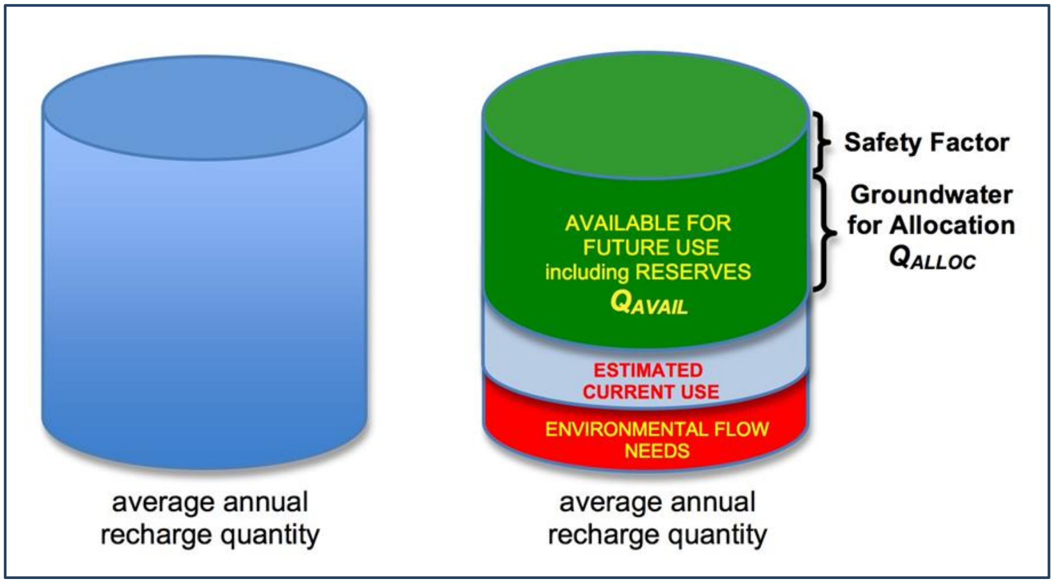
WATER SCIENCE SERIES

Estimating Groundwater Availability for Allocation in British Columbia

Alan P. Kohut



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FORWARD

by Water Protection & Sustainability Branch, Ministry of Environment & Climate Change Strategy

This report was prepared by Hy-Geo Consulting in June 2018 for the B.C. Ministry of Environment and Climate Change Strategy and the Ministry of Forest, Lands, Natural Resource Operations and Rural Development under contract with the Government of B.C. The intent of this project was to develop and test an initial approach for estimating available quantities of groundwater for allocation, particularly for areas with limited groundwater information.

Hy-Geo Consulting developed a spreadsheet based preliminary assessment tool termed the Groundwater Allocation Methodology (GWAM). Hy-Geo tested the GWAM approach through comparisons with four previously developed aquifer water budgets, which indicated GWAM is useful for compiling, interpreting, and comparing water budgets for particular aquifers or study areas of interest.

Results with GWAM depend on the availability and accuracy of the data sets, the validity of the hydrogeologic conceptual model, and assumptions made in the water budget. There can be a high degree of uncertainty due to lack of key data and imprecise estimates that are often associated with analysis of hydrologic systems. Commensurate with uncertainties, GWAM provides conservative estimates for groundwater availability. Accordingly, Hy-Geo states GWAM should be viewed as a preliminary decision support tool and not utilized in isolation as an allocation tool. Uncertainty in allocation quantities can be addressed by using GWAM to focus characterization and data collection on the most sensitive water budget components, and by employing more than one methodology for estimating allocation quantities and comparing results for consistency.

The work and conclusions expressed or implied in this report are those of Hy-Geo Consulting and should not be interpretated in any way as representing provincial government water management policy or practice. This report has been prepared for government staff as a supporting assessment tool for consideration as an initial estimation of available quantities of groundwater for allocation. The scope of this work does not comprehensively address the technical complexities and policy challenges associated with groundwater allocation among the diverse landscapes of B.C.

EXECUTIVE SUMMARY

This report outlines a methodology termed the Groundwater Allocation Methodology (GWAM) for estimating available quantities of groundwater for allocation purposes based on simplified water budget equations for known aquifers or areas where groundwater is of interest. While the methodology can be used generally it was developed specifically for areas with limited amounts of groundwater information. The method involves estimating the annual groundwater recharge quantity for an area by evaluating available hydrologic information on the other components of the water budget including current water use and environmental flow needs (EFN). EFN requirements are estimated based on a percentage (0 to 100 %) of the annual groundwater outflow or discharge. A confidence factor β, between 10 and 25% is then applied to the available quantity to assign a maximum annual allocation quantity above current use.

The GWAM was tested in four different aquifer areas in British Columbia where groundwater budgets had been previously completed. Aquifers tested included:

(a) **Gabriola Island**, representing a Type 5(a) fractured bedrock aquifer system along the southeast coast of Vancouver Island, near the city of Nanaimo;
(b) The **Westwold Valley Aquifer** representing a Type 1(b) unconfined, unconsolidated sand and gravel aquifer situated within the Salmon River Valley in the southern interior of the province, southeast of the city of Kamloops;
(c) The **West of Aldergrove Aquifer** representing a Type 4(b) confined, unconsolidated sand and gravel aquifer in the Fraser Valley, west of the city of Aldergrove; and
(d) The **Mill Bay Aquifer** representing a Type 4(a) unconfined, unconsolidated sand and gravel aquifer on the southeast coast of Vancouver Island, near the town of Mill Bay.

Overall results of the testing indicated that the GWAM is a useful preliminary assessment tool for compiling, interpreting and comparing the results of one or more water budgets that may have been conducted of any particular aquifer or area. The GWAM can be used as a stand-alone spreadsheet for conducting a water budget analysis of an aquifer or for incorporating data and documenting methods from previously prepared water budgets.

