, D. J. 1963. Late Pleistocene Glacial Events and Relative Sea Level Changes in the Northern Puget Lowland, Washington Geological Society of America.

Easterbrook, D. J. 1966. Glaciomarine Environments and the Fraser Glaciation in Northwest Washington.

Easterbrook, D. J. 1966. Radiocarbon Chronology of late Pleistocene Deposits in Northwest Washington. Science **152**:764-767.

Easterbrook, D. J. 1969. Pleistocene Chronology of the Puget Lowland and San Juan Islands, Washington. Geological Society of America Bulletin **80**:2,273-272,286.

Easterbrook, D. J. 1971. Geology and Geomorphology of Western Whatcom County, Washington. Western Washington University Bellingham WA.

Easterbrook, D. J. 1973. Environmental Geology of Western Whatcom County, Washington. Western Washington University Geology Department.

Easterbrook, D. J. 1976. Geologic Map of Western Whatcom County, Washington. United States Geological Survey

Easterbrook, D. J. 1976. Map Showing Engineering Characteristics of Geologic Materials, Western Whatcom County, Washington. U.S. Geological Survey

Easterbrook, D. J. 1992. Advance and Retreat of Cordilleran Ice Sheets in Washington. Geographie physique et quarternaire; **46**:51-68.

Easterbrook, D. J. 1994. Stratigraphy and Chronology of Early to Late Pleistocene Glacial and Interglacial Sediments in the Puget Lowland, Washington. University of Washington.

Easterbrook, D. J., D. R. Crandell, and E. B. Leopold. 1967. Pre-Olympia Pleistocene Stratigraphy and Chronology in the Central Puget Lowland, Washington. Geological Society of America Bulletin, **78**:13-20.

Easterbrook, D. J., D. J. Kovanen, and O. Slaymaker. 2007. New Developments in the Late Pleistocene and Holocene Glaciation and Volcanism in the Fraser Lowland and North Cascades, Washington. Geologic Society of America, Bulletin: 31-56.

Emcon. 1995. Hydrogeological Characterization Study East Blaine Annexation Area.

Erickson, D. 1991. Edaleen Dairy Lagoon Ground Water Quality Assessment, February 1990-February 1991. Page 33. Washington State Department of Ecology.

Erickson, D. 1992. Groundwater Quality Assessment Whatcom County Dairy Lagoon #2, Lynden, Washington. Washington State Department of Ecology.

Erickson, D. 1994. Water Level Monitoring, Bellingham Frozen Foods, September 14 through December 9, 1993, Bellingham, Washington.

Erickson, D. 1998. Sumas-Blaine Surficial Aquifer Nitrate Characterization in Washington State Department of Ecology, editor. Washington State Department of Ecology.

Gartner Lee and Consultants. 1993. Fraser Valley Ground Water Monitoring Program, Phase I Report. Page 150. Gartner Lee.

Gartner Lee Limited. 1999. Surrey Ground Water Supply Study-Phase 1 Report.

GeoEngineers Inc (GEI). 1994. Hydrogeologic Wellhead Protection Program Study Dodson's IGA Well, Whatcom County, Washington.

GeoEngineers Inc. (GEI). 1994. Hydrogeologic Services Installation and Testing of Production Well No. 3 Ferndale, Washington.

GeoEngineers Inc. (GEI). 1994. Report of Hydrogeologic Services Ground Water Monitoring Boundary Aggregate Site, Whatcom County, Washington.

GeoEngineers Inc. (GEI). 1998. Hydrogeologic Services Hydrogeologic Assessment and Water System Study, Blaine, Washington.

GeoEngineers Inc. (GEI). 2000. Hydrogeologic Services, Well Installation and Testing Production Well PW-1R, Whatcom County, Washington.

GeoEngineers Inc. (GEI). 2001. Hydrogeologic Services Installation and Testing of Production Well No. 2, Birch Bay, Washington.

GeoEngineers Inc. (GEI). 2002. Hydrogeologic Assessment Wellhead Protection Area Delineation Van Boven Gravel Company.

GeoEngineers Inc. (GEI). 2002. Hydrogeologic Services Groundwater Feasibility Study, Lynden, Washington.

Geological Survey of Canada. 1980. Surficial Geology of Vancouver, BC, Canada. Map 1484A New Westminster, Map 1485A Mission, Map 1486A Vancouver, Map 1487A Chilliwack (west half), Mission 92 G/1 Topographical Map.

Geological Survey of Canada. 1984. Environmental and Engineering Applications of the Surficial Geology of the Fraser Lowland, British Columbia, Canada.

Geological Survey of Canada. 1994. Hydrogeology of the Fraser Valley In-Situ Testing for the Characterization of Aquifers: Demonstration Project.

Geurink, J. S., and R. Basso. 2012. Development, Calibration, and Evaluation of the Integrated Northern Tampa Bay Hydrologic Model Tampa Bay Water and Southwest Florida Water Management District.

Gibbons, T., and T. Culhane. 1994. Whatcom County Hydraulic Continuity Investigation part 2 Basin Study of Johnson Creek.

Gill, P., and A. Atkenson. 2003. WRIA 1 Water Rights CD *in* PUD #1 of Whatcom County editor. Water Rights Stage 2 Deliverables. PUD #1 of Whatcom County Bellingham, WA.

Glacier Springs Water System. 1999. Wellhead Protection Program for Glacier Springs Water System.

Glenhaven Lakes Club. 1998. Wellhead Protection Plan-Glenhaven Lakes Club.

Glenn Community Water System. 1984. Report of Feasibility Study Alternatives - Glen Community Water System.

Golder Associates Inc. (Golder). 1987. Report to the City of Lynden Groundwater Exploration Program, May Road Site.

Golder Associates Inc. (Golder). 1988. Request for Designation as a Groundwater Management Area: City of Blaine.

Golder Associates Inc. (Golder). 1989. Hydrogeologic Investigation Cedarville Landfill, Whatcom County, Washington.

Golder Associates Inc. (Golder). 1992. Blaine Ground Water Management Program Final Hydrogeologic Report volume 1

Golder Associates Inc. (Golder). 1992. Preliminary Draft Hydrogeologic Assessment Report for the Proposed Columbia Aggregates Gravel Surface Mine.

Golder Associates Inc. (Golder). 1995. Report to the City of Blaine on Wellhead Protection Program. City of Blaine.

Golder Associates Inc. (Golder). 1996. Report on Construction and Testing of Replacement Well 1.

Golder Associates Inc. (Golder). 1998. City of Blaine Well No. 3 Replacement Well Drilling, Testing and Installation.

Golder Associates Inc. (Golder), and Adolfson Associates Inc. 1994. Blaine Groundwater Management Program.

Graham, D. N., and M. B. Butts, editors. 2005. Flexible, integrated watershed modelling with MIKE SHE. CRC Press.

Greenberg, J. 2004. Water Use and Water Rights (CIDMP) *in* EES Inc., editor. Bertrand Comprehensive Irrigation District Management Plan (CIDMP). WA State Department of Agriculture and the Bertrand Watershed Improvement District, Olympia, WA.

Greenberg, J. 2009. Water Use and Water Rights *in* J. Greenberg, editor. North Lynden Watershed Improvement District (NLWID) Watershed Management Plan. North Lynden WID, Lynden, WA.

Greenberg, J. 2012. Water Management: Agricultural Water. Pages pp. 217-246 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Greenberg, J. 2012. Water Management: Municipal/Industrial, Residential, Commercial Water Use. Pages pp. 247-274 *in* C. Bandaragoda, J. Greenberg, M. Dumas, and P. Gill, editors. Lower Nooksack Water Budget. WRIA 1 Joint Board, Whatcom County, WA.

Greenberg, J., K. Welch, and K. Kelleher. 2005. Results of Bertrand Creek Seepage Analysis-DRAFT.

Greenberg, J., K. Welch, M. Neuman, P. Willing, and M. Barclay. 1996. Catalogue of Existing Information on Water Resources and Fisheries *in* the Nooksack Basin, a report to the Nooksack Basin Water Users Steering Committee and the Washington Department of Ecology.

Ground Water Quantity Study Group. 2000. WRIA I Ground Water Quantity-Task 3&4 Preliminary Draft.

Guzha, A. 2008. Integrating Surface and Sub Surface Flow Models of Different Spatial and Temporal Scales Using Potential Coupling Interfaces. Doctoral. Utah State University, Logan, Utah.

Guzha, A., and T. B. Hardy. 2010. Application of the Distributed Hydrological Model TOPNET to the Big Darby Creek Watershed. Ohio USA. Water Resources Management **24**:979-1003.

Guzha, A., and T. B. Hardy. 2010. Simulating streamflow and water table depth with a coupled hydrological model. Water Science and Engineering **3**:241-256.

Guzha, A. C., and T. B. Hardy. 2008. Integrating Surface and Sub Surface Flow Models of Different Spatial and Temporal Scales Using Potential Coupling Interfaces. Graduate Studies. Utah State University, Utah State University Logan, Utah.

Guzha, A. C., and T. B. Hardy. 2010. Simulating streamflow and water table depth with a coupled hydrological model. Water Science and Engineering **3**:241-256.

Haberlandt, U. 2010. From Hydrological modelling to decision support. Advances in Geosciences **27**:11-19.

Halstead, E. C. 1966. Aldergrove Test Hole, Fraser Valley, BC *in* Geologic Survey of Canada Department of Mines and Technical Surveys, editor. Geologic Survey of Canada,.

Halstead, E. C. 1986. Groundwater Supply-Fraser Lowland, British Columbia. Inland Waters Directorate, Environmental Canada.

Hardy, McKee, Kaluarachchi, Kemblowski, Tarboton, Stenes, and Pack. 2002. WRIA I Watershed Management Project Phase II Technical Study Results: Executive Summary. Utah Water Research Laboratory, Utah State University.

Hardy, T. B. 2002. WRIA 1 Habitat Suitability Criteria Workshop Summary Report.

Hemmi Road Water Association. 1995. Hemmi Road Water Association Wellhead Protection Program.

Hii, Leibscher, Mazalek, and Tuominen. 1999. Groundwater Quality and Flow Rates in the Abbotsford Aquifer, British Columbia, Canada. Environmental Conservation Branch of Environmental Canada.

Houck, J., and J. R. Carr. 1985. 1985 City of Lynden Greenwood Test Well Drilling Report.

Hulsman, S. 1998. An Evaluation of Nitrate and Organic Chemical Contamination in Selected Drinking Water Wells in Central North Whatcom County. Summary Report.

Hydrologic Services Co. 2005. Draft Report Groundwater Study of Crystal and Larrabee Springs Tenmile Creek Watershed. Whatcom County Washington.

Hydrologic Services Co. 2005. Tenmile Creek Watershed Estimates of Current Irrigation Water Use. PUD #1 of Whatcom County, Bellingham, WA.

Interpre'Tech/SeisPulse. 2005. Seismic Reflection Survey Pranghorn Road, Lynden, Washington.

Jayatilika, C. J., B. Storm, and L. B. Mudgway. 1998. Simulation of water flow on irrigation bay scale with MIKE-SHE. Journal of Hydrology **208**:108-130.

Jones, M. 1996. Thickness of Unconsolidated Deposits in the Puget Sound Lowland, Washington and British Columbia, a Contribution of the Regional Aquifer-System Analysis Program.

Jones, M. A. 1995. Aquifer Delineation in the Sandy Point Area, Whatcom County, WA.

Jones, M. A. 1999. Geologic Framework for the Puget Sound Aquifer System Washington and British Columbia. US Geological Survey.

Kahle, S. C. 1990. Hydrostratigraphy and Ground Water Flow in the Sumas Area, Whatcom County, Washington. Western Washington University.

Kaluarachchi, J. J., and M. N. Almasri. 2002. Conceptual Model of Fate and Transport of Nitrate in the Sumas-Blaine Aquifer, Whatcom County, Washington. Draft Report, Utah State University, Logan Utah.

Kaluarachchi, J. J., and M. N. Almasri. 2004. A Mathematical Model of Fate and transport of Nitrate for the extended Sumas-Blaine Aquifer, Whatcom County, Washington Task 7.1. Utah State University.

Kaluarachchi, J. J., and M. N. Almasri. 2004. User Document for the Nitrate Fate and Transportation Model for the Extended Sumas-Blaine Aquifer, Whatcom County, Washington.

Kasier-Hill Company LLC. 2001. Model Code and Scenario Selection Report Site-Wide Water Balance Rocky Flats Environmental Technology Site.

Kemblowski, M., and T. Asefa. 2001. Analysis of Steady-State and Dynamic Behavior of Water Balance Components for Selected Reaches of WRIA 1 Streams.

Kemblowski, M., T. Asefa, and S. Haile-Selassje. 2001. Groundwater Quantity Report for WRIA 1, Phase II.

Klisch, M., and H. Kelsey. Hydrogeology and Groundwater Hydrology of Western Whatcom County, Washington.

Kohut, A. P. 1987. Groundwater Supply Capability Abbotsford Upland: Victoria British Columbia Canada. Page 18 *in* B. C. M. o. Environment, editor. Province of British Columbia, Ministry of Environment and Parks.

Kovanen, D., and D. Easterbrook. 2001. Late Pleistocene, post-Vashon, alpine glaciation of the Nooksack drainage, North Cascades, Washington. Geologic Society of America, Bulletin **2** 274-288.

Kovanen, D., and D. Easterbrook. 2002. Timing and Extent of Allerod and Younger Dryas Age (ca. 12,500-10,000 14C Y B.P.) Oscillations of the Cordilleran Ice Sheet in the Fraser Lowland, Western North America. University of British Columbia/Western Washington University, University of Washington.

Kovanen, D., and O. Slaymaker. 2003. Lake Terrell Upland Glacial Resurgences and Implications for Late-glacial History, Northwestern Washington State. Canadian Journal of Earth Sciences **40**:1767-1772.

Kovanen, D., and O. Slaymaker. 2004. Relict Shorelines and Ice Flow Patterns of the Northern Puget Lowland from Lidar Data and Digital Terrain Modelling. University of British Columbia, Vancouver, Canada.

Lake Samish Terrace Mobile Home Park Water Association. 2001. Wellhead Protection Plan - Lake Samish Terrace Mobile Home Park Water Association.

Lapen, T. J. 2000. Geologic Map of the Bellingham 1:100,000 quadrangle, Washington. Washington Division of Geology and Earth Resources

Loinaz, M. C., H. K. Davidsen, M. Butts, and P. Bauer-Gottwein. 2013. Integrated flow and temperature modeling at the catchment scale. Journal of Hydrology **495**:238-251.

Lummi Indian Business Council. 1981. Water Resources Inventory: Phase III-Discussion Alternatives.

Lummi Indian Business Council (LIBC). 1997. Lummi Nation Wellhead Protection Program, Phase I.

Lummi Water Resources Division. 2011. Lummi Nation Wellhead Protection Plan Update.

McCann, A., B. Neptin, and A. Gold. 2003. Groundwater Model Handbook. Page 19 Understanding Groundwater and Using the Groundwater Model.

Ministry of Environment and Parks Water Management Division. 1988. Fishtrap/Pepin/Bertrand Creeks Water Management Basin Plan; Groundwater Component. Ministry of Environment and Parks: Water Management Division.

Mitchell, D. R., and D. S. Babcock. 2000. Abbotsford-Sumas Aquifer Monitoring Project Final Report. Western Washington University.

Morgan, L. 1999. The Aquifer Vulnerability Project/Nooksack Pilot *in* Department of Ecology Water Quality Program, editor. Washington State Department of Ecology,.

Newcomb, Scevan, and Strome. 1949. Groundwater Resources, Western Whatcom County, Washington. Page 134. U.S. Geological Survey

Nooksack Basin Ground Water Quantity Study Group. 2000. Nooksack Basin: Ground-Water Quantity Study Group - Summary- Preliminary Data Review.

Northwest HydroGeo Consultants. 1997. Custer Water Association Wellhead Protection Plan Water System ID 17050R Parts I, II, and III.

Northwest Water Association. 2000. Wellhead Protection Plan for the Northwest Water Association.

Obert, W. C. 1973. Nitrate in Ground Water-Western Whatcom County, Washington. Masters. Western Washington University.

Old Settlers Water Association. 1999. Wellhead Protection Program for Old Settlers Water Association.

Pacific Ground Water Group. 1995. Results of Hydrogeologic Investigations for Deer Creek Water Association, Whatcom County, Washington.

Pacific Groundwater Group. 1995. Summary Update, Hydrogeologic Characterization and Monitoring, Sandy Point Improvement Company, Ferndale, WA.

Palmquist, R. 1991. Critical Aquifer Recharge Areas *in* Department of Ecology, editor. Department of Ecology,.

Plake, T. 1992. Depressional Areas in the Nooksack River Flood Plain.

Prucha, R., C. Hawley, T. Jacobsens, C. Dayton, I. Patons, and T. Illangaselcare. 2002. Development of an Integrated Hydrologic Model for Rocky Flats, Colorado. Groundwater/surface water Interactions AWRA Summer Specialty Conference.

Pruneda, E., M. Barber, J. Wu, and D. M. Allen. 2010. Use of stream response functions to determine impacts of replacing surface-water use with groundwater withdrawals. Hydrogeology Journal **18**:1077-1092.