The GWAM provides conservative estimates for groundwater availability (Q_{AVAIL}) above current estimated use and quantities available for future allocation (Q_{ALLOC}), including consideration of EFN. As a potential allocation tool, the GWAM should be viewed as a preliminary decision support tool and not utilized in isolation. Results of using the methodology are dependent on the availability and accuracy of the data sets examined, the validity and specifications of the conceptual model of the aquifer developed, and assumptions made in the water budget. A high degree of uncertainty, lack of key data and imprecise estimates are often associated with any analysis of hydrologic systems. The degree of certainty can be improved by using the GWAM to focus characterization and data collection on the most sensitive components, employing more than one methodology and comparing results for consistency.

Given the large degree of uncertainties in estimating various components of water budgets, efforts to refine the estimates of groundwater use should be considered before allocating any significant groundwater quantities for future use. Efforts to improve the accuracy of current groundwater use would be especially beneficial. Licensing of groundwater use and annual reporting requirements provide an opportunity to improve the water use estimates that have been made to date.

In evaluating the results of any water budget analysis it would be prudent to also consider any indicators or evidence of any groundwater stresses that may be occurring in the area of investigation related to: water quantity conflicts such as well interference, reported wells going dry, well deepening, declining

groundwater level trends, reduced spring flows, degradation of physical or chemical water quality including salt water intrusion, groundwater-surface water conflicts, drought impacts, low flow concerns and potential impacts on aquatic habitat and fisheries.

Recommendations for future consideration include:

(a) Conducting a survey of the specific methods used by other provinces and territories in Canada to determine groundwater availability and allocation quantities.
(b) Conducting a regional mapping program aimed at delineating groundwater discharge areas for all mapped aquifers, sensitive streams and streams with Water Allocation Restrictions.
(c) Developing baseflow indices (BFI) for watersheds in British Columbia where hydrometric data is available.
(d) Utilizing interdisciplinary teams of hydrologists, hydrogeologists and biologists to plan, investigate and integrate their approaches in future groundwater budget studies.
(e) Develop a standard set of symbols and terminology used to identify the specific budget components and subcomponents that are normally evaluated in groundwater budgets.

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ACRONYMS

BBM	Building Block Methodology
BCIFN	British Columbia instream flow needs method
BFI	baseflow index
CAM	conceptual aquifer model
DEM	Digital Elevation Model
EAFR	Ecologically Acceptable Flow Regime (England)
EcoCat	Ecological Reports Catalogue (B.C. ENV)
EFN	environmental flow needs
EFR	environmental flow requirements
ERT	electrical resistivity tomography
ET	actual evapotranspiration
ENV	Ministry of Environment and Climate Change Strategy, B.C.
FLNR	Ministry of Forests, Lands, Natural Resource Operations, and Rural Development, B.C.
GF	groundwater footprint
GW	groundwater
GWAM	Groundwater Allocation Methodology
IFN	instream flow needs
IFR	instream flow requirements
InSAR	interferometric synthetic aperture radar
MAF	mean annual flow (Canada), minimum acceptable flow (England)
MAR	mean annual runoff
MBR	Mountain Block Recharge
MIKE SHE	numerical computer model from DHI Corporation
MODFLOW	numerical computer model from USGS
OEFN	operational environmental flow needs
PEI	Prince Edward Island
PET	potential evapotranspiration
RBF	reference baseflow (PEI)
STN	station
SW	surface water
USGS	United States Geological Survey
WSA	Water Sustainability Act, B.C.

1. INTRODUCTION

Hydrogeologists with the Ministry of Forests, Lands and Natural Resource Operations and Rural Development (FLNR) and the Ministry of Environment and Climate Change Strategy (ENV) have identified the need for developing a relatively fundamental and practical methodology to determine groundwater availability for a given aquifer or area to assist with groundwater allocation decisions under the *Water Sustainability Act* (WSA). Previous investigations outlined in the 2014 Ministry of Environment report entitled, *Preliminary Conceptual Models and Water Budget Methodologies for Aquifers in British Columbia* identified available water budget methodologies and procedures that could be utilized by water managers or licensing officials to assist in the groundwater licensing process.

In December 2016-February 2017, Hy-Geo Consulting developed a groundwater allocation methodology (GWAM) based on water budgets for the Ministry of Forests, Lands and Natural Resource Operations. The fundamental methodology included; (1) quantifying average annual recharge including both direct infiltration of precipitation and subsurface flow (using aquifer type), (2) identifying and quantifying existing groundwater use and, (3) assessing hydraulic connectivity between groundwater and surface waters to estimate requirements for groundwater-dependent aquatic habitat. Based on this approach a portion of the unused groundwater (i.e., groundwater that is replenished annually that is not currently used or needed to support ecosystem health) would be considered available for future allocation.

1.1 Project Goals

The goal of this project was to review, adapt, refine and apply the GWAM methodology developed in 2016-2017 for determining groundwater availability for allocation in four areas in the province where previous water budgets have been completed. The project was undertaken utilizing available data and reports and did not involve any new data collection, use of proprietary databases or field studies.

1.2 Project Objectives

The main objectives or outcomes for the project were:

1. To complete a final report in a *Water Science Series* format documenting the GWAM methodology and results of application to four test areas.
2. To test the GWAM using data from four test areas with existing water budgets and utilizing sensitivity analysis to determine the effects of varying key parameters.
3. To provide guidance on the use of the GWAM for different aquifer types.
4. To refine a user-friendly Microsoft Excel® spreadsheet utilized to estimate groundwater availability and future allocation quantities for the test areas analyzed.
5. To determine groundwater availability above current use and potential allocation quantities based on the GWAM.
6. To provide recommendations for future investigations to support water allocation decisions in the province.

1.3 Report Outline

The report is set out in five main parts as follows;

PART 1 - Developing the Equations for the GWAM.
PART 2 - Development of the GWAM Spreadsheet Workbook
PART 3 - Application of GWAM to Four Test Aquifer Areas
PART 4 - Overall Conclusions
PART 5 - Recommendations for Future Consideration

Part 1 discusses the main factors involved in defining and determining groundwater availability, the use of water budgets for various aquifer types and the inclusion of groundwater discharge components for meeting environmental flow needs. Part 2 describes the GWAM user-friendly spreadsheet developed for water budget calculations. Part 3 discusses the four aquifer areas that were examined and tested using the GWAM. Part 4 provides a summary of the overall results of the testing and Part 5 discusses key recommendations as a result of the project.

2. PART 1 – DEVELOPING THE EQUATIONS FOR THE GWAM

2.1 Concept of Groundwater Availability

While knowledge of the amount of groundwater available in a particular area or aquifer for any period of time is a desirable goal for managing water resources, determining this quantity can pose several challenges. Some of these challenges, as outlined by Reilly *et al.*, (2008) and others, for example, are:

1. Some of the groundwater may not be economically recoverable or of poor or undesirable quality.
2. Some of the groundwater withdrawn in one part of an aquifer may not be consumed and may be returned to another part of the aquifer.
3. Groundwater withdrawals may affect groundwater quality and the amount and quality of interconnected surface waters.
4. The effects of drought conditions and pumping withdrawals are not necessarily instantaneous and often require time to propagate through the hydrologic system.
5. Shallow aquifers may respond differently to changing stresses (inputs and outputs) in comparison to deeper aquifers situated in the same area,
6. Groundwater withdrawals can change the dynamics of an aquifer's natural recharge and discharge regime, increasing recharge, decreasing discharge and removing water in storage (Alley *et al*., 1999).

The concept of groundwater availability is multifaceted and may be qualified in terms of quantity, timing, sustainability, water quality, means of accessibility, environmental, regulatory policy and socioeconomic factors that control its demand and type of use. The sustainability of groundwater is dependent upon many factors, including: the potential depletion of groundwater in storage, reductions in streamflows, loss of wetland and riparian ecosystems, land subsidence, saltwater intrusion, and changes in groundwater quality (Reilly *et al.*, 2008). Groundwater budgets are a key to understanding the sources of water for a groundwater system and how water diversions can change the components of flows in the hydrologic cycle. A water budget quantitatively accounts for the inflows, outflows, and changes in storage of a hydrologic system and can provide an indication of groundwater available for use (i.e. groundwater availability). Groundwater availability is a quantity, whereas, a groundwater budget is a water accounting process used to provide information on water availability.

> Groundwater availability is a quantity, whereas, a groundwater budget is a water accounting process used to provide information on water availability.

Under predevelopment conditions, water entering a groundwater aquifer or aquifer system, referred to as recharge, is generally balanced over the long-term by groundwater leaving the system (discharge). This general relationship is shown in Figure 1A. Sources of recharge generally include: (a) areal recharge from precipitation that percolates through the unsaturated zone to the water table, and (b) infiltration recharge from losing streams, lakes and wetlands (Alley *et al*., 1999). Healy (2010) defines recharge, as the downward flow of water reaching the water table, adding to groundwater storage. Recharge is usually expressed as a volumetric flow, in terms of volume per unit time (L^3/t), such as m^3/d, or as a flux, in terms of volume per unit surface area per unit time (L/t), such as mm/yr (Healy, 2010).

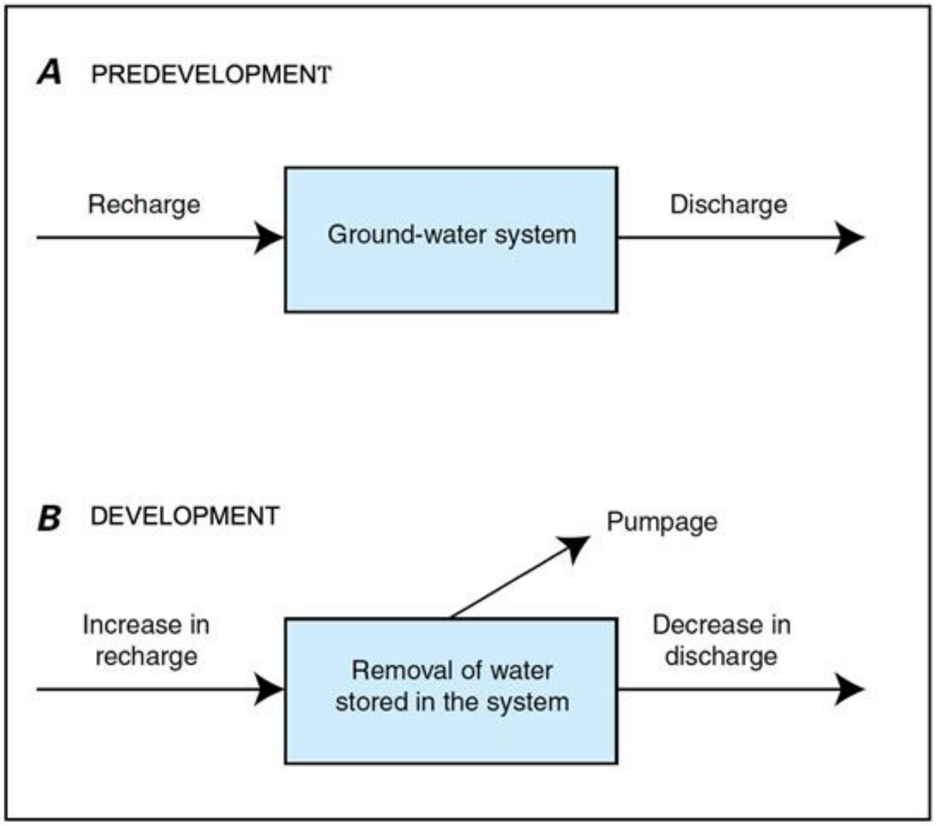


Figure 1: Water budget relationships for a groundwater system under (A) predevelopment and (B) development conditions. Figure adapted from Alley et al., 1999.