Pruneda, E. B. 2007. Use of Stream Response Functions and Stella Software to Determine Impacts of Replacing Surface Water Diversions with Groundwater Pumping Withdrawals on Instream Flows within the Bertrand Creek and Fishtrap Creek Watersheds, Washington State, USA. Washington State University, Washington State University.

Public Utilities District No 1 of Whatcom County. 1993. Letter Report on Regional Ground Water Supply Study, Ferndale-Birch Bay Vicinity.

Public Utilities District No 1 of Whatcom County. 2002. Surface Water Delineation Boundaries in WRIA 1, Version 3 DRAFT Map.

PUD No. 1 of Whatcom County. 2001. Water Rights Review Stage I Report.

Ricketts, B. D. 1998. Groundwater Flow Beneath the Fraser River Delta, British Columbia; a preliminary model. *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia (ed.) J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525 p. 241-255.

Robinson & Nobel Inc. 1978. The Water Resources of Lummi Island-An Inventory and Management Plan.

Robinson & Nobel Inc. 1983. City of Lynden Water System Plan, Groundwater Feasibility Study for the City of Lynden.

Robinson & Nobel Inc. 1992. Construction Report City of Sumas May Road Well 1.

Robinson & Nobel Inc. 1995. Construction Report City of Sumas May Road Well 3.

Robinson & Nobel Inc. 1995. Construction Report City of Sumas May Road Well 5.

Robinson & Nobel Inc. 2003. Sandy Point Improvement Company, Sandy Point Production Well, Construction and Testing Report.

Rodgey/Associates. 1988. Hydrogeological investigations for Lummi Indian Business Council located NW1/4, Sec. 4., T. 38N, R. 1E.

RZA Agra Inc. 1993. Regional Groundwater Supply Study Ferndale-Birch Bay Vicinity, Whatcom County, Washington.

Sandal, M. 1990. Water Balance and Hydrostratigraphy of the Dakota Creek Watershed, Whatcom County, Washington. Western Washington University.

Schmidt, Dogrul, Hanson, Kadir, and Chung. 2011. Comparison of Simulations of Land-use Specific Water Demand and Irrigation Water Supply by MF-FMP and IWFM. Page 80, California Water Science Center.

Schuurman, Deshpande, and Allen. 2008. Data Integration Across Borders: A Case Study of the Abbotsford-Sumas Aquifer (British Columbia/Washington State). Journal of the American Water Resources Association **44**:921-934.

Scibek, A. 2005. Numerical Groundwater Flow Model of the Abbotsford-Sumas Aquifer, Central Fraser Lowland of BC, Canada and Washington State USA.

Scibek, A. 2006. Groundwater Sensitivity to Climate Change: Abbotsford-Sumas Aquifer in British Columbia, Canada and Washington State USA.

Scibek, J., and D. M. Allen. 2006. Comparing modelled responses of two high-permeability, unconfined aquifers to predicted climate change. Global and planetary change **50**:50-62.

Shakya, S. R. 2007. Use of MIKE SHE for Estimation of Evapotranspiration in the Sprague River Basin.

Shannon & Wilson Inc. 1975. Potential Ground Water Supply Blaine Watershed.

Simpson, M. W. M. 2012. Assessing Risk to Groundwater Quality Using an Integrated Risk Framework. Simon Fraser University, Burnaby, British Columbia, Canada.

Singh, R., K. Subramanian, and J. C. Refsgaard. 1999. Hydrological modelling of a small watershed using MIKE SHE for irrigation planning. Agricultural Water Management **41**:149-166.

Smith, B. 1998. City of Blaine Well PW-9 Record of Examination *in* Washington State Department of Ecology, editor.

Tarboton, D. G. 2007. Water Quantity Model Development and Calibration, WRIA 1 Watershed Management Project Phase III, Task 4.1 report. Utah State University, Logan, Utah.

Thane, N., and D. R. Mitchell. 2013. A Groundwater Characterization of Squalicum Valley, Lake Whatcom Watershed, Whatcom County, WA. Western Washington University.

Tooley, J., and D. Erickson. 1996. Nooksack Watershed Surficial Aquifer Characterization *in* Washington State Department of Ecology, editor. Washington State Department of Ecology,.

United States Public Health Service. 1974. Groundwater Investigation Phase 1 and 2 Geoelectric Surveys Lummi Indian Reservation. United States Public Health Service.

USGS. 1999. Historical Ground-Water Levels in the WRIA 1 Study Area.

USGS. 1999. Summary Information for Wells in the WRIA 1 Study Area, Downloaded from the USGS National Water Information System (NWIS). USGS.

USGS. 2000. Approximate Locations of Aquifer Tests in the WRIA 1 Study Area. USGS.

USGS. 2000. Distribution of Soil Map Units in the WRIA 1 Study Area. USGS.

USGS. 2000. Generalized Pattern of Ground-Water Movement for the Puget Sound Aquifer System in the WRIA 1 Study Area. USGS.

USGS. 2000. Locations of Selected Wells in the WRIA 1 Study Area by Primary Water Use. USGS.

USGS. 2000. Locations of Selected Wells in the WRIA 1 Study Area with Sufficient Information to Compute Hydraulic Conductivities. USGS.

USGS. 2000. Soil Permeability in Parts of the WRIA 1 Study Area. USGS.

USGS. 2000. Summary Information for Aquifer Tests in the WRIA 1 Study Area. USGS.

USGS. 2000. Surficial Hydrogeologic Units of the Puget Sound Aquifer System in the WRIA 1 Study Area. USGS.

USGS. 2000. Water-Level Contours in the Uppermost Aquifer of the Lynden-Everson-Nooksack-Sumas (LENS) Study Area. USGS.

USGS. 2000. Wells with Sufficient Information to Compute Hydraulic Conductivities, Downloaded from the USGS National Water Information System (NWIS). USGS.

USGS-WRD Washington District. 1971. An Evaluation of Ground Water Conditions in the Vicinity of the Bel Bay Development, Lummi Indian Reservation, Washington. USGS, Lummi Indian Tribal Council, Tacoma, WA.

USU/DSS. 2002. USU/DSS Model Supplemental Scenario Documents.

Utah Water Research Laboratory. 2004. Groundwater Modeling of the Lowlands of WRIA 1 Watersheds. Ground Water Quantity (Task 5)-Final Deliverables Technical Memorandum.

Utah Water Research Laboratory. 2004. Groundwater Quantity (Task 5) Final Deliverables Technical Memorandum. Utah State University.

Utah Water Research Laboratory. 2004. Groundwater Quantity Modeling of WRIA I Watersheds Status Report.

Vaccaro, Hansen, and Jones. 1998. Hydrogeologic Framework of the Puget Sound Aquifer System Washington and British Columbia. USGS.

Van Siclen, C. C. 1994. Geologic, Hydrologic, and Climatic Factors Influencing Glacier Creek Basin, Whatcom County, Washington. Western Washington University.

W.D. Purnell & Associates Inc. 1988. Geohydrology Investigation of New Community Water Well Locations for the Town of Acme, Washington.

W.D. Purnell & Associates Inc. 1991. 24-Hour Aquifer Test Mission Road, Whatcom County, Washington.

W.D. Purnell & Associates Inc. 1993. Geohydrology Study of the Proposed Evergreen Limited Purpose Landfill, Everson-Goshen Road, Whatcom County, Washington.

W.D. Purnell & Associates Inc. 1993. Maple Falls Water Cooperative, Aquifer Testing Well No. 2, Maple Falls Washington.

W.D. Purnell & Associates Inc. 1993. Source Development Project Report/Joe Louie Water Association Water System.

Walker, Wyatt, and Glenn. 1990. Hydrology and Water Quality Cedarville Landfill, Whatcom County, Washington.

Washburn, R. L. 1957. Groundwater in the Lummi Reservation, Whatcom County, Washington. US Geological Survey.

Washington State Department of Conservation. 1960. Water Resources of the Nooksack River Basin and Certain Adjacent Streams Maps *in* W. R. Division, editor.

Washington State Department of Ecology. Groundwater *In* Whatcom County: A Natural Resource.

Washington State Department of Ecology. 1995. Watershed Briefing Paper for the Nooksack Water Resource Inventory Area. Department of Ecology.

Washington State Department of Ecology. 1999. Abbotsford-Sumas Well Data. Washington State Department of Ecology.

WEST Consultants Inc. Limited, Gartner Lee and Consultants, and AQUA TERRA. 2001. Scientific Review of the integrated hydrologic model ISGW/CNTB121. Tampa Bay Water, Clearwater, FL.

Whatcom County. 1992 updated 1995. Whatcom County Well Log Data Base. Whatcom County.

Whatcom County Conservation District. 1987. Agricultural Impacts on Water Resources in Dakota Creek Watershed, Whatcom County, Washington.

Whatcom County Conversation District. 1986. Agricultural Impact on Water Resources in Tenmile Watershed, Whatcom County, Washington. Prepared for the Lummi Tribal Fisheries Department.

Whatcom County Health and Human Services. 1999-2000. Public Water Systems in Whatcom County GPS Maps.

Whatcom County Health Department. 2000. Summary Information for Wells in the WRIA 1 Study Area, Downloaded from the Whatcom County Health and Human Services Department Database. USGS.

Whatcom County Health Department. 2003. Whatcom County Water District No. 13 - Wellhead Protection Area Map.

Whatcom County Planning and Development Services. 2011. 2010 State of the Watershed Report.

Whatcom County Planning Department. 1992. Whatcom County Planning Department Interim Report 2 on Aquifer Recharge Area Delineation, Whatcom County, Washington.

Whatcom County Water District No. 10. 1999. Wellhead Protection Program - Richalou Estates.

Whatcom Meadows Water Association. 1998. Wellhead Protection Plan for Whatcom Meadows Community.

Willing, P. 1991. Groundwater Resource Evaluation, Lummi Reservation: Phase One Report. Charles Howard & Associates, Ltd.

Wobus, C., R. Prucha, and D. Albert. 2012. Potential Hydrologic and Water Quality Alteration from Large-scale Mining of the Pebble Deposit *in* Bristol Bay, Alaska: Results from an Integrated Hydrologic Model of a Preliminary Mine Design. The Nature Conservancy, Anchorage, AK.

4.0 BIBLIOGRAPHY BY WRIA 1 MANAGEMENT AREA

Management Area	Drainage	Citation Type	Author	Date	Title
Birch Bay	Cherry Point	Drainage Scale Study	RZA Agra Inc.	1993	Regional Groundwater Supply Study Ferndale-Birch Bay Vicinity, Whatcom County, Washington
Birch Bay	Cherry Point	Drainage Scale Study	Aspect Consulting	2009	Aquifer Study of the Mountain View Upland-Lummi River Area
Birch Bay	Fingalson	Drainage Scale Study	RZA Agra Inc.	1993	Regional Groundwater Supply Study Ferndale-Birch Bay Vicinity, Whatcom County, Washington
Birch Bay	Lake Terrell	Drainage Scale Study	RZA Agra Inc.	1993	Regional Groundwater Supply Study Ferndale-Birch Bay Vicinity, Whatcom County, Washington
Birch Bay	Lake Terrell	Drainage Scale Study	Aspect Consulting	2009	Aquifer Study of the Mountain View Upland-Lummi River Area
Birch Bay	Semiahmoo	Site specific Study	GeoEngineers Inc. (GEI)	2000	Hydrogeologic Services, Well Installation and Testing Production Well PW-1R, Whatcom County, Washington
Campbell River	Little Campbell	Regional Study	Earth Tech (Canada) Inc.	2001	Hazelmere Agricultural Servicing Study, City of Blaine
Drayton Harbor	Blaine	Drainage Scale Study	GeoEngineers Inc. (GEI)	1998	Hydrogeologic Services Hydrogeologic Assessment and Water System Study, Blaine, Washington
Drayton Harbor	Blaine	Drainage Scale Study	Golder Associates Inc. (Golder)	1992	Blaine Ground Water Management Program Final Hydrogeologic Report volume 1
Drayton Harbor	Blaine	Drainage Scale Study	Golder Associates Inc. (Golder) and Adolfson Associates Inc.	1994	Blaine Groundwater Management Program
Drayton Harbor	Blaine	Drainage Scale Study	Golder Associates Inc. (Golder)	1995	Report to the City of Blaine on Wellhead Protection Program
Drayton Harbor	Blaine	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2008	Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area
Drayton Harbor	Blaine	Site specific Study	Associated Earth Sciences Inc. (AESI)	2007	Installation and Testing of Production Well PW-8.1, City of Blaine Public Works, Birch Bay Water and Sewer District
Drayton Harbor	Blaine	Site specific Study	GeoEngineers Inc. (GEI)	2001	Hydrogeologic Services Installation and Testing of Production Well No. 2, Birch Bay, Washington

Drayton Harbor	California	Drainage Scale Study	GeoEngineers Inc. (GEI)	1998	Hydrogeologic Services Hydrogeologic Assessment and Water System Study, Blaine, Washington
Drayton Harbor	California	Drainage Scale Study	Golder Associates Inc. (Golder) and Adolfson Associates Inc.	1994	Blaine Groundwater Management Program
Drayton Harbor	California	Drainage Scale Study	Golder Associates Inc. (Golder)	1995	Report to the City of Blaine on Wellhead Protection Program
Drayton Harbor	California	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2008	Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area
Drayton Harbor	California	Drainage Scale Study	Northwest HydroGeo Consultants	1997	Custer Water Association Wellhead Protection Plan Water System ID 17050R Parts I, II, and III
Drayton Harbor	Haynie	Drainage Scale Study	Golder Associates Inc. (Golder)	1992	Blaine Ground Water Management Program Final Hydrogeologic Report volume 1
Drayton Harbor	Haynie	Drainage Scale Study	GeoEngineers Inc. (GEI)	1998	Hydrogeologic Services Hydrogeologic Assessment and Water System Study, Blaine, Washington
Drayton Harbor	Haynie	Drainage Scale Study	Golder Associates Inc. (Golder) and Adolfson Associates Inc.	1994	Blaine Groundwater Management Program
Drayton Harbor	Haynie	Drainage Scale Study	Golder Associates Inc. (Golder)	1995	Report to the City of Blaine on Wellhead Protection Program
Drayton Harbor	Haynie	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2008	Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area
Drayton Harbor	Lower Dakota	Drainage Scale Study	Golder Associates Inc. (Golder)	1992	Blaine Ground Water Management Program Final Hydrogeologic Report volume 1
Drayton Harbor	Lower Dakota	Drainage Scale Study	Emcon	1995	Hydrogeological Characterization Study East Blaine Annexation Area
Drayton Harbor	Lower Dakota	Drainage Scale Study	GeoEngineers Inc. (GEI)	1998	Hydrogeologic Services Hydrogeologic Assessment and Water System Study, Blaine, Washington
Drayton Harbor	Lower Dakota	Drainage Scale Study	Golder Associates Inc. (Golder) and Adolfson Associates Inc.	1994	Blaine Groundwater Management Program
Drayton Harbor	Lower Dakota	Drainage Scale Study	Golder Associates Inc. (Golder)	1995	Report to the City of Blaine on Wellhead Protection Program
Drayton Harbor	Lower Dakota	Drainage Scale Study	B. Smith	1998	City of Blaine Well PW-9 Record of Examination

Drayton Harbor	Lower Dakota	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2008	Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area
Drayton Harbor	Lower Dakota	Site specific study	Associated Earth Sciences Inc. (AESI)	2007	Installation and Testing of Production Well PW-5.1, City of Blaine Public Works, Birch Bay Water and Sewer District
Drayton Harbor	Lower Dakota	Site specific study	Golder Associates Inc. (Golder)	1998	City of Blaine Well No. 3 Replacement Well Drilling, Testing and Installation
Drayton Harbor	Lower Dakota	Site specific study	Golder Associates Inc. (Golder)	1996	Report on Construction and Testing of Replacement Well 1
Drayton Harbor	Lower Dakota	Site specific study	Shannon & Wilson Inc.	1975	Potential Ground Water Supply Blaine Watershed
Drayton Harbor	North Fork Dakota		Golder Associates Inc. (Golder)	1992	Blaine Ground Water Management Program Final Hydrogeologic Report volume 1
Drayton Harbor	North Fork Dakota	Drainage Scale Study	GeoEngineers Inc. (GEI)	1998	Hydrogeologic Services Hydrogeologic Assessment and Water System Study, Blaine, Washington
Drayton Harbor	North Fork Dakota	Drainage Scale Study	Golder Associates Inc. (Golder) and Adolfson Associates Inc.	1994	Blaine Groundwater Management Program
Drayton Harbor	North Fork Dakota	Drainage Scale Study	Golder Associates Inc. (Golder)	1995	Report to the City of Blaine on Wellhead Protection Program
Drayton Harbor	North Fork Dakota	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2008	Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area
Drayton Harbor	South Fork Dakota	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2008	Geologic, Hydrogeologic, and Ground water Right Evaluation, Technical Report City of Blaine Ground Water Management Area
Lake Whatcom	Agate Bay	Drainage Scale Study	N. Thane and D. R. Mitchell	2013	A Groundwater Characterization of Squalicum Valley, Lake Whatcom Watershed, Whatcom County, WA
Lake Whatcom	Carpenter	Drainage Scale Study	N. Thane and D. R. Mitchell	2013	A Groundwater Characterization of Squalicum Valley, Lake Whatcom Watershed, Whatcom County, WA
Lake Whatcom	Carpenter	Site specific Study	BEK Engineering & Environmental Inc.	2000	Phase I Hydrogeologic Investigation Y-Road Landfills, Whatcom County Washington
Lake Whatcom	Olsen	Drainage Scale Study	N. Thane and D. R. Mitchell	2013	A Groundwater Characterization of Squalicum Valley, Lake Whatcom Watershed, Whatcom County, WA
Lower Mainstem Nooksack	Scott	Drainage Scale Study	Robinson & Nobel Inc.	1983	City of Lynden Water System Plan, Groundwater Feasibility Study for the City of Lynden

Lower Mainstem Nooksack	Scott	Site specific Study	Converse Consultants NW	1993	Hydrological Investigation Strandell Well Field, Everson, Washington
Lummi Bay	Jordan	Drainage Scale Study	RZA Agra Inc.	1993	Regional Groundwater Supply Study Ferndale-Birch Bay Vicinity, Whatcom County, Washington
Lummi Bay	Jordan	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Lummi Bay	Jordan	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I
Lummi Bay	Jordan	Drainage Scale Study	Aspect Consulting	2009	Aquifer Study of the Mountain View Upland-Lummi River Area
Lummi Bay	Lummi Peninsula West	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Lummi Bay	Lummi Peninsula West	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I
Lummi Bay	Lummi Peninsula West	Drainage Scale Study	R. L. Washburn	1957	Groundwater in the Lummi Reservation, Whatcom County, Washington
Lummi Bay	Lummi Peninsula West	Drainage Scale Study	B. Droost	1996	Selected Ground-Water Data for the Lummi Indian Reservation, Whatcom County, Washington 1995
Lummi Bay	Lummi Peninsula West	Drainage Scale Study	Aspect Consulting	2009	Lummi Peninsula Ground Water Investigation
Lummi Bay	Lummi Peninsula West	Drainage Scale Study	Lummi Water Resources Division	2011	Lummi Nation Wellhead Protection Plan Update
Lummi Bay	Lummi Peninsula West	Site specific Study	Associated Earth Sciences Inc. (AESI)	1999	Well Rehabilitation Assessment Lummi Tribal Water and Sewer District
Lummi Bay	Lummi River	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Lummi Bay	Lummi River	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I
Lummi Bay	Lummi River	Drainage Scale Study	R. L. Washburn	1957	Groundwater in the Lummi Reservation, Whatcom County, Washington
Lummi Bay	Lummi River	Drainage Scale Study	Aspect Consulting	2009	Lummi Peninsula Ground Water Investigation
Lummi Bay	Lummi River Delta	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington

Lummi Bay	Lummi River Delta	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I
Lummi Bay	Lummi River Delta	Drainage Scale Study	R. L. Washburn	1957	Groundwater in the Lummi Reservation, Whatcom County, Washington
Lummi Bay	Lummi River Delta	Drainage Scale Study	Aspect Consulting	2009	Lummi Peninsula Ground Water Investigation
Lummi Bay	Sandy Point	Drainage Scale Study	RZA Agra Inc.	1993	Regional Groundwater Supply Study Ferndale-Birch Bay Vicinity, Whatcom County, Washington
Lummi Bay	Sandy Point	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Lummi Bay	Sandy Point	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I
Lummi Bay	Sandy Point	Drainage Scale Study	Aspect Consulting	2009	Aquifer Study of the Mountain View Upland-Lummi River Area
Lummi Bay	Sandy Point	Drainage Scale Study	M. A. Jones	1995	Aquifer Delineation in the Sandy Point Area, Whatcom County, WA
Lummi Bay	Sandy Point	Drainage Scale Study	Pacific Groundwater Group	1995	Summary Update, Hydrogeologic Characterization and Monitoring, Sandy Point Improvement Company, Ferndale, WA.
Lummi Bay	Sandy Point	Drainage Scale Study	Robinson & Nobel Inc.	2003	Sandy Point Improvement Company, Sandy Point Production Well, Construction and Testing Report.
Lummi Bay	Sandy Point	Drainage Scale Study	Rodgey/Associates	1988	Hydrogeological investigations for Lummi Indian Business Council located NW1/4, Sec. 4, T. 38N, R. 1E.
Lummi Bay	Schell	Drainage Scale Study	RZA Agra Inc.	1993	Regional Groundwater Supply Study Ferndale-Birch Bay Vicinity, Whatcom County, Washington
Lummi Bay	Schell	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Lummi Bay	Schell	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I
Lummi Bay	Schell	Site specific Study	GeoEngineers Inc. (GEI)	1994	Hydrogeologic Services Installation and Testing of Production Well No. 3 Ferndale, Washington
Lummi Peninsula/Portage Island	Lummi Peninsula East	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Lummi Peninsula/Portage Island	Lummi Peninsula East	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I

Lummi Peninsula/Portage Island	Lummi Peninsula East	Drainage Scale Study	R. L. Washburn	1957	Groundwater in the Lummi Reservation, Whatcom County, Washington
Lummi Peninsula/Portage Island	Lummi Peninsula East	Drainage Scale Study	B. Droost	1996	Selected Ground-Water Data for the Lummi Indian Reservation, Whatcom County, Washington 1995
Lummi Peninsula/Portage Island	Lummi Peninsula East	Drainage Scale Study	Aspect Consulting	2009	Lummi Peninsula Ground Water Investigation
Lummi Peninsula/Portage Island	Lummi Peninsula East	Drainage Scale Study	Lummi Water Resources Division	2011	Lummi Nation Wellhead Protection Plan Update
Lummi Peninsula/Portage Island	Portage Island	Drainage Scale Study	Department of Ecology	1994	Lummi Island Groundwater Study Final Report
Lummi Peninsula/Portage Island	Portage Island	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Lummi Peninsula/Portage Island	Portage Island	Drainage Scale Study	Lummi Indian Business Council (LIBC)	1997	Lummi Nation Wellhead Protection Program, Phase I
Lummi Peninsula/Portage Island	Portage Island	Drainage Scale Study	R. L. Washburn	1957	Groundwater in the Lummi Reservation, Whatcom County, Washington
Lummi/Eliza Islands	Lummi Island	Drainage Scale Study	Department of Ecology	1994	Lummi Island Groundwater Study Final Report
Lummi/Eliza Islands	Lummi Island	Drainage Scale Study	Robinson & Nobel Inc.	1978	The Water Resources of Lummi Island-An Inventory and Management Plan
Lynden North	Bertrand	Drainage Scale Numerical Model	C. Bandaragoda	2008	Bertrand Creek Hydrologic Model Update and Assessment
Lynden North	Bertrand	Drainage Scale Numerical Model	M. Barber and J. Wu	2008	Groundwater Investigations of Bertrand and Tenmile Watersheds
Lynden North	Bertrand	Drainage Scale Numerical Model	E. Pruneda, M. Barber, J. Wu and D. M. Allen	2010	Use of stream response functions to determine impacts of replacing surface-water use with groundwater withdrawals
Lynden North	Bertrand	Drainage Scale Study	K. Creahan	1988	Water Table Evaluations and Groundwater Flow in an Unconfined Aquifer in Northern Whatcom County, Washington
Lynden North	Bertrand	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2004	Groundwater Feasibility Study Delta Water Association

Lynden North	Bertrand	Drainage Scale Study	D. Erickson	1994	Water Level Monitoring, Bellingham Frozen Foods, September 14 through December 9, 1993, Bellingham, Washington
Lynden North	Bertrand	Drainage Scale Study	J. Greenberg, K. Welch and K. Kelleher	2005	Results of Bertrand Creek Seepage Analysis-DRAFT
Lynden North	Bertrand	Drainage Scale Study	E. B. Pruneda	2007	Use of Stream Response Functions and Stella Software to Determine Impacts of Replacing Surface Water Diversions with Groundwater Pumping Withdrawals on Instream Flows within the Bertrand Creek and Fishtrap Creek Watersheds, Washington State, USA
Lynden North	Bertrand	Regional Study	Earth Tech (Canada) Inc.	2001	Hazelmere Agricultural Servicing Study, City of Blaine
Lynden North	Bertrand	Site specific Study	Associated Earth Sciences Inc. (AESI)	2009	Stream Flow Augmentation Well DeHaan Property
Lynden North	Bertrand	Site specific Study	Associated Earth Sciences Inc. (AESI)	2007	Irrigation Well Testing DeHaan Property
Lynden North	Bertrand	Site specific Study	E. C. Halstead	1966	Aldergrove Test Hole, Fraser Valley, BC
Lynden North	Bertrand	Site specific Study	Associated Earth Sciences Inc. (AESI)	2007	Streamflow Augmentation Evaluation
Lynden North	Bertrand	Site specific Study	Associated Earth Sciences Inc. (AESI)	2008	Bertrand Creek DeHaan Property and Vicinity
Lynden North	Fishtrap	Drainage Scale Numerical Model	M. Barber and J. Wu	2008	Groundwater Investigations of Bertrand and Tenmile Watersheds
Lynden North	Fishtrap	Drainage Scale Numerical Model	E. Pruneda, M. Barber, J. Wu and D. M. Allen	2010	Use of stream response functions to determine impacts of replacing surface-water use with groundwater withdrawals
Lynden North	Fishtrap	Drainage Scale Study	K. Creahan	1988	Water Table Evaluations and Groundwater Flow in an Unconfined Aquifer in Northern Whatcom County, Washington
Lynden North	Fishtrap	Drainage Scale Study	D. Erickson	1991	Edaleen Dairy Lagoon Ground Water Quality Assessment, February 1990-February 1991
Lynden North	Fishtrap	Drainage Scale Study	D. Erickson	1992	Groundwater Quality Assessment Whatcom County Dairy Lagoon #2, Lynden, Washington

Lynden North	Fishtrap	Drainage Scale Study	GeoEngineers Inc. (GEI)	2002	Hydrogeologic Services Groundwater Feasibility Study, Lynden, Washington
Lynden North	Fishtrap	Drainage Scale Study	Hii, Leibscher, Mazalek and Tuominen	1999	Groundwater Quality and Flow Rates in the Abbotsford Aquifer, British Columbia, Canada
Lynden North	Fishtrap	Drainage Scale Study	InterpreTech/SeisPulse	2005	Seismic Reflection Survey Pranghorn Road, Lynden, Washington
Lynden North	Fishtrap	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2004	Groundwater Feasibility Study Delta Water Association
Lynden North	Fishtrap	Drainage Scale Study	Robinson & Nobel Inc.	1983	City of Lynden Water System Plan, Groundwater Feasibility Study for the City of Lynden
Lynden North	Fishtrap	Drainage Scale Study	Geological Survey of Canada	1994	Hydrogeology of the Fraser Valley In-Situ Testing for the Characterization of Aquifers: Demonstration Project
Lynden North	Fishtrap	Drainage Scale Study	E. B. Pruneda	2007	Use of Stream Response Functions and Stella Software to Determine Impacts of Replacing Surface Water Diversions with Groundwater Pumping Withdrawals on Instream Flows within the Bertrand Creek and Fishtrap Creek Watersheds, Washington State, USA
Lynden North	Fishtrap	Regional Study	Earth Tech (Canada) Inc.	2001	Hazelmere Agricultural Servicing Study, City of Blaine
Lynden North	Fishtrap	Site specific Study	Associated Earth Sciences Inc. (AESI)	2007	Installation and Testing of Production Well PW-3 Whatcom County, Washington
Lynden North	Fishtrap	Site specific Study	Associated Earth Sciences Inc. (AESI)	2009	ASR Feasibility Assessment/Installation and Testing of Exploration Well OW-1
North Fork Nooksack	Kendall	Drainage Scale Study	Aspect Consulting	2008	Water Quantity and Quality Report, Foothills Subarea
Silver/Nooksack Channel & Delta	Nooksack River Delta	Drainage Scale Study	Lummi Water Resources Division	2011	Lummi Nation Wellhead Protection Plan Update
Silver/Nooksack Channel & Delta	Nooksack River Delta	Drainage Scale Study	D. R. Cline	1974	A Groundwater Investigation of the Lummi Indian Reservation Area, Washington
Silver/Nooksack Channel & Delta	Nooksack River Delta	Drainage Scale Study	R. L. Washburn	1957	Groundwater in the Lummi Reservation, Whatcom County, Washington
Silver/Nooksack Channel & Delta	Nooksack River Delta	Drainage Scale Study	B. Droost	1996	Selected Ground-Water Data for the Lummi Indian Reservation, Whatcom County, Washington 1995
Silver/Nooksack Channel & Delta	Nooksack River Delta	Drainage Scale Study	Aspect Consulting	2009	Lummi Peninsula Ground Water Investigation

South Fork Nooksack	South Acme Area	Site specific Study	W.D. Purnell & Associates Inc.	1988	Geohydrology Investigation of New Community Water Well Locations for the Town of Acme, Washington
Sumas River	Breckenridge	Drainage Scale Study	V. J. Cameron	1976	The Late Quaternary Geomorphic History of the Sumas Valley
Sumas River	Breckenridge	Drainage Scale Study	S. C. Kahle	1990	Hydrostratigraphy and Ground Water Flow in the Sumas Area, Whatcom County, Washington
Sumas River	Johnson	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	1996	City of Sumas Wellhead Protection Plan
Sumas River	Johnson	Drainage Scale Study	V. J. Cameron	1976	The Late Quaternary Geomorphic History of the Sumas Valley
Sumas River	Johnson	Drainage Scale Study	Hii, Leibscher, Mazalek and Tuominen	1999	Groundwater Quality and Flow Rates in the Abbotsford Aquifer, British Columbia, Canada
Sumas River	Johnson	Drainage Scale Study	S. C. Kahle	1990	Hydrostratigraphy and Ground Water Flow in the Sumas Area, Whatcom County, Washington
Sumas River	Johnson	Drainage Scale Study	D. R. Mitchell and D. S. Babcock	2000	Abbotsford-Sumas Aquifer Monitoring Project Final Report
Sumas River	Johnson	Drainage Scale Study	T. Gibbons and T. Culhane	1994	Whatcom County Hydraulic Continuity Investigation part 2 Basin Study of Johnson Creek
Sumas River	Johnson	Drainage Scale Study	Golder Associates Inc. (Golder)	1992	Preliminary Draft Hydrogeologic Assessment Report for the Proposed Columbia Aggregates Gravel Surface Mine
Sumas River	Johnson	Drainage Scale Study	T. Culhane	1993	Whatcom County Hydraulic Continuity Investigation part 1 Critical Well Stream Separation Distances for Minimizing Stream Depletion
Sumas River	Johnson	Site specific Study	Golder Associates Inc. (Golder)	1987	Report to the City of Lynden Groundwater Exploration Program, May Road Site
Sumas River	Johnson	Site specific Study	Robinson & Nobel Inc.	1992	Construction Report City of Sumas May Road Well 1
Sumas River	Johnson	Site specific Study	Robinson & Nobel Inc.	1995	Construction Report City of Sumas May Road Well 3
Sumas River	Johnson	Site specific Study	Robinson & Nobel Inc.	1995	Construction Report City of Sumas May Road Well 5
Sumas River	Johnson	Site specific Study	B. Clothier	1997	Construction Report for the City of Sumas Well Field Replacement Well 4
Sumas River	Saar	Drainage Scale Study	V. J. Cameron	1976	The Late Quaternary Geomorphic History of the Sumas Valley

Sumas River	Swift	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	2013	Swift Creek Draft Environmental Impact Statement
Tenmile	Deer	Drainage Scale Study	Pacific Ground Water Group	1995	Results of Hydrogeologic Investigations for Deer Creek Water Association, Whatcom County, Washington
Upper Mainstem Nooksack	Nooksack Deming to Everson	Drainage Scale Study	Associated Earth Sciences Inc. (AESI)	1994	Wellhead Protection Plan for the City of Everson, Washington
Upper Mainstem Nooksack	Nooksack Deming to Everson	Site specific Study	GeoEngineers Inc. (GEI)	1994	Report of Hydrogeologic Services Ground Water Monitoring Boundary Aggregate Site, Whatcom County, Washington
Upper Mainstem Nooksack	Nooksack Deming to Everson	Site specific Study	GeoEngineers Inc. (GEI)	2002	Hydrogeologic Assessment Wellhead Protection Area Delineation Van Beven Gravel Company
Upper Mainstem Nooksack	Nooksack Deming to Everson	Site specific Study	Golder Associates Inc. (Golder)	1989	Hydrogeologic Investigation Cedarville Landfill, Whatcom County, Washington
Upper Mainstem Nooksack	Nooksack Deming to Everson	Site specific Study	Walker, Wyatt and Glenn	1990	Hydrology and Water Quality Cedarville Landfill, Whatcom County, Washington
Upper Mainstem Nooksack	Nooksack Deming to Everson	Site specific Study	W.D. Purnell & Associates Inc.	1993	Source Development Project Report/Joe Louie Water Association Water System

Appendix B. Technical Input on Recommendations for Data Collection and Model Integration

June 2013

1.0 OVERVIEW

Preparation of the *WRIA 1 Groundwater Data and Model Assessment* included compilation of existing technical models, studies, and data into an assessment of groundwater in WRIA 1. The technical input from the WRIA 1 Joint Board Watershed Management Staff Team provided the foundation for the development of a comprehensive bibliography (more than 200 previous studies and reports) conducted on groundwater resources in WRIA 1 assembled into an Endnote^{TM} database (see Chapter 2 for detailed introduction to bibliography and functionality of database searches).