Natural discharge sources include; (a) outflow to streams, lakes, wetlands, springs and saltwater bodies (bays, estuaries, or oceans), and (b) groundwater evapotranspiration. Under groundwater pumping or other development conditions, e.g. drainage works, the source of withdrawals needs to be supplied by; (1) more water entering the groundwater system (increased recharge), (2) less water leaving the system (decreased discharge), (3) removal of water that was stored in the system, or some combination of these three (Alley *et al*., 1999). Removing water from the system doesn't necessarily cause an increase in recharge, but it could.

Changes in the flow system including some removable water in storage enables groundwater to be diverted for allocation purposes. How much groundwater is available for this use ultimately depends upon how the changes in inflow and outflow affect the surrounding hydrologic and physical environment. As human activities change the system, the components of the water budget (inflows, outflows, and changes in storage) also will change (Alley *et al*., 1999). In addition to human-derived stress, the possibilities of long-term droughts and climate change may also result in reduced groundwater recharge and groundwater availability.

Groundwater systems can change in response to development and should be monitored and evaluated on a regular basis to quantify the amount of water available for use and the ramifications of using the resource, (Council of Canadian Academies, 2009).

2.2 Water Budgets, Aquifer Types and Recharge Equations

The 2014 Ministry of Environment report entitled, *Preliminary Conceptual Models and Water Budget Methodologies for Aquifers in British Columbia* provides a starting point for examining the water budget equations that were developed for the various types of aquifers found in British Columbia. Appendix A, Table A1 outlines the representative water budget equations that were developed for each aquifer type and subtype. Further information on aquifer types is available in Wei *et al*., (2009 and 2014).

A water budget simply states that, the difference between the rates of water flowing into and out of an aquifer is balanced by a change in water storage (Healy *et al*., 2007) and can be expressed as:

$$\textit{Flow In} - \textit{Flow Out} = \textit{Change In Storage} \qquad \text{(Equation 1)}$$

The following major inflow, outflow and storage components are shown in the equations listed in Appendix A, Table A1.

Inflow Components

P = precipitation (rain and snow)

Q^{SW}_{in} = surface water inflow

Q^{GW}_{in} = groundwater inflow

R = groundwater recharge (based on all sources)

Q^{GWLeak}_{in} = groundwater leakage from overlying deposits (confined aquifers)

$Q^{IRReturn}_{in}$ = irrigation/septic return flow

Outflow Components

ET = evapotranspiration

Q^{GWpump}_{out} = groundwater pumping

Q^{SWpump}_{out} = surface water pumping

Q^{SW}_{out} = surface water outflow

Q^{GW}_{out} = groundwater outflow

Storage Components

ΔS^{SW} = change in surface water storage

ΔS^{GW} = change in groundwater storage

A review was conducted of these previous equations and a revised set of simplified equations for each aquifer type was developed for the recharge factor (***R***) based on the fundamental water-budget equation for a watershed outlined by Healy (2010) which when using the above symbology, and not considering the unsaturated zone, can be expressed as:

$$R = P + Q^{SW}_{in} + Q^{IRReturn}_{in} - ET - \Delta S^{SW} - Q^{SW}_{out} - Q^{SWpump}_{out} \qquad \text{(Equation 2)}$$

Equation 2 is applicable to unconfined aquifers.

R can also be expressed as:

$$R = \Delta S^{GW} + Q^{GW}_{out} + Q^{GWpump}_{out} - Q^{GW}_{in} \qquad \text{(Equation 3)}$$

Equation 3 is applicable to both unconfined and confined aquifers.

Table 1 shows the suggested recharge equations for the various aquifer types. Recharge in these equations may represent a portion of the precipitation that percolates through the unsaturated zone to the water table plus any infiltration from surface water sources (losing streams, lakes and wetlands) over the aquifer, plus any irrigation/septic return flow and in the case of confined aquifers, leakage from overlying units. These general equations are meant as a guide and may need to be modified depending upon the conceptual model developed for any particular aquifer and availability of data on individual components.

In terms of these equations, the groundwater recharge component (R) is a principle indicator of the potential amount of groundwater that may be available for future use for any time period examined.

It should be pointed out that these equations are meant to be used as a general guide only and should be reviewed in context with the conceptual aquifer model that is developed for each aquifer or area under investigation. Some components such as P are measured or extrapolated from measured sites while others may need to be estimated using various methods available. Estimates of some components, for example, such as Q^{SW}_{out} in some cases may negate the need to account for Q^{SWpump}_{out}. Groundwater inflow Q^{GW}_{in} is not considered part of recharge R, but is related to the difference between Q^{GW}_{out} and Q^{GW}_{in} in Equation 3 (Healy, 2010).

The groundwater recharge component (R) determined from these water budget equations is a principal indicator of the potential amount of groundwater that may be available for use for any time period examined.