Work was conducted by an interdisciplinary team of water resource technical specialists working with input from WRIA 1 Joint Board Staff Team during draft and final review stages of this WRIA 1 Joint Board project. Whatcom County PUD #1 managed this project funded by Department of Ecology Grant No 1200070 Task 9 Groundwater Study; June 2013. The study examined existing information available for the components of groundwater characteristics that can be critical for the development of a groundwater flow model.

WRIA 1 Watershed and Salmon Recovery Staff Teams members provided valuable local insight throughout development of the 2013 *WRIA 1 Groundwater Assessment* including comments to draft and review draft compilation, supporting descriptions, figures, and tables, as well as discussions summarizing the technical work status, areas for improved groundwater data accessibility, and integration with other WRIA 1 technical resources and tools. The following technical reviewers contributed to the *WRIA 1 Groundwater Assessment.* A complete list of technical contributors is provided in *Chapter 4 - Recommendations for Data Collection and Model Integration.*

Table 1. Complete list of participants in the *WRIA 1 Groundwater Assessment* technical work review, review orientation sessions, and phone consultations regarding model integration recommendations.

WRIA 1 Technical Reviewers	Review Packet & Orientation Recipients	
Rebecca Schlotterback, PUD No. 1 of Whatcom Co.	Rebecca Schlotterback, PUD No.1 of Whatcom Co.	Mark Personius, Whatcom Co. Planning Dept.
Peter Gill, Whatcom Co.	Jon Hutchings, City of Bellingham	Peter Gill, Whatcom Co. Planning Dept.
Clare Fogelsong, City of Bellingham	Clare Fogelsong, City of Bellingham	John Thompson, Whatcom Co. Public Works Dept.
Jon Hutchings, City of Bellingham	Doug Allen, Dept. of Ecology	Chris Brueske, Whatcom Co. Planning Dept.
Jeremy Freimund, Lummi Nation Natural Resources	Kasey Cykler, Dept of Ecology	Oliver Grah, Nooksack Tribe Natural Resources
Kasey Cykler, Dept. of Ecology	Jeremy Freimund, Lummi Nation Natural Resources	Victor Johnson, Lummi Nation Natural Resources
	Steve Jilk, PUD No. 1 of Whatcom Co.	Frank Lawrence III, Lummi Nation Natural Resources

2.0 TECHNICAL REVIEW METHODS

2.1 Input on Draft and Final Technical Work

WRIA 1 Watershed Staff Team members used the following schedule to provide input throughout development of the data compilation current available resources in WRIA 1 (Table 2). Table 3 summarizes comments provided regarding orientation presentations and for the technical documents described below. A separate questionnaire was used to collect WRIA 1 Joint Board Staff Team member input on development of data integration recommendations (see compilation of questionnaire responses in Section 2.2). Additional technical input was collected through brief phone consultations conducted with technical specialists familiar with existing WRIA 1 groundwater datasets and technical resources to gather perspectives regarding potential options for improved ground and surface water model integration (see Appendix B to Chapter 4 for the input gathered through phone consultations).

Table 2. Technical review tasks, focus of input and sequence.

Focus of Input	Technical Review Tasks	Sequence
Compilation of WRIA 1 groundwater data and information	Electronic comment on resource compilation (Task 1) Status update and overview on catalogue approach (Tasks 2 & 3) Questionnaire on desired future functionality, by scale(s) (Task 4)	April 2013
WRIA 1 Groundwater information catalogue development	Review of technical work products summarizing information compil-ation approach and current groundwater information (Tasks 2 & 3)	May 2013
Recommendations on future improvements to groundwater information for WRIA 1	Searchable groundwater catalogue approach and visualization tools (Task 2 & 3) Questionnaire results and identifying near and long term improvements (Task 4)	June 2013

Technical comments provided on the *2013 WRIA 1 Groundwater Assessment* work products are summarized in the matrix on pages 4 through 25. Input was provided during review orientation presentations conducted in April and June 2013, and via comment s submitted on draft and final review work products (identified in the central column of the matrix). The project team's responses and/or actions are provided on the far right column and are intended to support future efforts to improve the groundwater information catalogued in this effort. Note: technical comments provided at meetings is not attributed to individuals or organizations; input submitted via email in report chapters is attributed by initial of the technical reviewer.

Table 3. Compilation of comments to the *2013 WRIA 1 Groundwater Assessment* work products.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Overview			
Figure 3	It's difficult to understand where larger location text on map is geographically referencing (particularly for western portion of WRIA). KC	Final Draft	Agreed. The labeling of maps was improved.
Section 3.2.4	Paragraph incomplete, grammatical corrections on 1st sentence; on page 8 last paragraph. KC	Final Draft	Thank you. Edits addressed.
2003 Analysis	The summary re: the 2003 analysis is not clear. It should say who did it (not ECY)/ Should "data" be "date?) Also, ECY mapped water rights took several years to complete and began in 2007. It is ongoing (as new apps are received their mapped, etc.), so consider removing 2009 date or reword. KC	Final Draft	This section was removed.
Table 2	Table format is confusion, the data sources the same (if so, why the date/name reversal between the 2 rows)? The row titles ("2004 CIDMP irrigation water use;" "CIDMP 2004 Water…") aren't clear w/o text in accompanying section. KC	Final Draft	This section was rewritten and clarified.
Public data	Pg 9, 3rd paragraph. Please include what "available public information" you're referring to. KC	Final Draft	Aerial photos, parcel maps, etc…added to text.
Table 3	Is the Public Water Systems "Known Issues w/Dataset" shows this as a question (if not, remove question mark). Water service areas tend to be consistent with water system plans. I would edit the "No"s in the "Source Known" & "Location Known" columns to "some." KC	Final Draft	This table was modified in Chapter 3 and the Overview. Thank you.
Table 6	Since so much is duplicative between the 3 columns, reduce to just include different data requirements (or bold face differences). As is, differences are visually lost b/c so much is the same across the different model types. KC	Final Draft	Agreed. This table is modified.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Chapter 2			
General	Clarify punctuation in page 6 line 7, pg 8, lines 17-19, 19-21. KC	Final Draft	Edits addressed.
Figure 1 & 2	Problems with the legends. KC	Final Draft	Legends improved.
Well log	Add a statement on pg 6: about well logs not historically required so numbers and maps are not complete data sets for existing wells in WRIA 1. KC	Final Draft	Statement added. Thank you.
Wells	What does "abandonment" mean? "Decommissioned"? Abandonment tends to indicate an existing well that's not in use. KC	Final Draft	Clarifying text added.
Table 2	What does "Ecology Scanned" mean? Should it just be "Ecology"? Same for USGS title. KC	Final Draft	Agreed. Edits addressed.
Table 3	Please put table on one page. KC	Final Draft	Edits addressed.
Figure 3	Legend title should be modified—remove "low flow." Problem with Water Level Data Wells icon (in legend and in map). Modify "(Ecology wells)" in figure title to indicate that it's based upon ECY Well Log Database data, rather than indicating they are ECY's wells. KC	Final Draft	Legends improved. Edits addressed.
General	Correct typos, pg 9, line 2; line 11. Start new sentence at "the map areas…", remove extra rows in Electronic tables. KC	Final Draft	Edits addressed.
Figure 4	Problems with legend—problems with top 4 labels/items. KC	Final Draft	Legends improved. Edits addressed.
Chapter 4			
Section 1.0	Mid-paragraph: should be "data need" rather than "data needs" remove pg 6 quotation mark on top bullet. KC	Final Draft	Edits addressed.
Section 2.3	Seems to skip from brief description of INTB to even briefer description of IHM. What about Topnet-WM, Mike-SHE, etc. info? Also, it would be nice to have a simple comparison table of the different models (advantages, disadvantages, etc.) KC	Final Draft	Descriptions added, section reorganized, and advantages and disadvantages added.

Topic	Technical Review Comment	Source:	Project Team Response & Action
IHM	Why IHM info here (under INTB model summary)? KC	Final Draft	Edits addressed.
General	Last sentence in Section 2.4.1 s run-on sentence. KC	Final Draft	Edits addressed.
Table 6	I don't think this table/information is very helpful. Don't think the example data provides any additional information; recommend removing. KC	Final Draft	Agreed. Edits addressed.
Table 10	Remove "i.e. , accurate to justify water right decisions" statement. Put all of Table 10 on one page. KC	Final Draft	This phrase was removed. Table adjusted.
Section 4.1	Not clear what this means: [followed by the status of completion for WRIA 1] include: For (4) reword: "water pumpage" to "water withdrawals." For (7): incomplete sentence. KC	Final Draft	This phrase was removed. Edits addressed.
Table 12	This is helpful. How were cost estimates developed? Not clear on the following: - why two of the rows have bifurcated columns; why some info repeated in both. - what's meant by Decision Making rows—this seems more like an activity governments /entities would undertake do themselves, rather than hire out. - outreach/education does not belong in this row—what decisions (and by who) are you envisioning happening here? Maybe remove Decision Making row altogether. - Corrections general: data exists" should be "data exist;" "based" should be "basis;" "anticipate" should be "anticipated." KC	Final Draft	1. Options are shown in bifurcated rows. Updated with 'Option' labels. 2. Decision making renamed 'Local Use and Applications' 3. This refers to issue framing and pubic orientation to a technical tool. We can also call it technical transfer. Also for development of information catalogue tools and plain language documents, etc. 4. Addressed.
Tables 13-15	Public outreach costs seem excessive and possibly not appropriate as specified; see earlier comments. KC	Final Draft	10% is a typical industry standard for developing technical transfer documents for multiple user groups.
Section 5.0	Yes, there is interest--please include the suggested information.	Final Draft	Information on previous work was included in the main body of the text, rather than as a separate section.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Review Orientation			
Aquifer locations	Does the Sumas-Blaine Aquifer include the Sumas-Abbotsford Aquifer? Is there a divide between these two aquifers or is there a single name used to refer to this aquifer in WRIA 1?	Meeting – 6-6-2013	The compilation found multiple names used in studies of this shallow unconfined aquifer in the northern portion of the watershed. The project team developed the naming conventions used in this report based on the common terms used in WRIA 1 compiled surficial aquifer studies, and for the bedrock aquifers, the USGS hydrology classifications. See definitions of aquifer names and classifications in Chapter 1.
Aquifer classify-cations	Could these deeper units be more extensive and we just don't have the data?	Meeting – 6-6-2013	Yes, it is possible that these are more extensive, we don't know with the data and information available today. These aquifers may or may not be continuous. The assessment only deals with the locations of where studies on groundwater have been conducted in WRIA 1.
Aquifer data	The deep regional aquifer in the north is deep. The northern Lummi aquifer was not nearly as deep, at least 100-200 feet shallower. In the final report please reclassify this aquifer, see Ecology and Lummi Nation groundwater studies.	Meeting – 6-6-2013	This aquifer will be classified as upland discontinuous as it is 100-200ft shallower than the deeper regional aquifer classifications.
Aquifer mapping	Dose the Sumas-Blaine Aquifer extend to the northwest? It appears to be cut off at the map based on WRIA 1 boundaries not the physical boundary of the watershed.	Meeting – 6-6-2013	The map cuts off at the extent of the WRIA 1 boundary due to USGS layer used to create this map.
Aquifer depth	Does the surface elevation in the aquifer classification system come from elevation or LIDAR datasets?	Meeting – 6-6-2013	The project team used a surface elevation dataset <insert method here> Most of the accuracies were 5-10ft accuracy. This information will be used to give seasonal depth information.
Aquifer data	Department of Health has GPS located 400-500 wells in WRIA 1, which is included in the 2001 data set, has this been improved on?	Meeting – 6-6-2013	No additional work has been conducted on the DOH dataset completed in 2002.
Data gap maps	It looks like there are no citations to the east of the confluence of the Three Forks of the Nooksack River? Is this accurate?	Meeting – 6-6-2013	This is the thickness characterization and there are no studies on the thickness in this area. This is a draft product, so we have others that have All classifications have not been proofed yet, that work is still underway.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Water elevation	Are you identifying additional work that needs to be done to improve data and modeling functions that is beyond the scope of this project's assessment? One of the big challenges regarding well location and depth is the estimates used from well driller logs are plus minus 10 ft. With LIDAR data this can be improved to integrate surface location in order to get to a more accurate picture of depth to water. GPS plus LIDAR has been successful in some places and could be extended to other locations for drainage-scale issues.	Meeting – 6-6-2013	We can frame seasonal water elevation maps based on current data and then give recommendations on how to achieve better representation across a span of years, as current data only provides a rough surface picture. Given the well data set has a wide range of data accuracy, it helps to start with the point on the map where the most accuracy can be achieved, and has been confirmed in studies in WRIA 1. This project did not include that level of analysis, and that could contribute to locating where these are distributed across boundary areas for aquifer, drainages and sections. This information plus well depth are available today. The data compilation in Chapter 1 provides a Yes check option for studies that include field located wells with existing locations identified. So this can be sorted in the new groundwater catalogue.
Data gap maps	While the map classifies where data is located, is there a way to know the quality of those assessments? Will you also list out the gaps you've identified in the assessment?	Meeting – 6-6-2013	The maps were prepared to visualize those locations in WRIA 1 where you don't have data and to identify those locations with more concentrated data. It is much easier to classify the types of information you do have (searchable by groundwater characteristics) than it is to list all the locations and types of data gaps that exist there. So the catalogue search will indicate if the studies address any one of the 12 groundwater classifications, but it does not provide an additional layer of analysis. It is made clear in the text that the user needs to recheck the assessments and referring sources for quality and repetition.
Data gap maps	Organization for the regional and drainage studies should be searchable by watershed names not aquifers, as that is the more common way of referring across planning bodies and organizations.	Meeting – 6-6-2013	This organizational scheme was used.
Well map	Use a shallower cut off for this map (20 ft) to knock out the test wells when mapping the well density.	Meeting – 6-6-2013	This was a good idea, but the analysis did not change.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Well map	Improve visualization for the well density map. Present at most accurate information level for well location (at the section level), and use circles of increasing scale to show number of wells in the section remove individual lines.	Meeting – 6-6-2013	Data set on well density needs a lot of work and it will take a lot of work to make it useful to filter things out. A person who will use this will be able to do so; it's all in one place.
Well depth	Where the well is located on the land surface elevation really matters to put well depth into perspective to the aquifer where it is located. A visual map of where studies are located on this characteristic this is not so helpful in isolation.	Meeting – 6-6-2013	The summer topography of depth to water was created to address this issue.
Seasonal water table elevation	Use a different graphic to present depth to water visualization. The contour map reads as flow direction and this is not really expressing that information here. Maybe broader color gradations or shading could be used to convey the depth to water, instead of elevation and contours.	Meeting – 6-6-2013	Dataset used to create this map separates depth to water into grouping of: < 75 feet, and those > 75 ft. 75ft was selected due to typical thickness of depth to ground and that was a filter. There is not good information on summer water depth in WRIA 1.
Depth to water	Can you correct this information to a base level, like sea level so that you are accounting for the drainage surface?	Meeting – 6-6-2013	We don't have an elevation analysis separate from the one in the DEM. This seasonal water table elevation is very rough, as it's not designed to figure out the flow direction for the entire WRIA 1 it's a seasonal water table elevation you can come up with for the data you have right now. Groundwater flow direction and hydraulic gradient are both characteristics sorts for the bibliography
Depth to water	The summer and winter data sets are more useful aquifer information to see. Want to be able to see the depth to water is in summer and what it is in winter.	Meeting – 6-6-2013	Depth of water to the wells can be shown, and then there are seasons and different depths of wells. So there are only so many ways to show this much information on one map.
Data gaps	There a quite a few studies done in Lummi Reservation, such as the drainage studies on Lummi on the prairie (Lake Terrell), and these don't seem to show up on the map visualization.	Meeting – 6-6-2013	The map presented in the meeting is on regional studies level information compiled. There are additional site-specific and drainage studies for these areas that get filtered out when searching the catalogue for regional studies.
Site specific	Is there a site specific map for studies at the site level too?	Meeting – 6-6-2013	That can be done. This is still being coded by study type, so each of these visualizations helps us see finer classifications. We are looking for each of the types of studies you want to sort for.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Data gaps	The maps need work on the titles so you understand scale, e.g., drainage or regional, and characteristics featured (or available, not featured in this characterization). It's confusing when you know there are types of studies that are from that area and you don't see these.	Meeting – 6-6-2013	Maps have improved labels as well as the number of studies per drainage in the database has been summed to include site, drainage, and regional scale studies.
Data gaps	Visualization is great on the database to show where the gaps are, e.g., will the maps also include the types of information gaps that exist in these areas and any recommendations on how to improve in these locations and/or characteristics? Could you include general statements on these other drainages don't have data in this is what needs to happen here. So show where we have data but where areas are missing	Meeting – 6-6-2013	It is easier to say where you have data, because the area where you don't have data is so huge. So the spatial display is what is used to show where gaps exist. So we can show the map that is not parameter specific and show where we don't have any data and then build out. Citations are site, regional, drainage and we're showing these individually by region.
Water sources	Does municipal use also include the PUD? Use municipal /industrial or separate out the industrial all together given PUD is now all industrial. You can use the state definition of industrial which includes PUD, just be clear which is used.	Meeting – 6-6-2013	PUD is only industrial, other utilities are municipal.
Water rights	In the report on supply, irrigation clearly is the biggest user and this is the area of groundwater information and data that is most unreliable.	Meeting – 6-6-2013	Two types of information we know the least about is gw/sw irrigation and berry/dairy processing. We did not identify public water systems in the Water Budget, so we don't know sources for these users. We do know for water rights and studies (with Bertrand example). When the 2004 CIDMP was done for Bertrand, the data was collected by map-based conversations with actual growers on sources, crop type and application type (first line item is 80% gw and 20 % sw). Then looked at water rights and checked for overlapped rights (this comes up with 74% and 27% on water rights). So there is a high degree of inaccuracy in this basin when reviewing the water rights (permits and certificates) quantities and actual use estimates and surface and groundwater sources.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Water rights	This project is not looking at parcel-level information so we need to see basin-wide information, not site-specific visualizations, as we don't have this type of data support to be specific and accurate at parcel levels.	Meeting – 6-6-2013	Circle, pie visualization will be used to give proportion of one to the other in mapped visualizations.
Water sources	Do the unpermitted uses show up under water rights map? This should be made clearer through titles and key.	Meeting – 6-6-2013	No, water rights map was deleted.
Acres irrigated	Does this include all actual irrigation on the ground (groundwater and/or surface water sources) or only the irrigation water rights? Proportion of irrigated acres should be factored using actual on-the- ground irrigation (both permitted and unpermitted users).	Meeting – 6-6-2013	There is information on actual irrigated on the ground compared to water rights for Bertrand Creek only, which is presented in table format.
Water rights	Take an approach to identify sources and quantities based on water rights (permits and certificates only). Include table with Bertrand example to quantify how unreliable the water rights estimates are compared to the Bertrand CIDMP actual on the ground irrigation estimated figures. Explain how this can have an effect on planning for future needs and gaining fuller understanding of the water resource.	Meeting – 6-6-2013	The total acreage irrigated under water rights is different than the actual acreage totals irrigated, so it would not be possible to average across two numbers. Proportion of irrigation rights is the correct title (qualify this includes e claims and rights in the key).
Updated Ecology datasets	ECY include mapped claims, permits, certificates, and allows you to pull up electronic records organized on a map base layer, it is online for review and viewing. Place of use and point of diversion is mapped and online but only one water right at a time. In contrast Gill and Atkeson's set was already analyzed for outlier claims and verification consultations to look at cfs and gallons per minute and analyzed for likely use adjustments a. Use Gill and Atkeson's mapped water rights data for this assessment.		The Ecology Assessment will deliver the WRIA 1 data, the Gill-Atkeson dataset will be used since it included some analysis and excludes unrealistic claims.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Mapped datasets	The assessment was conducted based on WRIA 1 water rights analysis of small percentage of claims that were identified as likely to be real. Use certificates and permits to show representation of water source proportion and compare to on the ground information. Be careful with the claims, as the information in the Ecology Water Rights database is not analyzed and these will include claims locations spanning sections and the whole county due to insufficient information.		Thank you for this background information.
Water sources	Please clarify map and legend titles to make it consistent for reader to understand context of what is represented (certificates, permits and/or claims) and the water rights paperwork limitations.	Meeting – 6-6-2013	The map titles were cleaned up and clarified and only pie charts showing source distribution were used.
Ground-water data	Provide recommendations on how to get surface water and groundwater information in areas that don't have the detailed data like Bertrand CIDMP. Include brief description on how you would go about doing that work to get improved accuracy.	Meeting – 6-6-2013	Recommend starting in smaller areas where existing data can support the development of a groundwater model. Right now you have a little information everywhere and only a few places with enough detailed information to conduct finer analysis. Recommend iterative improvements over time to improve Topnet-WM.
Ground-water data	Groundwater modeling for future desired needs seems to be focused on a site specific scale groundwater model. If the goal is to be able to design some scenarios you can evaluate, in terms of groundwater and surface water interactions, at the drainage or site-specific scale. The idea of calibrating a regional model doesn't make sense. We need to calibrate a really good groundwater model that has some spatial scale limitations with the information we have within a particular basin. Unless you go out and survey all those wells, it would be difficult to get to that level of accuracy for those types of site-specific questions. That doesn't mean you can't get a characterized regions on a map and show seasonally how the groundwater is connected and shifting.	Meeting – 6-6-2013	The survey results show that in the 1 to5 year range, organizations want a functional groundwater model that can answer site specific questions. Questions seem to be dependent on individual well location. While regional scale model is easier to make, it was not identified as a high ranked priority for those responding to the survey.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Model options	What integration option do you recommend?	Meeting – 6-6-2013	Need values correct at the places where you are making the most current decisions.
Maps	The one page master graphic should be reformatted so the combination graph is one page, then zoom in on the blow out of key featured elements (like the upper left graphic)	Meeting – 6-6-2013	These maps were redesigned.
Chapter 1 Draft Document for Review			
Figure 2	WRIA 1 Primary Aquifers Map. Please make this a full page map. Also please vary the colors of shading to standout from one another more significantly. KC	Review Draft	Maps enlarged.
Sumas-Blaine Aquifer	General comment for this chapter. You switch between current and past tense when discussing information from others' studies. Please use present tense. KC	Review Draft	Agreed. Uses present tense.
Figure 2	Show Mountain View Upland aquifers on the map. KC	Review Draft	This map has changed. Only primary aquifers are shown in Figure 3. More detail is included in Chapter 2.
Figure 2	Show Boundary Upland aquifers on the map. KC	Review Draft	This map has changed. Only primary aquifers are shown in Figure 3. More detail is included in Chapter 2.
Figure 2	Show Deer Creek aquifers on the map. KC	Review Draft	This map has changed. Only primary aquifers are shown in Figure 3. More detail is included in Chapter 2.
Figure 2	Show Deep Regional aquifers on the map. KC	Review Draft	This is shown in Figure 3.
Elevation	The aquifer appears to generally be located below elevations of approximately depths below 200 to 300 feet within permeable portions of older undifferentiated glacial and nonglacial deposits, and is separated from the ground surface and overlying aquifers by over 100 feet of low permeability Olympia nonglacial sediments. KC	Review Draft	Yes.
General	Remove passive voice writing. KC	Review	Agreed.
Add	Add Department of Conservation (1960) to the bibliography JF	Review Draft	Added.

Topic	Technical Review Comment	Source:	Project Team Response & Action
General	There are obviously many more or many fewer sub watersheds within WRIA 1 depending on the scale of analysis and purpose of a particular evaluation. JF	Review Draft	Agreed.
Table 1	The drainages [Samish bay, Blanchard, Larrabee, Oyster creek, Whitehall] fall within what could be call the Samish Bay Management Area. Hopefully this is a typo and the County is not considering the drainages [Jordan, Lummi Peninsula West, Lummi River Delta, Lummi River, Sandy Point, Schell] to be in the Samish Bay. The drainages highlighted in green largely discharge to Lummi Bay (although part of Sandy Point discharges directly to Georgia Strait). JF	Review Draft	Table edited.
Aquifers	Did you also want to include Esperance Sand (formerly Mountain View Sand and Gravel) by Easterbrook in this characterization also? JF	Review Draft	The Chapter 1, Section 3.3 discussion regarding Vashon advance outwash was expanded to address Esperance Sand and Mountain View Sand and Gravel.
Primary aquifers	I do not think that the mapping of the Lummi River and lower Nooksack River deltas as a discontinuous aquifer area is appropriate. As documented by Cline (1974), ground water in this alluvial area is either saline and/or the aquifer is not productive. An exception is the area along the southern extents of Ferndale where artesian wells have been encountered so perhaps only show this area as a productive aquifer. Include the mapping by Cline regarding productive aquifer areas near the Reservation as this figure is missing the productive aquifer east of Neptune Beach and the productive aquifer within the southern half or so of the Lummi Peninsula. This figure also raises the issue about ground water quality. As noted by Cline, there are many areas of the Lummi Reservation where the ground water is too salty for potable or agricultural uses. This seems likely in other coastal areas that may be both underlain by marine waters and/or subject to lateral and vertical salt water intrusion. JF	Review Draft	Qualifying language about water quality was added to the text. The water quality limitations in the Lummi Peninsula area have been briefly addressed in Chapter 1 Section 4.2.4

Topic	Technical Review Comment	Source:	Project Team Response & Action
Aquifer	Please provide additional information as to why it is also likely that this type of aquifer is present in these areas (e.g., based on well logs). JF	Review Draft	Text added: *Surficial and/or Deeper (non-surficial) discontinuous aquifers have been identified beneath the Boundary Upland just east of Blaine, the Mountain View Upland west of Ferndale, the Birch Point Upland southwest of Blaine, Lummi Peninsula, and in the Ten Mile management area. It is also likely that deep discontinuous aquifers are present in the Squalicum, Lake Whatcom, and Upper Mainstem Nooksack management areas. The identified deeper discontinuous aquifers appear to be located in Everson-age and older glaciofluvial deposits consisting of sand with some gravel and silt.*
Vertical datum	Please identify your vertical datum – I am assuming here below ground surface but you could mean below sea level. see: JF	Review Draft	Text added: *Associated Earth Sciences, Inc. (AESI, 2008) indicates that groundwater in the Boundary Upland discontinuous aquifer appears to be semi-confined to confined with elevations varying from less than 50 feet to over 250 feet below ground surface*.
Deep Regional aquiver	Consider reversing the order of presentation to align with the subsequent text (i.e., 4.4.1 is about the Blaine Aquifer not the Mountain View Aquifer) , JF	Review Draft	Text added: *Deep regionally extensive aquifers have been identified beneath Mountain View Uplands (Mountain View Aquifer) and in the northwestern portion of WRIA 1 near Blaine and Lynden (Blaine Aquifer)*.
Vertical datum	Please identify the vertical datum here and be consistent with other areas of the report – is it below ground surface or preferably below mean sea level. In multiple locations line 3 page 6 and repeated throughout. JF	Review Draft	The text of Chapter 1 has been revised to indicate that all depth are relative to ground surface unless otherwise noted (section 4.1) and that all elevations are relative to mean sea level unless otherwise noted (section 4.2.1)
Chapter 2 Bibliography Draft Document for Review			
Add entries	Add the following citations: Aspect Consulting LLC. 2003. Lummi Peninsula Ground Water Investigation, Lummi Indian Reservation, Washington. Aspect Consulting LLC. 2009. Aquifer Study of the Mountain View Upland – Lummi River Area. JF	Review Draft	Added Citation. Thank you.
Add entry	Lummi Water Resources Division. 2011. Wellhead Protection Plan Update JF	Review Draft	Added Citation. Thank you.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Add entry	Pacific Groundwater Group. 1995. Summary update, hydrogeologic characterization and monitoring, Sandy Point Improvement Company, Ferndale, WA. JF	Review Draft	Added Citation. Thank you.
Add entry	Robinson & Noble, Inc. 2003. Sandy Point Improvement Company, Sandy Point Production Well, Construction and Testing Report. JF	Review Draft	Added Citation. Thank you.
Add entry	Rongey/Associates. 1988. Hydrogeological investigations for Lummi Indian Business Council located NW1/4, Sec. 4., T. 38N, R. 1E. JF	Page 8	Added Citation. Thank you.
Add entry	Washington State Department of Conservation. 1960. Water Resources of the Nooksack River Basin and Certain Adjacent Streams, Water Supply Bulletin No. 12. JF	Review Draft	Added Citation. Thank you.
Chapter 3 Draft Document for Review			
Clarify text	"Typically, in states where water rights are strictly administered water use records are required to be submitted by water users on at least an annual basis. However, water rights regulations are generally not enforced in many parts of Washington State for various reasons and as a result, information on actual water use is only collected in certain areas or when certain conditions are met (e.g., municipal purveyor). Irrigation is the main sector in which water sources and actual water use from the sources are generally unknown." JF	Review Draft	Change accepted.
Dairy source GW/SW	Do you mean to say here that 20% of the dairies were assumed to be supplied by ground water and 80% of the dairies were assumed to be supplied by surface water or do you mean to say that a typical dairy gets 20% of its water from groundwater and 80% of its water from surface water? JF	Review Draft	The former….*the water source proportion for dairies is 20% from groundwater and 80% from surface water.* We don't really know the correct distribution between and ground and surface water sources. This is a data gap.
GW/SW sources	Regarding… This adjusted distribution of water source between surface and ground water replaced the generalized	Review Draft	No, we did not assume the water allocation documented on water rights was the correct source distribution since there are many

Topic	Technical Review Comment	Source:	Project Team Response & Action
	assumption of the source distribution of acres irrigated noted on water rights that was developed for model input. But did you ensure that the overall allocation within the watershed aligned with the water right documents? JF		acres of unpermitted irrigation.
GW water rights	ADD,…As a result, reliance on water rights documents in WRIA 1 to estimate the quantity of water use, the water source, and the place of use is not considered to be reliable.	Review Draft	True and this text was added to the chapter.
Examples	In the example on impact of single claim information on overall study information….This 20 AF of water over 20 acres only translates to 12 inches of irrigation per year, which is in the reasonable range. Are you referring to the 105 cfs claim rather than the 20 AF claim? Also ADD the following for further clarification: In addition, there are several ground water points of withdrawals shown in Figure 1 where either the aquifer cannot produce the yields identified in the water rights documents or the ground water in the aquifer is not potable due to elevated salinity levels. JF	Review Draft	This was awkward phrasing in the draft. The claim noted 105 cfs diversion rate for 20 acres using 20 acre feet. This phrase has been added.
Data options	ADD…Additional effort should be focused on field observations to better understand and document water sources used in WRIA 1. JF	Review Draft	This was added but in the framework of interviews and not necessarily direct field observations for each parcel.
Table 2 acres irrigated	To better quantify how unreliable the water rights documents are for the purposes of identifying water sources, it would be helpful to have a new Table 4 that compares the data in Table 2 with similar information developed from the water rights documents that are included in Table 3. Column titles for this table could be: TRS, CIDMP irrigated acres ground water, Water Rights documents irrigated acres ground water, percent difference, CIDMP irrigated acres surface water,	Review Draft	This table will not be added here since the two existing tables basically present all this information. The reader can assemble this table, but we don't want to lose the potential cooperation from farmers if they are disturbed about the information presented.

Topic	Technical Review Comment	Source:	Project Team Response & Action
	Water Rights documents irrigated acres surface water, percent difference. JF		
Figure 3 Number of Claims	MAP feedback .It is not clear from Figure 3 if the locations identified by the dots are the point of withdrawal/diversion or place of use? Also why there are lines connecting the dots. JF	Review Draft	This figure has been deleted.
WR analysis	Clarify reference……What water rights analysis? Is this referring to the PUD work (2003) or analysis conducted for the present effort? JF	Review Draft	The water rights analysis conducted as part of the Bertrand CIDMP (2004).
General	The overall point that is being made is that the water rights documents are not a reliable foundation for determining /estimating the sources of water used in WRIA 1. Since there is at least limited more accurate information for at least Bertrand Creek (weren't CIDMPs also developed for Fishtrap Creek and Tenmile Creek?); seems the Bertrand Creek info could be used to more quantitatively describe the "error bounds" for the allocation of water sources from the water rights documents. From Bertrand Creek, it appears that the information obtained from water rights documents are so unreliable (nearly ½ of the water use is not permitted to start with and then many of the existing certificates, claims, and permits do not reflect reality) that they should not be used at all. What seems to be needed is a specific/ systematic study using high resolution aerial photographs, property boundary mapping, well log mapping (which will have no higher spatial resolution than +/- 10 acres at best), interviews, and field observations utilizing GPS units and photographs to get a more reliable understanding of the conditions. JF	Review Draft	CIDMPs were not done for Fishtrap or Tenmile. The NLWID prepared an overall natural resources management plan for Fishtrap. An irrigation water use study was completed for Tenmile and a study addressing Crystal Springs in Tenmile. Extrapolating error bounds from Bertrand to other watersheds could be as erroneous as using water rights. Each drainage is unique and specific information to that drainage will be the most accurate method for depicting water sources. We are recommending that the work done for the Bertrand CIDMP be used as a template or model for collection of similar data in other drainages.
Figure 4	This figure and what it shows should be referenced and described in the text. Is there mapping available to contrast where actual water use is occurring versus where the water rights documents indicate water use is occurring. JF	Review Draft	The two maps in the revised chapter show source water distribution for both "on the ground" irrigation in 2004 and the water rights analyzed in that same effort.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Table 4	Citation needed for this information. JF	Review Draft	Added.
Figure 6	CORRECTION This mapping is not accurate for the Lummi Reservation. The former Gooseberry Point, Fisherman's Cove, and Horizon Heights water associations' wells appear to be shown yet these systems were integrated with the Lummi Water District system and are no longer regulated by Washington State. The Lummi Water District is regulated by the EPA and none of their production wells are shown. It appears like the Neptune beach Water Association but not the Sandy Point Improvement Company water association is shown. The Bel Bay water association is not shown and neither is the Fertile Meadows water association. JF	Review Draft	This figure was deleted. The drainages were provided by the WRIA 1 Project. File name = bsnwria1_v7.* For this report, we used the management areas identified in the watershed characterization report. The specific public water system information will not be included in this chapter since the goal is to identify steps to eliminate data gaps and not to analyze or summarize specific data.
General	Unfortunately, this chapter, as a whole, was not very helpful to me and provided very little to no new information. I'm disappointed in the overall work product as it's less than I was hoping for. Seems like most the information could be condensed into 1-2 pages. KC Recommend change to intro …. In the State of Washington, the Department of Ecology manages water resources under the prior appropriation system of water right permitting. Sources of water in WRIA 1 include a mix of surface (lakes, rivers, and springs) and groundwater (surficial and deep aquifers) sources. In WRIA 1, non-permitted irrigation is the largest sector in which water sources are unknown.	Review Draft	This chapter was not intended to provide new information. The goal was to identify data gaps and methods to fill those data gaps.
Prior WR work	Not sure what you mean by this introductory sentence… With the exception of public water systems, the most comprehensive data available on sources of water supply in	Review Draft	This sentence was rewritten. The website does not allow a download of data but only to look at one water right at a time. The Staff Team agreed that the data