A number of other jurisdictions, for example, Prince Edward Island (PEI Department of Environment, Labour & Justice, 2013), the Waikato Regional Council in New Zealand (Waikato Regional Council, 2016) and Government of Western Australia (Department of Water, 2013) set groundwater allocation based on a percentage of precipitation recharge only. It should be noted that different jurisdictions may define and quantify recharge in different ways. Due to the complex nature of recharge processess, however, an exact determination of recharge is not possible (Healy, 2010).

Table 1. Summary of representative recharge equations for various aquifer types.

TYPE	DESCRIPTION	REPRESENTATIVE RECHARGE EQUATIONS	COMMENTS
A.	***UNCONSOLIDATED AQUIFERS***		
1.	predominantly unconfined aquifers of fluvial or glaciofluvial origin, along river or stream valleys		changes in surface water storage ΔS^{SW} along streams not considered for unconsolidated aquifers
1a.	aquifers along major rivers of higher stream order	$R = P + Q^{SW}_{in} + Q^{IRReturn}_{in} - ET - \Delta S^{SW} - Q^{SW}_{out} - Q^{SWpump}_{out}$	***Equation 2:*** ***P, ET*** and Q^{SW} will likely be significant. Recharge primarily due to infiltration of precipitation and surface water.
1b.	aquifers along rivers of moderate stream order	*as above*	***P, ET*** and Q^{SW} will likely be significant
1c.	aquifers along lower order (< 3-4) streams	*as above*	***P, ET*** and Q^{SW} will likely be significant
2.	predominantly unconfined deltaic sand and gravel aquifers	*as above*	hydraulic connection with surface waters significant, recharge primarily due to infiltration of precipitation and surface water
3.	predominantly unconfined alluvial fan, colluvial sand and gravel aquifers.	*as above*	hydraulic connection with surface waters significant, recharge primarily due to infiltration of precipitation and surface water
4.	sand and gravel aquifers of glacial or pre-glacial origin		
4a.	predominantly unconfined sand and gravel aquifers of glaciofluvial origin	$R = P + Q^{SW}_{in} + Q^{IRReturn}_{in} - ET - \Delta S^{SWLakes} - Q^{SW}_{out} - Q^{SWpump}_{out}$	***Equation 2:*** ***P*** and ***ET*** will likely be significant, recharge primarily due to infiltration of precipitation and surface water.
4b.	predominantly confined sand and gravel aquifers of glacial or pre-glacial origin	$R = Q^{GWLeak}_{in} = (Q^{GW}_{out} + Q^{GWpump}_{out}) - (Q^{GW}_{in}) + \Delta S^{GW}$ where $\Delta S^{GW} = (Q^{GW}_{in} + Q^{GWLeak}_{in}) - (Q^{GWpump}_{out} + Q^{GW}_{out})$	***Equation 3:*** (a) ***P*** and ***ET*** may not be significant, (b) *Mountain Block Recharge* (MBR) and leakage under pumping conditions from overlying layers may be significant. Recharge primarily due to leakage from overlying formations.
4c.	predominantly confined sand and gravel aquifers associated with glaciomarine environments	*as above*	***Equation 3:*** (a) ***P*** and ***ET*** may not be significant, (b) *Mountain Block Recharge* (MBR) and leakage under pumping conditions from overlying layers may be significant. Recharge primarily due to leakage from overlying formations.

Table 1 (cont.): Summary of representative recharge equations for various aquifer types.

TYPE	DESCRIPTION	REPRESENTATIVE RECHARGE EQUATIONS	COMMENTS
B.	***BEDROCK AQUIFERS***		
5.	sedimentary rock aquifers		
5a.	fractured sedimentary bedrock aquifers	$R = P + Q^{SW}_{in} + Q^{IRReturn}_{in} - ET - \Delta S^{SWLakes} - Q^{SW}_{out} - Q^{SWpump}_{out}$	***Equation 2***: (a) ***P*** and ***ET*** will likely be less significant and limited by aquifer storativity, (b) groundwater flow and available storage calculations should be considered. Recharge primarily due to infiltration of precipitation and surface water.
5b.	karstic limestone aquifers	*as above*	(a) ***ET*** may be less significant, (b) aquifer storativity may be highly variable and high in some areas, (c) groundwater flow and available storage calculations should be considered,(d) interaction with surface water regimes likely. Recharge primarily due to infiltration of precipitation and surface water.
6.	crystalline bedrock aquifers		
6a.	flat-lying or gently-dipping volcanic flow rock aquifers	*as above*	(a) ***ET*** may be less significant, (b) aquifer storativity may be highly variable and high in some areas, (c) groundwater flow and available storage calculations should be considered,(d) interaction with surface water regimes likely. Recharge primarily due to infiltration of precipitation and surface water.
6b.	crystalline granitic, metamorphic, meta-sedimentary, meta-volcanic and volcanic rock aquifers	*as above*	(a) ***P*** and ***ET*** will likely be less significant and limited by aquifer storativity, (b) groundwater flow and available storage calculations should be considered. Recharge primarily due to infiltration of precipitation and surface water.

2.3 Determining Groundwater Availability and Sustainability

The concept that the development of a groundwater system is considered to be “safe” if the rate of groundwater extraction does not exceed the rate of natural recharge has been referred to as the “Water-Budget Myth” (Bredehoeft *et al.,* 1982). It is a myth, because it is an oversimplification of the information that is needed to understand the effects of developing a groundwater system. *The Expert Panel on Groundwater* also advises that naïve usage of the recharge calculation from a water budget (or some percentage of it) as a direct estimate of sustainable groundwater yield is not recommended (Council of Canadian Academies, 2009). Van der Gun and Lipponen (2010), nevertheless, contend that evaluation of recharge is important for rational planning of groundwater development and management.

Various jurisdictions determine groundwater availability in different ways. The Waikato Regional Council in New Zealand, for example, estimates groundwater availability based on 50% of groundwater recharge derived from precipitation, allowing the remaining 50% to be lost via springs and submarine discharges (Waikato Regional Council, 2016).

Alley *et al*., (1999), define ***groundwater sustainability*** as the “development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.” The definition of “unacceptable consequences” is largely subjective and may involve a large number of criteria. Even with assumptions about acceptable changes, the concept of a sustainable quantity of groundwater may not be realistic in light of potential changes in hydrology from land-use activities and climate change as urbanization and agricultural development in a basin will affect infiltration, runoff, evapotranspiration and recharge, effectively changing the hydrologic cycle through time (Alley and Leake, 2004).

For British Columbia, the ***groundwater availability*** **or** ***groundwater available for use*** for an aquifer or aquifer system can be expressed as the quantity of water (Q_{AVAIL}) that is available for future use over time (*t)* without causing unacceptable environmental, economic or social consequences.

For purposes of this project, only the physical hydrologic quantity and timing aspects for individual aquifers and areas hydraulically interconnected with surface waters are being considered to determine groundwater availability. Water quality, economic and social factors are not addressed in this assessment.

If a specified time period is considered, the quantity of groundwater available for future use (Q_{AVAIL}) can be expressed as;

$$Q_{AVAIL} = R - Q^{GWpump}_{out} - \alpha Q^{GW}_{out} \quad \text{(Equation 4)}$$

where:

Q_{AVAIL} = potential quantity available for future use;

R = recharge quantity;

Q^{GWpump}_{out} = quantity of existing groundwater pumping;

Q^{GW}_{out} = quantity of groundwater outflow or discharge including the groundwater-derived baseflow component (Q^{GW}_{BF}) of interconnected streams; and

α = percentage of groundwater outflow needed to meet environmental flow needs (EFN).

In British Columbia *environmental flow needs* (EFN) are defined in Section 1 of the *Water Sustainability Act (WSA) as,* “in relation to a stream, means the volume and timing of water flow required for the proper functioning of the aquatic ecosystem of the stream." Groundwater diversions from aquifers that are hydraulically connected to a stream can significantly diminish streamflow, particularly in small streams during critical low flow periods where groundwater discharges contribute a high percentage of base flow in streams (FLNR and ENV, 2016). *WSA* also defines *critical environmental flow threshold*, as: "in relation to the flow of water in a stream, means the volume of water flow below which significant or irreversible harm to the aquatic ecosystem of the stream is likely to occur". Further discussion on assessing groundwater quantities for meeting *environmental flow needs* is provided in Appendix B.

Equation 4 can be related to the groundwater footprint (***GF***) developed by Gleeson *et al.*, (2012) wherein:

$$GF = A[Q^{GWpump}_{out} / (R - \alpha Q^{GW}_{out})] \qquad \text{(Equation 5)}$$

The groundwater footprint ***(GF)*** is defined as the area required to sustain groundwater use and groundwater-dependent ecosystem services of a region of interest **(*A*)**, such as an aquifer, watershed or community (Gleeson *et al.*, 2012).

2.4 Time Period Dependence

Concepts of groundwater availability and "safe yield" are almost always defined in terms of an annual water withdrawal, while sustainability often examines a longer term approach utilizing groundwater in storage during periods of drought balanced by replenishment during wet periods (Alley and Leake, 2004). Under the *Water Sustainability Act* most water use authorizations are allocated on the basis of a daily or annual quantity. Determining groundwater availability on an annual basis, therefore, would seem most appropriate. Nevertheless, assessing seasonal dependent requirements such as EFNs and monthly variations in recharge and discharge components should also be considered.

A conservative approach, would be to consider a worst-case climate scenario (e.g. the driest year on record for a given area) while a more reasonable approach could be based on data for the normal or average year on record. In terms of evaluating groundwater availability over the long term and properly account for annual precipitation (***P***) variability, Ponce *et al*., (2000) recommend using the average value of ***P*** for the past N years of record, in which N is the typical recurrence interval of drought events in the given geographical location. For most regions of practical interest, they report that N varies between 3 and 25 years, being 3-6 years for arid regions, 6-12 years for semiarid regions, and 12-25 years for subhumid regions (Ponce *et al*., 2000).

Determining groundwater availability on an annual basis would be appropriate as the majority of water use authorizations in British Columbia are allocated on the basis of a daily or annual quantity. Nevertheless, assessing seasonal dependent requirements such as EFNs and monthly variations in recharge and discharge components should also be considered.

2.5 Availability Versus Allocation Limits

Some jurisdictions such as Prince Edward Island (PEI), for example, have limited groundwater allocation on the basis that up to 50% of the annual precipitation recharge could be extracted without adversely impacting the environment (PEI Department of Environment, Labour & Justice, 2013). In addition, PEI has introduced a policy for groundwater extraction that specifies groundwater extraction should not be permitted to reduce the mean summer base flow in the main branch of streams by more than 35%. In PEI, mean summer base flow is referred to as the Reference Base Flow (RBF), and is determined as the median of base flow for the period of August through September.

As discussed earlier, the Waikato Regional Council in New Zealand (Waikato Regional Council, 2016), estimates groundwater availability based on 50%of groundwater recharge derived from precipitation, allowing the remaining 50% to be lost via springs and submarine discharges. They also recognize that 50% is not conservative enough to adequately protect connected surface water bodies. Elsewhere, in the Bay of Plenty Region in New Zealand, the regional council has set an interim groundwater allocation limit at 35% of the average annual precipitation recharge (Bay of Plenty Regional Council, 2016). In the Canterbury Region of New Zealand, Environment Canterbury (2004) has established 30 Groundwater Allocation Zones and specified that allocation limits are to be annual volumes with interim limits set using a precautionary approach to protect environmental values. They utilize two alternative methods for determining interim allocation blocks; (a) as 15% of average annual rainfall (1st order approach) or, (b) if there is sufficient data, as 50% of average annual land-surface recharge including the recharge component contributed by intermittent streams (2nd order approach).