Topic	Technical Review Comment	Source:	Project Team Response & Action
	WRIA 1 is in the water rights database assembled by Gill and Atkeson (2001). What about Ecology's Water Resources databases-- The WR Explorer: https://fortress.wa.gov/ecy/waterresources/map/WaterResourcesExplorer.aspx and Water Rights Tracking System? KC		mapped and assembled by Gill and Atkeson was more appropriate to use for this chapter.
Use of interview approach	Disagree with this statement. How does the source make this task more or less onerous? It is unrealistic given current staff and resources. *While it may be onerous to interview every water user in WRIA 1, or even in the Lower Nooksack Subbasin, obtaining information from surface water users may not be unrealistic, since most of the water use is derived from a groundwater source.* KC	Review Draft	This section was deleted.
Proposed methods	This is not a realistic assumption. KC *"This could be done by first investigating the current uses derived from water rights designating surface water as the source of supply, and assuming that all other uses are groundwater?* KC	Review Draft	This section was deleted.
Options	How would we determine all irrigators? KC "Response rate likely to be extremely low. Another approach is to design a questionnaire to be mailed for all irrigators;	Review Draft	This idea was deleted from the text.
Methods	"A follow-up methodology must also be developed" For what purpose? KC	Review Draft	This was deleted from the text.
Previous sources used	You need to be sure to specify between permitted & non-permitted irrigation throughout the document. KC "With the exception of Bertrand Creek drainage, water sources for non-permitted irrigation are generally not known."	Review Draft	Yes. We know very little about sources of supply for non-permitted irrigation. This is a data gap.
Dairy source	Is this supposed to be opposite?...KC "Dairies were assumed to be supplied 20% groundwater and 80% surface water."	Review Draft	No, this is correct the way it is stated.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Single claims and impacts of errors	Replace text with….KC Without a detailed analysis, the proportion of water withdrawn from either groundwater or diverted from surface water can be skewed by a number of factors, including a single large water right, actual water use versus certificated use, overlapping or duplicative water rights etc. In addition, the relative percentages of ground- vs. surface water sources for non-permitted irrigation may not be the same as permitted irrigation.	Review Draft	This was rewritten and comments were considered as part of the rewrite.
Example question	Example needs clarification. What's wrong/inconsistent with this claim? 1 Af/acre is not an abnormal rate of irrigation. KC	Review Draft	This claim noted 105 cfs diversion rate for the irrigation of 20 acres using 20 AF. This was not stated clearly in the text and has been rewritten.
Spatial datasets	What are spatial datasets? KC	Review Draft	Datasets that can be mapped; they are in a GIS format, i.e., shapefiles, geodatabases.
Figure 1	Map correction. KC. Watershed for Lummi Peninsula is not correct.	Review Draft	These data were from the WRIA 1 Project and not developed by us. The file name is bsnwria1_v7.* as noted previously in this matrix.
Figure 2	Please mark Pepin as Double Ditch in all figures (better local recognition). Also on legend for this map Sorry, but I am still confused by what this means. Also need units. KC	Review Draft	Corrected but it doesn't show up on the map due to scale or length of name.
Figure 3	So does each dot represent a water right document? Please clarify KC	Review Draft	Figure deleted.
Table 3	Inconsistent titles—clarify all caps; lower case here. KC	Review Draft	Corrections made in final document.
Figure 4	Please enlarge legend; hard to read. KC	Review	Corrections made in final document.
Water sources	This doesn't real provide much helpful information. Seems like just a very brief summary of the previous Topnet-WM & LNWB work. KC	Review Draft	Corrections made in final document.
Supply sources	"The City of Lynden, the PUD #1, and the City of Bellingham were designated 100% surface water sources in both versions." Include as recommendation for updating. KC	Review Draft	Corrections made in final document.

Topic	Technical Review Comment	Source:	Project Team Response & Action
Self supply	"In 2012, the self-supplied water users (residential, commercial, and industrial) were assigned groundwater as their only source of supply ". How about some analysis of the assumptions and how to improve? KC	Review Draft	Done mostly by identifying all other uses. The population not under public water systems once those service areas are defined will be assumed as self-supplied.
Figure 5	General formatting and grammar corrections including: Need to capitalize all words or not. Be consistent.	Review Draft	Corrections completed in final document.
Orientation Session for Draft Document Review			
Citations	So citations identified in the literature review will be labeled in the database by location, so you can search by drainage name, e.g., Deer Creek?	Meeting – 4-25-2013	Yes, from the Access Database < WRIA1Groundwater06282013.mdb>
Value of Endnote	It makes sense to export the information out into a table for accessibility by the public. The EndNote system is a good value for those working with these datasets regularly.	Meeting – 4-25-2013	The Bibliography will be available to the public. We will add an exported table as well. See Electronic Appendix Table for Chapter 1.
Endnote	So is it recommended to purchase EndNote software for linked document and word database for 125 of the 150+ studies compiled? One approach is to purchase this individually.	Meeting – 4-25-2013	The deliverables will be provided in table format and in EndNote library which is a searchable database linked to work and linked electronic studies. The tabbed format system is based on types of data common to all documents and can be exported to word and other users.
Maps	The LENS study could have contours for groundwater elevations that could be helpful in this groundwater compilation.	Meeting – 4-25-2013	Part of the literature review includes; citation, included datasets to the study, and we are also collecting any additional aquifer characteristics studies and identified field testing wells with well data-level information. Peter is also helping us identify other studies that may have components like the LENS.
Data sources	What data are you also providing interpretation of?	Meeting – 4-25-2013	Yes, Chapter 1 is the literature reviews already conducted (10 places to go for more information on aquifers) and then specific linked citations by drainage for that drainage. Chapter 2 will be an overview of data details and how it might be used, and Chapter 3 is sources, groundwater, surface sources, and Chapter 4 is the recommendations for future improvements.
Add	Are all the Lummi Natural Resources and Ecology data in; did	Meeting –	This was added, thank you.

Topic	Technical Review Comment	Source:	Project Team Response & Action
	a mass measurement in March and August 2008 for Ferndale West and South (spring/fall) to see if there is a difference, the overall goal was to delineate the north Lummi aquifer.	4-25-2013	
Search	Literature review should include physical attributes of the aquifer, variations underlying the different geology. Keep it readable down to 30-45 pages maximum, showing the areas.	Meeting – 4-25-2013	We can have a readable approach to review the available resources and literature and if you want a table of citations there are other details available in the database.
Add	Does it include that study that was conducted as part of looking for natural gas resources in the county, conducted by Hayes Drilling (Sedro Woolley) in the 1960s which included a number of really deep wells and an output map is available?	Meeting – 4-25-2013	Not specifically. The information referred to is proprietary information regarding a coal/gas exploration program conducted in Whatcom County in the 1980s. The available information is primarily in the form of exploration logs filed with Ecology.
1962 Blue Book	Do you have the 1962 Blue Book Water Resource Bulletin 12, which has a lot of maps and work on groundwater, it was a WA Conservation document. Lummi has an electronic version of the document.	Meeting – 4-25-2013	Yes. This is in the database.
Target audience	Keep it readable, because once published there are a lot of people who will want to read it that have less technical background. And when people review back, they want to see a quick look at what it covers to see if it relates to what they are working on, and then click to get more information.	Meeting – 4-25-2013	Agreed.

2.2 Survey on Key Functions for Integrated Groundwater Information

Participating WRIA 1 Joint Board Watershed Staff Team member organization's provided insight on needs for integrated surface/ground water information for each scale included in the groundwater information assessment: site-specific, drainage, and regional. Technical reviewers were provided electronic review of the aquifer and groundwater information compiled for the assessment prior to completing the questionnaire, which included a substantial number of publications available regarding regional or general studies for WRIA 1. A number of these studies contain data useful for populating a regional groundwater model, e.g., the numbers of studies containing data inputs necessary for a drainage scale model are available for 20 of the 172 drainages located in WRIA 1.

While five of the drainages, Bertrand, Fishtrap, Johnson, Lower Dakota and Nooksack to Deming, have a significant number of technical studies with very useful data, fewer studies have been completed for the remaining 15 drainages. The purpose of the questionnaire was to identify desired data improvements and timeframes for model integration tools. The survey included sample planning questions, which prepared by the project team following compilation of 200+ prior studies conducted on groundwater resources in WRIA 1. A compilation of questionnaire responses is provided in this section summarizing input provided. This information informed the development of recommendations on future improvements groundwater model information and integration with WRIA 1's existing Topnet model (further outlined in Chapter 4 to the WRIA 1 Joint Board Groundwater Assessment report).

Question 1: *INPUT on SCALE: What areas, drainages, and/or watersheds are in need of further data and improved model to support knowledge-based planning? On the following page, please add if there are specific sites or drainages of particular interest for specific planning or management questions.*

Responses to Question 1:

- We need to be as inclusive as possible of all the drainages in the Lower Nooksack (all lowlands). If we can move this process to the next level of producing a "real time" model that is able to consider a site specific quantification of surface to surficial relationship so we can start making decisions on water availability and on moving water to where it is needed.
- Sumas-Abbottsford aquifer; South Fork Nooksack River from Saxon bridge to Potter Bridge; Anderson Creek from base of Stewart Mtn. to confluence with Nooksack River.
- All lowland drainages including the drainages that discharge to Lummi Bay and Georgia Strait. Ground water/surface water interactions and stream flow depletion due to pumping ground water wells in the upper watershed (e.g., South Fork Nooksack downstream from essentially Skookum Creek but inclusive of the area recently proposed to be rezoned for mineral extraction [gravel mining], North Fork Nooksack [particularly Kendall Creek/Peaceful Valley area), lower Middle Fork Nooksack River). Ground water use on Lummi Island and Point Roberts is important but not critical.

Question 2: *FUNCTIONALITY: The Groundwater Assessment Project examined the need for surface and ground-water models in WRIA 1. After reviewing supporting resources the team framed a general, overarching functionality goal, formed around a central question that emerged from over X year period of studies and technical consideration of ground and surface watershed modeling to support watershed planning and management. Technical reviewers were asked to confirm and/or amend the question below:*

"What can we do to allocate water for existing and future uses and how can we best mitigate impacts while maintaining instream flow and reduce uncertainty in low flow period?"

Responses to Question 2:

- "What do we need to know and how do we build a real time model so we can make decisions on how to allocate water for existing and future uses and how can we best mitigate impacts while maintaining instream flow and reduce uncertainty in low flow period?"
- How, when, and where do we withdraw groundwater so as not to impact instream flows during the low flow period? What options are available to mitigate potential impacts?
- What is the return flow from irrigation? How does it contribute to baseflow in the late summer months?
- In the Lower Nooksack where are the gaining and losing reaches of the streams in the late summer?
- ***"What can we do*** to ***allocate water for existing and future uses and how can we best avoid, reduce magnitude, and mitigate impacts while maintaining instream flow and reduce uncertainty in low flow period?***

Question 3 and compiled responses are provided in on pages 26-28; the questionnaire template is available on Page 29.

Data & Model Input Scale: *Site-Specific*

Locations of Interest (see Chapter 1, Figure 1)	Rank in order of importance 1 = most important, 8 = less important	Planning Horizon 1 to 5 yrs OR 5 to 10 yrs 10 to 20 yrs OR > 20 yrs	Technical Guidance Concepts for Groundwater Model Development * presented by project team
– Lower Nooksack, Nooksack Forks, Coastal North – All lowlands, including forks – Lower Nooksack – Western Whatcom Co. from Canada south to Tenmile Creek and from Everson west to Haxton Road	1 , 1, 1 3 4	*4* ---- 1-5 yrs *1* ---- > 20 yrs	*What is the effect of groundwater pumping on surface water? i.e., days, months, feet or miles?*
– Lower Nooksack, Nooksack Forks, Coastal North – All lowlands, including forks – Need general time of influence map. – Each change would need its own hydrologic analysis given the investment [a] There is not enough detail in a basin wide model for analysis of change resulting from individual site change	1 2, 2 [a] 3 6	*3* ----1-5 yrs *1* ----> 20 yrs Basin model should provide enough certainty for pilots and influence a policy change	*How accurate should model predictions be to determine the benefit of moving a surface water withdrawal to a groundwater withdrawal?*
– Lower Nooksack, Nooksack Forks, Coastal North – All lowlands, including forks – Fishtrap – Bertrand – Kamm – Drayton	1 2, 2 3 4	*3* ----1-5 yrs *1* ----> 20 yrs	*Ability to evaluate down-gradient impacts of changes in water and land use to support mitigation and natural resource trading.*

** Questions presented by GW Assessment Project Team provided as examples of typical groundwater analysis questions that might be answered at this scale.*

Data & Model Input Scale: *Drainage Scale*

Locations of Interest (see Chapter 1, Figure 1)	**Rank in order of importance** 1 = most important, 8 = less important	**Planning Horizon** 1 to 5 yrs OR 5 to 10 yrs 10 to 20 yrs OR > 20 yrs	**Technical Guidance Concepts for Groundwater Model Development** * presented by project team
– Lower Nooksack, Nooksack Forks, Coastal North – All lowlands, including forks – South Fork	2 3 5, 5 7	3 ----1-5 yrs 1 ---- > 20 yrs	*Can timing of irrigation water use be modified to result in a net benefit to streamflow while maintaining crop production?*
– This makes farming unviable in many places. Consider temporary holding back water – Lowlands below Deming – Lower Nooksack, Nooksack Forks, Coastal North	2 5 6 7 8	4 ---- 1-5 yrs 1 ---- 5 to 10 yrs	*What is the effect of the addition or removal of tile/ditch drainage to increase/decrease storage?*
– All lowlands, including forks – Lower Nooksack, Nooksack Forks, Coastal North	1 2 5 5 7	4 ----1-5 yrs 1 ---- > 20 yr s	*What is the effect of changing water use from self-supplied to municipally supplied?*

** Questions presented by GW Assessment Project Team provided as examples of typical groundwater analysis questions that might be answered at this scale.*

Data & Model Input Scale: *Regional Scale*

Locations of Interest (see Chapter 1, Figure 1)	Rank in order of importance 1 = most important, 8 = less important	Planning Horizon 1 to 5 yrs OR 5 to 10 yrs 10 to 20 yrs OR > 20 yrs	Technical Guidance Concepts for Groundwater Model Development * presented by project team
– Forks – All watershed – Lower Nooksack, Nooksack Forks, Coastal North	2 2 6 8	*1* ----1-5 yrs *1* ----1-10 yrs *1* ---- 5-10 yrs *1* ---- > 20 yrs	*What will be the impacts of climate change in WRIA 1? i.e., snow pack, timing of snow melt, glacial contribution to streamflow.*
– Forks – All watershed – Lower Nooksack, Nooksack Forks, Coastal North	1 1 3 4 8	*2* ---- 1-5 yrs *1* ---- 3-8 yrs *1* ---- 5-10 yrs *1* ---- > 20 yrs	*Improve the Lower Nooksack Water Budget model inputs, calibration and outputs to apply model across WRIA 1.*

SAMPLE WRIA 1 Groundwater Assessment Questionnaire for Developing Technical Direction

The questionnaire below was developed to help identify key topics of importance to you in developing technical guidance for future groundwater models, integrated surface/ground water models, or integrated groundwater model with Topnet, per Task 4. The responses to the questionnaire will be used by the consultants to develop the Use-Data-Model framework matrix. The potential application for any model dictates the level of detailed data required as inputs. We have assembled a list of sample questions framed for site, drainage and regional scales based on information gathered during our review of resources, however, this list is not exhaustive and your additional input will be very helpful to towards making appropriate data needs and model recommendations. Please add management questions that are important for your organization is not found in the list. Ranking is intended to capture the level of importance to you: 1 is most important, 8 is least important in the next 5 year period. Identify the scale at which the question needs to be addressed and the planning horizon under which you think this question needs to be answered.

Respondent Name(s):

Organization:

What areas, drainages, and/or watersheds are in need of further data and improved model to support knowledge-based planning? On the following page, please add if there are specific sites or drainages of particular interest for specific planning or management questions.

After reviewing supporting resources, it appears that the following is a central question in WRIA 1 regarding the need for integrated ground and surface watershed modeling. Would you state the need for surface and groundwater models differently? If so, how?

> ***"What can we do to allocate water for existing and future uses and how can we best mitigate impacts while maintaining instream flow and reduce uncertainty in low flow period?"***

Please continue to following page.

WRIA 1 Groundwater Assessment Questions cont.

Data & Model Input Scale	Locations of Interest See Chapter1, Figure 1.	Rank in order of importance (insert 1-8) 1 is most important: 8 is less important	Planning Horizon (insert one) 1 to 5 yrs 5 to 10 yrs 10 to 20 yrs > 20 yrs	Technical Guidance Concepts for Groundwater Model Development
Site specific				What is the effect of groundwater pumping on surface water? i.e. days, months, feet or miles?
				How accurate should model predictions be to determine the benefit of moving a surface water withdrawal to a groundwater withdrawal? i
				Ability to evaluate down-gradient impacts of changes in water and land use to support mitigation and natural resource trading.
Drainage scale				Can timing of irrigation water use be modified to result in a net benefit to streamflow while maintaining crop production?
				What is the effect of the addition or removal of tile/ditch drainage to increase/decrease storage?
				What is the effect of changing water use from self-supplied to municipally supplied?
Regional scale				What will be the impacts of climate change in WRIA 1? i.e. snow pack, timing of snow melt, and glacial contribution to streamflow.
				Improve the Lower Nooksack Water Budget model inputs, calibration and outputs to apply model across WRIA 1.

Please add additional technical questions your organization will be facing in the next 5 years on the back side of this page. Then provide ranking for new technical questions added.

Appendix C: Technical Consultations on Recommendations for Data Collection and Model Integration

June 2013

1.0 OVERVIEW

The *2013 WRIA 1 Groundwater Assessment* examined existing information available for the components of groundwater characteristics that can be critical for the development of a groundwater flow model. WRIA 1 Joint Board Watershed Staff Team members provided valuable local insight throughout development of the including comments to draft and review draft compilation, supporting descriptions, figures, and tables, as well as discussions summarizing the technical work status, areas for improved groundwater data accessibility, and integration with other WRIA 1 technical resources and tools.

The following technical reviewers provided input on this WRIA 1 Joint Board project funded by Department of Ecology Grant No 1200070 Task 9 Groundwater Study; June 2013, This appendix provides a compilation specialists consulted during the development of the *2013 WRIA 1 Groundwater Data Assessment*, see Table 1 below with list of those contacted and interviewed. See *Chapter 4* for a summary of recommendations for further improvements to groundwater datasets and integrated model functions; see *Appendix B* for a summary compilation of technical reviewer input and comments.

Table 1. Complete list of participants in the *WRIA 1 Groundwater Data Assessment* technical conversations.

Technical Contributors
Diana Allen, Ph.D., Simon Fraser University
Michael E. Barber, Ph.D., State of Washington Water Research Center
Norm Crawford, Ph.D. Hydrocomp, Inc.
Jeffrey S. Geurink, Ph.D., P.E., Tampa Bay Water Authority
Maria C. Loinaz, Ph.D., P.E., Danish Hydrologic Institute (DHI)
Robert J. Mitchell, Ph.D., L.HG, Western Washington University
Bob Prucha, Ph.D., P.E., DHI
David Tarboton, Ph.D., Utah State University

2.0 TECHNICAL CONTRIBUTERS

Conversation responses to local questions are summarized by in this section. Participants' names, qualifications and organizational affiliations are provided followed by the following key information gathered during the phone and/or email conversations:

- Name
- Affiliation
- Expertise
- Prior experience with WRIA 1 models/tools
- Key points, experience with integrated modeling and their recommendations for data collection and integration of groundwater models, and/or recommendations for future improvements
- Interview logistics and contact information

2.1. Diana M. Allen, Ph.D.

Affiliation: Department of Earth Sciences, Simon Fraser University

Expertise: Groundwater Resources, Groundwater Modeling, Climate Change

Prior experience with WRIA 1 models/tools:

Key points contributed:

There are so many people working on the aquifer it is hard to keep track of all the work. Environment Canada continues to monitor groundwater nitrate. Bernie Zebarth (with Agriculture and Agri-Food Canada) is leading a project related to nitrogen loading that involves a large team of researchers, including Cathy Ryan (with U of Calgary). Cathy has been doing treatments on an agricultural site in Abbotsford, among other activities related to nitrogen loading. The team has developed a root zone model. A proposal has been submitted by Ag Canada to extend the research. The project will make progress towards the development of an integrated tool that combines a GIS model with land use and management information with an unsaturated-saturated 3-D groundwater model (using HydroGeoSphere) for the purposes of examining temporal and spatial trends in groundwater nitrate contamination resulting from changes in land use, management practices and climatic conditions. In addition, the project will perform on-farm demonstration and economic evaluation of improved raspberry production practices, disseminate research findings to growers, and inform and engage stakeholders. Diana Allen is a member of the research team.

Backing up to 2005, a SFU student developed a MODFLOW groundwater model used for climate change. Following that, SFU began to tackle the nitrate leaching issue, particularly how much nitrate might be arriving at the water table. This nitrogen loading to the water table is a critical boundary condition for any groundwater flow and transport model at the regional scale. Several papers examined nitrate leaching through the vadose zone; the codes SEEPW/CTRAN were used. Three papers derived from this work: one looked at heterogeneity of hydraulic conductivities in the vadose zone; a second paper used one fixed initial concentration and simulated leaching seasonally; a third paper used groundwater age dates to constrain the flow model.

The problem with all of this is that Waterloo and others (Diana included) are not convinced that Visual Modlflow is the right code to use under transient conditions for the regional model that covers the Abbotsford-Sumas. Mike Simpson, former SFU M.Sc. student, set up a regional FEFLOW model for the Lower Fraser Valley, and ran some transport simulations as part of a groundwater risk assessment. It is a big 3 D model for entire region but not all of

WRIA 1, all of Abbotsford Sumas, to the Nooksack. The model does not extend up into the mountains. The FEFLOW model domain currently includes the unconsolidated materials, with bedrock forming the base. The last chapter of Mike's thesis talks about the model development. The model could very much be updated with US data.

FEFLOW does integrate with MIKE11. FEFLOW is a super sophisticated groundwater modeling code, one of the top in the world. If you add the other modules on, it will do solute and heat transport. MIKE 11 is a river network model with surface water routing, surface water model. MIKE 11 can be connected to MIKE SHE (simple subsurface treatment) or FEFLOW.

Costs estimate is about $16,000 for the full package , or $6000 for just FEFLOW.

It took her student (Mike Simpson now works for the Ministry of the Environment) a long time to build the model and Dr. Allen would prefer the model reside in Canada as it is primarily a research model. However, she feels that it could be used for Canada/US work. The model has not been fully exploited from a research perspective, so there are concerns about it going out in the consulting world before all the research has been completed. The cost to develop a model like this is $100,000 plus. Normally, for any SFU models, Dr. Allen invites people to come to SFU to use the model, without giving them the model files.

We discussed two options for collaboration. For both options, Dr. Allen would be engaged via her role as a university professor, whereby she can be an advisor, but not a consultant. Option 1 (most complicated pathway) would be to share the model with the US, but for reasons above, this would be difficult. If this were the desired pathway, Dr. Allen suggests that Abbotsford Sumas International Task Force become involved, along with SFU, the BC Ministry of Environment (former student Mike Simpson) and the State of Washington to figure out how to undertake some type of cross-border collaboration with the objective of managing water across the border. Collectively, the group would identify a reasonable way to use the model on both sides of the border. She is willing to collaborate on the project, but notes that the logistics will need to be developed if the model is to be used as a long term tool. A transparent process is needed for model sharing. It could be that Mike Simpson at Ministry of the Environment could take on the responsibility of communicating with the State of Washington communicating as part of an international group. Option 2 (most reasonable pathway) is for SFU (Dr. Allen) to hire a Research Associate familiar with modeling and WRIA 1 project for a two year model development collaboration. The model could be further enhanced as discussed below.

Recommended future improvements:

Regional models need to be updated on a regular basis, and it is a big human resource investment to keep the model up and running. Also, if the decision making is wanted on the well scale or local scale, a regional scale model is not an appropriate tool. Rather local scale models are needed, and these are best developed by consultants (this is not a research activity that would be undertaken by a University). A regional scale model can be used to establish boundary conditions for sub-scale models such that they capture the regional groundwater flow, but are detailed enough to address local scale issues.

In order to capture the full WRIA1 region, the SFU FEFLOW model will first need to be extended into the mountains. Second, MIKE 11 needs to be coupled with FEFLOW to enable streamflow to be properly simulated. These are non-trivial tasks and are within the realm of research. Third, the model would benefit from additional well lithology information on the US side of the border. Once the model is updated, a research project could focus on identifying areas of concern.

If DHI is willing to partner with us, we could do a case study for local scale water issue to demonstrate how the regional scale model could be adapted for this purpose. This would be a research effort within the Pacific Northwest across the international border, the tools can be adapted to climate change. A research associate hired by SFU (but paid with WRIA 1 or State or Washington funding) would be ideally suited to undertaking this further model development and testing. A new license would be required for FEFLOW and MIKE 11. The research associate could work remotely (i.e. In the US).

Other research interests include: Human health angle, International Joint Commission (responsible for trans-boundary waters) has an interest in health in the Abbotsford-Sumas aquifer. A colleague (Tim Takaro) put a proposal to them for human health issues, the Abbotsford Sumas is on their radar.

Logistics: June 28, 2013

Contact: 7239 TASC I Building, 8888 University Drive, Burnaby, BC, Canada V5A 1S6; Phone: (778) 782-3967 Fax: (778) 782-4198; E-mail: dallen at sfu.ca

2.2. Dr. Michael E. Barber

Affiliation: Washington State University; State of Washington Water Research Center SWWRC

Expertise: Professor and Director; water quantity and quality modeling; surface-ground water interaction

Prior experience with WRIA 1 models/tools: Developed MODFLOW for Fishtrap and Bertrand

Key points contributed: The core MODFLOW model is Diana Allen's, Simon Fraser University. She allowed WSU to run the model with the explicit understanding that she owns it, using a subcontract with her to allow use. Future uses are uncertain.

Set up the regional model then use the real time data to make the decisions where you have real time data, and use the real time data to continuously improve the model. $200,000 would cover a regional model, but everyone needs to understand the error bars on estimates of hydraulic conductivity, layer thickness, and transmissivity. The coarseness will have to be done to fit the budget.

Could compare WRIA 1 data network to Skagit data network. Even with the loosely coupled model, you could target where the stream and groundwater interactions are most sensitive, and then target that for future data collection. Interesting question: Does doubling hydraulic conductivity double the streamflow?

Match up realistic places for management with sensitivity outputs and needs for more data to improve the model in those locations. Get a couple wells with piezometers that are a couple of feet away from the stream; the water table is higher/lower. Network of piezometers up and down creek and at distances away from the stream.

Recommended future improvements: GSFlow might be a better option than Mike-SHE. Diana Allen's model is a good model for the level of information that is available. Used tubes in the subsurface, seepage rates and bed characteristics. Needs pump tests to look at connectivity and more bed characteristics using the tubes. A good well pump with upstream and downstream gages during low flows would be useful.

The cleanest next step would be to have Diana provide the boundary conditions at the US/Canada border. The new model would be from that location through the rest of the domain. Explicit well pumping in Canada is not going to be of interest to WRIA 1. Has been doing stream and groundwater interaction work in Spokane the past 15 years. Different here to come up with DSS. Usually they come up with the MODFLOW model from scratch. But Diana has spent hundreds of thousands of dollars and years.

Data collection: Cheap to collect streamflow data and time series data from wells at multiple distances from the well. $600 data logger attached to a pressure transducer dropped in the well. Hard when it is in a pumping well when it's difficult to smooth the effect of the pump being turned on. Irrigation well with a regular schedule is a little bit better, but not for domestic wells. When asked if prior work and results was sufficient for daily management decisions, local efforts indicated that the participating parties don't have enough data. They need better localized characterizations of the subsurface. There is so much variability, e.g., source and actual numbers for what people are pumping is unknown. To do daily management you would need real-time information , e.g., can this person pump today? Who else is pumping today? How much are they using? Alternatives include putting in soil moisture probes under irrigated area. As you can't do everything everywhere because it is too expensive, you have to quantify where the pumping is occurring at what rates or you are kidding yourself that the model will be useful.

Model development: For daily or weekly management decisions, the local geologic features need to be put in the model eventually. Bob found some cool features and more layers. The characteristics of how deep you have to concern yourself varies, as a first cut maybe we don't care about the deeper water. Bob Mitchell was doing localized groundwater work. Diana was doing regional scale. Code on these effort were not delivered to the WRIA 1 Joint Board Staff Team. Geology is complex with multiple layers. The analysis of putting that together won't be easy. Without looking at well data, we might not have anything deep enough to get the 15 layers of data. Estimated costs could be $200,000 depending on use of Canadian models for the northern boundary condition. The usability of well logs for identifying is limited. The extent of the model depends on the amount of data. High resolution Bertrand would be nice, but if you have too small an area the boundary condition is watershed scale wide. While this is worth setting up because you have changes in recharge everywhere that effects everywhere else, it still is animprovement with limited amounts of field data. Once the latest version of the Allen SFU model is available, the recharge can be added in, if this will be agreeable to model developer. Team has been working on the Spokane MODFLOW model for 15 years and there are still a lot of data gaps; currently there are four weather stations with soil probes at 10, 30, and 100 cm. To get better estimates for recharge when they get funding to update the model. Look at process used by the Idaho Dept. of Natural Resources. CAMP process studying how future growth and artificial storage and recharge and recovery impacts, proposing an instream flow at the moment and how City of Spokane will impact their water rights.

Logistics: Phone conversation June 21, 2013 Contact information: email: meb@wsu.edu

2.3. Norm Crawford, Ph.D.

Affiliation: Hydrocomp, Inc.

Expertise: Developer of Stanford Watershed Model which became HSPF; Expert (to put it mildly) numeric modeler

Prior experience with WRIA 1 models/tools: Developer of HFAM used for the City of Bellingham water supply

Key points contributed: The following are impressions from a brief review of your Chapter 4 draft plus other background information provided. You have a clear statement of what your clients want -- a defensible model that would show low streamflow/groundwater pumping interactions. You have a good summary of how far they are away from a defensible model system - a long way. (I define a 'model system' as the combination of the code and the data used to calibrate and apply it). As you point out, data to drive a model are deficient in the Nooksack plains (Lower Nooksack). I would make that clear to clients - there are no shortcuts when you are trying to create a defensible model system.

Recommended future improvements:

I would emphasize filling in data gaps over short and medium terms. Model code, if you use an established model, is much easier to get than data to drive the model code. The following are overall impression of Chapter 4 rather than a line by line review.

1) You propose a 'pilot study', a small scale analysis of groundwater/surface water interactions. I don't think a pilot study will advance your goal of understanding groundwater/surface water interactions in the lower Nooksack. Groundwater/surface water interactions vary spatially and are time dependent. As you go to smaller areas unknown boundary conditions become dominant. Even if you get a 'good' result in your pilot study, extension to other areas is not trustworthy. In Tampa Bay, despite topographic, and soil similarity and near uniform precip and PET in the study area, mean annual runoff from sub-basins ranged from 3 to 28 inches due to heterogeneous subsurface characteristics.

The alternative to pilot studies, followed in Tampa Bay, is to set up a coarse resolution model in the entire study area and increase its resolution (increasing meteorologic stations and land use detail --- increasing model elements like land segments and channel reaches and reducing the groundwater grid size where needed). This approach helps define where more data and model elements are required.

2) Although DHI's Mike SHE is a competent off-the-shelf integrated model, I think it should be compared with other codes (GSFLOW, IHM and others) when model data in the lower Nooksack has expanded to the point where a model code can be run. Some public agencies and stakeholders will not accept model results unless source code is available and can be readily changed. "More is better" is a major misconception in modeling; in fact "less is better." For example, more groundwater layers is a serious disadvantage if fewer layers reproduce observed water table dynamics. More physical elements introduce more parameters and more difficulties with calibration.

Data Management: 3) I have the impression that model time series data in the study area is both fragmented and scattered among different agencies. If this is true a data management tool like WISKI could be a good investment. . The other major data needed for modeling are GIS files; Tampa Bay spent a great deal of time using GIS to set and adjust model parameters in their study area with GIS tools.

Porting input data and parameters: 4) While time series and other data developed for TOPNET are useful, TOPNET parameters would not be of value in other surface water models: Model parameters are not transferable unless the model structure and algorithms are identical. I found the TOPNET low flow calibration results for lower Nooksack tributaries poor (Ross Woods, May 2005). It may be that rainfall inputs are insufficient as Ross says (data are never sufficient) but if TOPNET continues to be used on the tributaries, improvements in modeling data and calibration will be needed.

Additional Resources: Another person who has wide experience in groundwater modeling and might be willing to answer a few questions is E.J. Wexler at Earthfx.com. (Toronto, Canada, ejw@earthfx.com)

Logistics: Email June 25, 2013

Contact: Email norm@hydrocomp.com

2.4. Jeffrey S. Guerink, Ph.D., P.E.

Affiliation: Tampa Bay Water Authority

Expertise: Principal Water Resources System Engineer; Numerical hydrologic modeling expert

Prior experience with WRIA 1 models/tools: Not discussed

Key points contributed: It is reasonable to recommend IHM model integration system for HSPF and MODFLOW be used to address coupling Topnet and MODFLOW by replacing HSPF (in IHM) with Topnet. They are on their third generation of the coupling and can now reproduce dynamic behavior in a much better way. Components to the integration that didn't used to exist are now available, which people should take advantage of. To get the coupling to work, there has to be code put inside HSPF and MODFLOW so they can talk to each other, with checks for unintended consequences to maintain mass balance. Models are in Fortran. Integration code is VB.net. IHM is the mother ship that starts and stops each of the models, inputs and outputs from HSPF and MODFLOW. Use the concept and recode to match up Topnet-WM. Mike –SHE is integrated for land and groundwater. By the time Mike-SHE was known to the folks in the US, the coupling of HSPF and MODFLOW for South Florida was already on its way. But when 2001 came time to decide, they looked at Mike-SHE and decided to retool what they had 1) they felt like they knew what they needed to do with what they had, 2) they would not release the code to show what was in the box.