In Western Australia, the Department of Water (2013) sets allocation limits for various aquifers and areas based on a percentage of the annual precipitation recharge recognizing:

(a) a component for consumptive use and,
(b) water to be left in aquifers to maintain water quality, aquifer productivity, groundwater-dependent values and other non-consumptive uses.

For administrative purposes the Department of Water (2015) divides the allocation limit into three portions, namely:

(i) water available for licensing,
(ii) current licensed use, and
(iii) unlicensable use (e.g. stock and domestic).

In the Gingin groundwater area of Western Australia, for example, allocation limits for various aquifers range from 20 to 90% of the annual precipitation recharge volume (Department of Water, 2015). It should be noted that allocation limits in Western Australia are not set arbitrarily, but are developed as part of an allocation plan based on hydrogeological considerations and consultation with stakeholders. The limits are not necessarily fixed but subject to future monitoring, evaluation and planning revisions. Figure 2 illustrates the relationship between groundwater availability and an allocation limit for the Gingin groundwater area in Western Australia.

In British Columbia, the water budget analysis undertaken for Mayne Island (Ministry of Environment, 2015) reported recharge amounts, equivalent to about 25 to 30% of the annual precipitation, to represent the maximum potential amounts available for allocation purposes and recommended an interim safety factor of at least 50% (i.e. approximately 12 to 15% of normal year precipitation) for future groundwater allocation decisions.

A survey of the specific methods used by other provinces and territories in Canada to determine groundwater availability and allocation quantities has not been carried out for this project. There may be some merit in contacting the various agencies responsible for groundwater allocation across the country to assess their experience with this activity.

Various jurisdictions determine and quantify groundwater availability and groundwater allocation in different ways dependent upon which factors they consider important.

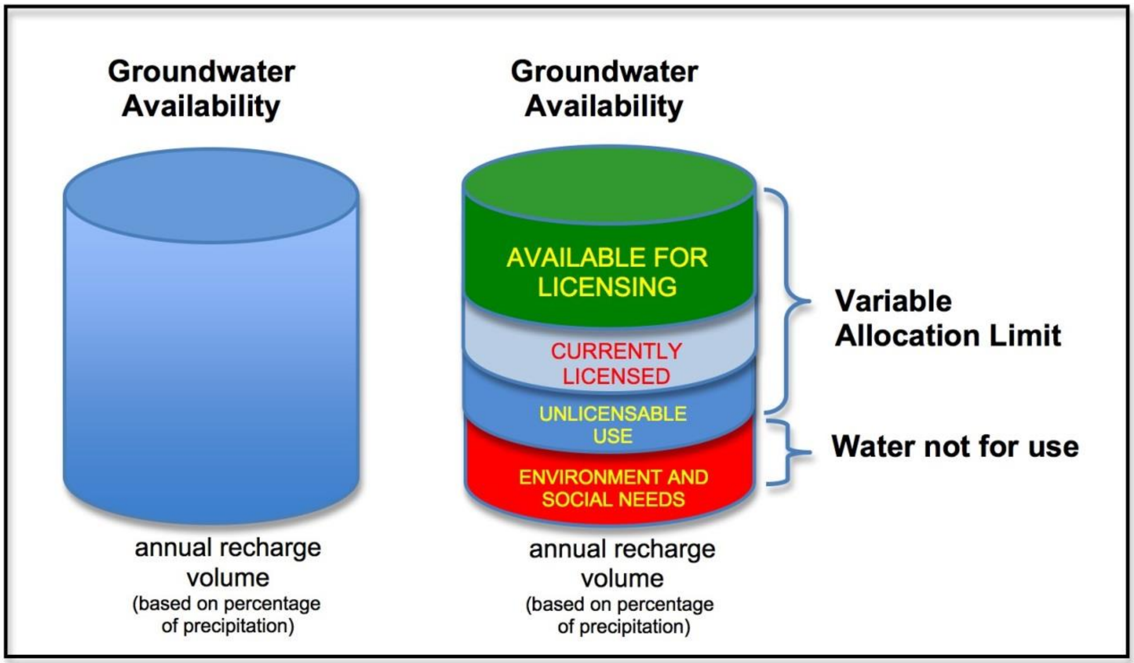


Figure 2: Relationship between groundwater availability and an allocation limit for the Gingin groundwater area in Western Australia. Adapted from Department of Water (2015).

2.6 Hydrologic Uncertainties and Safety or Confidence Factors

Any methods used to assess groundwater availability in an aquifer or area will introduce a level of uncertainty due to the inherent heterogeneity of natural hydrologic systems and inadequacies in data required to characterize the systems accurately (National Research Council, 1997). Uncertainties related to groundwater quantification can include, for example, insufficient or erroneous data from imprecise measurements and observations, sampling errors, or statistical errors, inappropriate model assumptions, and inadequate characterization of subsurface hydrology. Uncertainty with regard to potential future effects of severe, long-term droughts and climate change may also need to be considered in evaluating groundwater availability. Further discussion on uncertainties related to assessing groundwater availability for the test areas is presented in Sections 4.3 to 0.

In light of the potential uncertainties associated with any water budget analysis it may be prudent to assign a safety or confidence factor when evaluating quantities (annual volume) of groundwater for allocation purposes, considering:

$$Q_{ALLOC} = \beta Q_{AVAIL} \qquad \text{(Equation 6)}$$

where:

Q_{ALLOC} = quantity available for future allocation;

Q_{AVAIL} = potential quantity available for future use; and

β = confidence factor (e.g. percentage).