Cost: 1-2 years of work, $100,000 is too low a cost estimate for integrated model functions. As a public agency, going to a court hearing for using the model is not viable operationally, agencies have to show the funders or the court cases the source code and to be able to explain it. Now DHI is more forthcoming and they will give you a license to look at and study the code (but you can't copy or use it or show it to anyone else). Mike-SHE has a lot of physics based formulation of the hydrology, but applying it to a large area (4000 sq mile) takes a very long time for it to run. There are currently some short cuts that make it run faster; but there was too much uncertainty with the Mike-SHE model and relationships.

They recently spent $150,000 on peer review. 400 wells, 40 stream flow gauges, 7 springs, how many calibration locations have to be checked and verified. To set up IHM is on the order of $200,000 - use their code, models calibrated by the same or communicating teams, but together models in one framework (IHM). Depends on area and all they have now is the model report, and developing the theory model, and still planning user manual (in development for early next year). A lot of variables involved in cost. If other people want to use it, they will be helpful to having them apply it. Put out open source code, helps validate their framework, they will accept the code into their process. By other people using it, add credibility and supports the water resources community. They won't go on the road to do training, but would invite people to Tampa Bay to be trained.

Integration*:* Key learning when Intera was hired to retool the integration (3^{rd} generation) but made a whole new model of integration. Costs were $1.4 million 12 years ago. Project included reconceptualization of integration, design code, write code, verify code, test and calibrate model over 4000 square miles. Finished in 2004; found more things that weren't working right and Tampa Bay took over. More code changes and calibration work conducted in the 2012 report. St.Johns District, FL is interested in using these integrated technical tools, currently using HSPF 12.2 and MODFLOW 96. The Southwest district has been using the model, adding water quality and looking at how it affects the Bay (algae blooms in drier conditions).

Calibration*:* When things get coupled, there will be some parameters that need to change. Specific yield in the unconfined aquifer changes over time, soil moisture changes, and the amount of water that can hold is changing. If the surface water system isn't connected, the recharge reparameterization will need to be changed. HSPF does not use a gridded network, so is like Topnet-WM. Several different land segments based on overlay of soils and land use.

Recommended future improvements:

Option 1: Short-term, not dynamically coupled, loosely coupled. Before HSPF was integrated they first did independent calibrations. Some point along the way, the recharge that leaves the HSPF vadose zone is called recharge and input to MODFLOW. HSPF does all the rainfall runoff and gives recharge to Modflow. This is loosely coupled integration. Then calibrate MODFLOW. Do the same thing with Topnet-WM and apply it to MODFLOW model. Check remaining potential ET. Iterative approach of Topnet recharge to MODFLOW, water table level back to Topnet, and keep iterating. It's a way to get closer.

Option 2: Long-term approach is to have a coupled integrated model working, possibly change IHM to switch out Topnet for HSPF. If the water table is near the surface, you will need to dynamically modify the thickness of the vadose zone. Regional components of recharge that are outside the basin we are looking at – this has to be handled in a coupled model like IHM.

Other options: GS flow is the USGS integrated model that couples MODFLOW with PRMS. IHM is a U of CA physics based intensive model, which eventually branched off to create HydroGeoSphere, which does a good job on small scale area. Land hydrology is run on 15 minutes. Reservoir routing is 24 hr time step. MODFLOW has a daily stress period with three logarithmic relationships, sub daily computations. HSPF and MODFLOW talk daily. Well fields have daily pumping rates.

Logistics: Phone conversation June 10, 2013

Contact information: Tampa Bay Water, 2575 Enterprise Road, Clearwater, FL 33763-1102; Voice: 727-791-2312; Email: jgeurink@tampabaywater.org

2.5 Maria C. Loinaz, Ph.D., P.E., Integrated watershed modeler

Affiliation: Danish Hydrologic Institute (DHI)

Expertise: Water Resources Engineer – Ecohydrologist, MIKE-SHE modeling in Idaho and other locations

Prior experience with WRIA 1 models/tools: None

Key points contributed: MIKE-SHE customized by DHI aimed at supporting complex decision making in water environment management. MIKE-SHE has an irrigation component from priority system to apply the water, surface or ground or controlled or physical process delivery. Similar to MODFLOW, finite difference model, spatially distribute aquifer and thickness parameters. Fixed grid size depending on regional scale or sub-model size integrated within it, extract boundary conditions from the large model. Dynamically couples with the rest of the hydrologic components and surface water model. The source code is not public domain. The user and reference manual is very specific and detailed with all the numerical solutions that the code uses. It is hard to know how much it would take to merge the water management module of Topnet and MIKE-SHE. We could use the Topnet setup and try to use their functionality. There is a MIKE-SHE irrigation module, which is very flexible and can do many of the things that Topnet-WM seems to do. Licenses for every agency probably discount with a customized quote based on the services used. You don't need a license to see the model or run the model. You can get away with most of it for a demo version. Basic license is around $20,000 for infrastructure, water quality. There is also a land use/vegetation component. You enter the map with land use and crops, which links to the vegetation database which links crop coefficients and other parameters which can be time varying.

Recommended future improvements: There is very little difference between MODFLOW and the groundwater portion of Mike-SHE. They use the same numerical solvers. Mike-SHE is a fixed grid and you can't have smaller sized grids mixed in with large grids, you have to run a Mike-SHE sub-model with larger model boundary conditions. The issue of making code changes – if a user finds a potential problem with a component In the code or can be adjusted to represent something more accurately, the developers in Denmark will add the code change to their list for Service Pack updates or include the fix in their next release. This can often be done without charge. There is a drainage module that works similar to MODFLOW Drainage. Enter a drainage map and specify areas that have drains. If the water table is above a certain level, the water will be drained based on a spatially variable drain release rate. Ditches and drains could also be specified in a channel routing module in Mike-11 and Mike-SHE linked together.

MIKE SHE Details: Mike-0 interface connects to the main * .she file, which connects to multiple other files, like the river file, the boundary shape files, etc. But the *.she file can be opened as a text file which shows all the components and the links. Mike-0 is the Windows shell for the model. Time series have to be in the DSS-0 format, which can be imported from Excel. It is a user friendly interface with a couple of days training on it. Some of the dialogues, like the land use parameters for the irrigation module, if there is too much detail, then entering some of the data can get tedious. However, codes can be developed to make that more automated by reading and writing to text files. Time variance is user defined. There are three different methods to calculate soil processes and unsaturated soil zone flow – 2-layer= least data required; 3-layer gravity flow without accounting for capillary size; Richard's Equation = most data defined by soils database van Geuneten soil retention curves. The irrigation module calculates irrigation demand based on soil moisture content, or potential ET - you can choose how you define user demand – or input a predefined user demand.

Spatially distribute uses and source and by any type. Point wells or from surface locations. You can establish a system of priorities, which sources have higher priorities. You can establish priorities which would help in representation of the water rights. It could specify based on date. You can input shapefiles for the model components, for surface and groundwater, or you could do GIS processing to convert into grid files.

Scope per project is based on data available. Set up, calibration, running scenarios. Ballpark $200,000. She will email the user manual with extensive technical details and places where the Mike SHE is run. Most of the models have complex mixing of lots of Mike components, and DHI provides training, instruction and/or coaching.

Integration Details: Do they have experience with code porting? Yes, like taking MODFLOW inputs and putting them into Mike-SHE, rare to get one like Topnet with all the integrated components. Having the data available would cost less money, especially if they are already in standard files like ascii and shapefiles. Mike-SHE has been applied in Florida for Everglade restoration projects with mulitple parties involved; usually projects are run by the Corp of Engineers and Water Districts. and are peer reviewed. Each own a license and the other non-modelers don't run the model. DHI provides trainings or coaching for local teams to train others

Costs include cost estimate of hours to build the model, software sales can sell a standard training course conducted by webinars or by someone in the US. There is a learning curve to using Mike-SHE and the user interface. Most people come from simpler models, and those accustomed to integrated models will find it to be manageable.

Most complicated $16,000 for one-time license with all the components for 2013 price list. Smaller amount added on every year for upgrades and limited software support. There are special deals for certain agencies. May be less if consulting work with them is included. DHI is looking at opening an office in the Bay area. She just finished her PhD project in Idaho, used Mike 11-SHE in an agricultural valley. It's not part of DHI-US because she worked on it from Denmark. There are more examples in Florida, but there is an interest in the Western market. Mike-SHE has gone through many reviews and comparisons, the code has been verified and applied all over the world with many success stories.

Logistics: Phone conversation June 8 & 12, 2013, Email: mcl@dhigroup.com
Sales: 201-253-7042 Portland Office: 503-442-3711

2.6. Robert J. Mitchell, Ph.D., L.HG.

Affiliation: Western Washington University

Expertise: Geology, Hydrology, Climate change, MODFLOW and DHSVM modeling; numerical modeling expert

Prior experience with WRIA 1 models/tools: DHSVM modeling in Upper Forks and MODFLOW modeling in Lake Whatcom.

Key points contributed: I have a student currently setting up a MODFLOW model in the Squalicum Valley in the Lake Whatcom watershed. 100 domestic wells (Ecology database) used as a database. Water level measurements from October 2012. Using GMS to establish cross-sections. The motivation behind this project is that Ecology TMDL is forcing so much - to compensate for the phosphorus loading, they are accounting for it to be in the groundwater. Qual2E is being used by Ecology for water quality and their groundwater volume that they input may not be realistic (his hypothesis). Graduate student Thane gave a poster at the hydrogeology symposium with an abstract. On Mitchell website, the main page has a research link. It's good to have a lot of models, because no model is perfect. Slightly different model looking at different things. It's important to understand model uncertainty.

Diana Allen (Simon Fraser University) should be contacted. Years ago there was site study looking at nitrate issues in Sumas area. Diana's is the only grant funded.

DHSVM Summary:

DHSVM is a surface water model. It treats the watershed like a closed system, three soil layers from soil thickness to parameterize and calibrate, effects the recession curve on the hydrograph. Each layer has its own lateral and vertical hydraulic conductivity, and infiltration. The groundwater isn't lost within a deeper aquifer system, it stays in the three layers and eventually makes it to an outlet. Matt Wiley tried to compensate for vertical loss to a deeper groundwater system. DHSVM could serve as the recharge tool. It is a complicated system of how the groundwater aquifers are feeding the lowland. Outputs can breakdown transpiration, soil evaporation, and intercepted water evaporation. Over the course of the year, ET is really high if you account for canopy evaporation. Winter ET accounts for a lot of water if the model captures canopy interception. Agreed that we should sit down with Joanie and compare interception canopy parameters between Topnet-WM and DHSVM.

Recommended future improvements:

Need sub-daily data to get the energy right to melt snow; -running DHSVM upstream of Cedarville. Open source model. Developed for natural systems. Snowpack driven. They have been rerunning at different glacier size, although not a receding glacier to understand boundary conditions.

Logistics: Phone conversation June, 2013

Contact information: Email: robert.mitchell@wwu.edu; 516 High Street, Bellingham, WA 98225-9080
360-650-3591; FAX 360-650-7302

2.7. Bob Prucha, PH.D.

Affiliation: Manager Water Resources, North America, DHI

Expertise: Senior Water Resources Engineer/Hydrogeologist

Prior experience with WRIA 1 models/tools: None, MIKE-SHE

Key points contributed: Mike SHE is good at understanding the interaction between surface and groundwater. Manual calibrations can be good enough since it is physically based, it requires less calibration, but good to calibrate against multiple objectives: streamflow, snowpack, water level, soil moisture. The coupling of groundwater becomes a much tougher calibration. Some people claim that integrated models are over-parameterized, but when you get a tighter coupling it is a good approach to use more data to calibrate.

They have more functionality in terms of subsurface drains compared to MODFLOW. MODFLOW has the unsaturated zone and farm package, but it is not fully dynamic like in the Mike-SHE coupling. They don't have the capability of adding in management components. Strength in tracking the water balance components within time or cell by cell. Generate an enormous amount of outputs if you are not careful.

How is HSPF different than Topmodel? HSPF you have to go and define everything. When you do land use changes that falls short because you have to recalculate everything. It is one step more realistic and fully distributed physically based cell by cell.

The issue is to model surface water capture of groundwater pumping. Defining impact zones. They run into this issue all the time, from plot to 1 km scale to 100,00 km scale. The tar sands models are really large, what are the impacts on surface water bodies of huge amounts of groundwater pumping. A lot of that kind of work in Florida. In a lot of instances, you don't need 10 m resolution data to capture that. There are ways to route the water to the streams using coarser grids. 200 m, 100 m resolution grids to run the model. The MIKE-SHE model is coupled to a river model with cross sections at a higher resolution than the MIKE-SHE model. The surface water model has a different resolution than the subsurface grid.

With GSFLOW, they coupled PRMS and MODFLOW, like SWAT coupled with MODLFOW, another HSPF type model like the Tampa Bay model. When you have lumped linkages and trouble with time steps and they still have to calibrate separately the groundwater and surface water system. It has to work well at various time scales. They won't for a long time have the functionality that MIKE 11 has the operational structures. Can do MODFLOW – SURFACT. Using FE-Flow which is integrated with Mike11. It does full 3D unsaturated flow. Handles ocean and salinity issues. Does transport of heat and solute and water quality processes in Mike 11, linked for Idaho PhD but also applied in Alaska. Maria used Ecolab- an addon for flow modeling and water quality. Very flexible for adding your own equations for water quality and for fish that depend on the water quality of the flow.

Possible limitations: Hourly run for 25-50 years, 50,000 cells might take 1-2 hours per year to run. Depends on how complicated the model is. What is the effect of groundwater pumping on this main river? The groundwater has to be accounted for, might as well account for it in a fully dynamically coupled model.

You have to embrace new technology. Has nice snow melt module, but no glaciers. But they just got a Greenland project with glaciers which will be eventually added in to the commercial code.

Why do people not use integrated models? Universities teach one or the other, not both. Professors at universities don't have a history of using integrated models. Within consulting it is an extra cost and does not fit the world of demand they are facing, they address the problem just looking at one or the other in smaller projects. When people see the integrated tool, you can see how the full system works and they don't go back to running a simple model. What can happen in a groundwater model when you don't estimate recharge properly?

They look at university codes as competing software, although many don't compete on a functional level. Code comparisons like ParFlow or HydroGeoSphere are research codes for specific problems not developed for the real world? Mike 11 has functions of realistic problems that are focused on management. Research code is focused on research questions. This code solves 100 standard problems and is functional, can be simplified or made more complex.

Cost: Pilot model can be done relatively quick if there is already of MODFLOW model, snow information, streamflow gages, and just show how it could be expanded. $15,000-$20,000 they can do it. As a pilot, for less than two months they can give us a license. If we do the model setup, but include them at some level, they can mentor us. Learn how to run it, add in a percentage for them, they want to help make sure it works and is successful. The software group in DHI is separate from the consultants. So if the consultants help and are involved in the project they can reduce the cost. Bob would help, Maria would help. They want to get the word out of having successful projects and publish papers that demonstrate the usefulness of Mike-SHE. They are interested in how systems like ours work.

Offices in Tampa, Denver, San Diego, Toronto, two guys in Portland (DSS tool guy and a coastal marine area).

DHI has been around for 50 years, 1100 people, 30 countries. Started as a non-profit and research group. Profit goes back to code development. Halfway between consulting and academia. Software business is 20% and 80% is consulting. Every year the code is updated.

Logistics: Phone conversation June 20, 2013

Contact: email rhp@dhigroup.com

2.8. David Tarboton, Ph.D.

Affiliation: Professor, Utah State University

Expertise: Civil and Environmental Engineering, Surface Water Hydrology

Prior experience with WRIA 1 models/tools: Developer of Topnet-WM

Key points contributed: You get what you pay for in hydrology models. MIKE-SHE is commercial, it costs some money and license maintenance. It is an integrated professionally supported product. Recommend using the next project as a pilot study in exploring the MIKE-SHE option. One objective would be to learn about MIKE-SHE in a pilot and be better informed about the limitations. You have to embrace new technology. It's much better to use commercial off the shelf software, e.g., ArcGIS, Microsoft Office, Excel. Mainstream off the shelf is good; DHI is trying to take it there. Our job as consultants is to help WRIA1 get a good solution in an impartial way. WRIA 1 invested a lot in Topnet-WM, we know about the parameters, but it is not sustained on a commercial basis and making changes is expensive, more expensive than a license.

Recommended future improvements: When Topnet-WM was developed for WRIA 1, the processes they wanted represented were not available in a commercial package. If they are now, then that makes this is a different decision point. MIKE SHE is commercially supported software with a lot of investment put into the integration and user interfaces. Topnet is fragile and not on a sustainable path; changes require heroic efforts. There is a lot to be said for going commercial, but if WRIA 1 organizations want to make changes on their own they may have less flexibility. There will be a dependency on the relationship with DHI to get developers to make any changes at low or no cost. Academia is trying to advance the knowledge about the physical process and hope that the learning gets absorbed into commercial systems.

Interview logistics: Phone conversations on May 22, June 24, 2013

Contact information: dtarb@usu.edu