The value of β could be set by policy, as this has been done by other jurisdictions mentioned previously (e.g. PEI, Waikato Regional Council), or tailored to specific aquifers and areas as done in Western Australia (Department of Water, 2015). The latter approach would be more scientifically-defensible and area-based.

The general relationship between groundwater availability and allocation limit for an aquifer or area, suggested for British Columbia, is illustrated in Figure 3. The average annual recharge quantity would be based on an estimate of all known sources of recharge and could be determined by considering normal precipitation or “worst case” drought conditions. Estimated current groundwater use in Figure 3 would include licensed and unlicensed (domestic) wells. Groundwater available for allocation includes; approvals and future wells to be licensed. Under Sections 39 through 41 of the *Water Sustainability Act,* the Lieutenant Governor-in-Council may reserve all or part of the water that is in the stream or the aquifer, and that is unrecorded for various purposes including for the benefit of the Crown and for treaty First Nation water reservations.

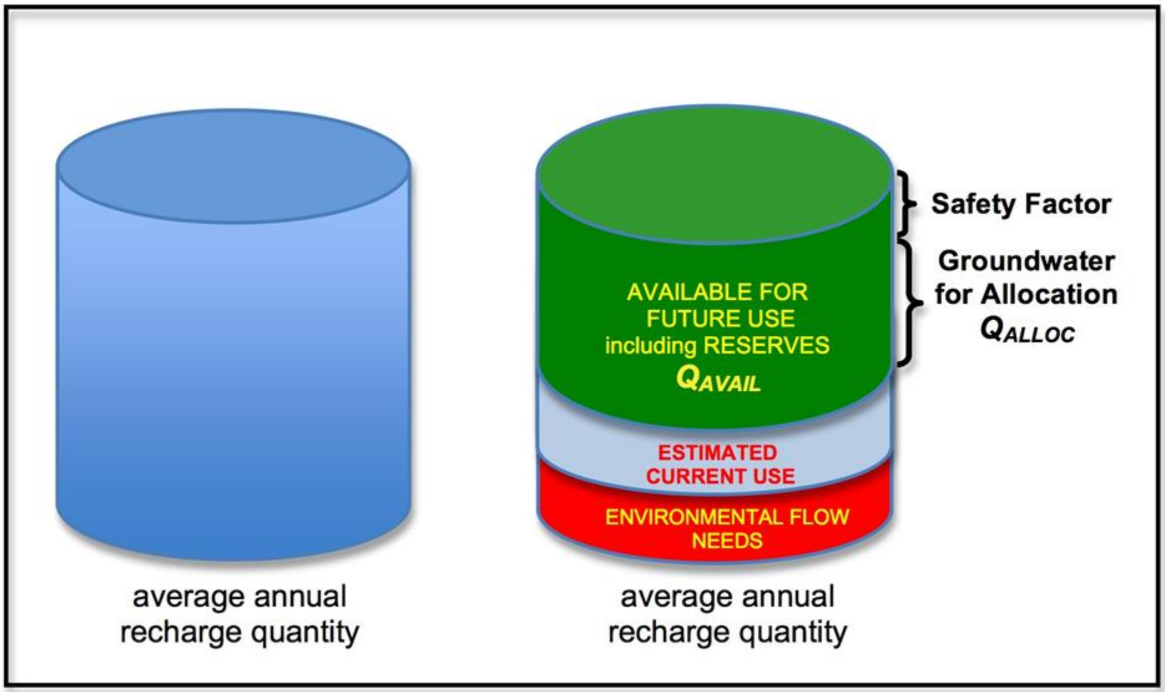


Figure 3: Proposed relationship between annual quantity of groundwater recharge versus groundwater available for allocation in British Columbia, incorporating an appropriate allocation safety factor.

2.7 Determining an Allocation Safety or Confidence Factor

An allocation safety or confidence factor for any area or aquifer could be set by policy, through a groundwater allocation planning process, during an aquifer characterization investigation, stakeholder consultation process or other methods that assess aquifer complexity and various degrees of uncertainty. The process could also be linked with EFN assessments of interconnected surface waters. Aquifers or areas for example where there is a high degree of uncertainty with regard to the determination of water availability could be assigned a low confidence factor (e.g. = 10%). Aquifers or areas where there is a higher degree of certainty could be assigned a high confidence factor (e.g. = 25%). A confidence factor of 25% would be equivalent to assigning a safety factor of 75%.

One possible method for assigning preliminary confidence factors would be to use an aquifer rating guide or screening tool that identifies and qualitatively assesses the importance of a number of key aquifer criteria for estimating groundwater availability in any area. Such criteria could include, for example: aquifer morphological considerations, aquifer type, availability of meteorological and hydrogeologic data, importance of connected ecosystems, degree of hydrologic complexity, number of watersheds involved, reported water conflicts in the area and other related issues.

2.8 Proposed Aquifer/Area Rating Guide or Screening Tool

An interim aquifer/area rating guide, applied to a specific aquifer or area, could for example, result in assigning one of three levels of confidence, where the level of confidence factor β in the allocation determination (Equation 5) ranges from 10 to 25%. This guide is regarded as a conservative measure due to the often limited availability and uncertainties associated with groundwater data and would be subject to revisions dependent upon the results of future groundwater monitoring and evaluation. A maximum confidence factor of 25% is currently proposed which would be equivalent to assigning a safety factor of 75%. The three confidence levels would be as follows:

Level I where β = ***10%*** *(low level of confidence)*
Level II where β = ***15%*** *(moderate level of confidence)*
Level III where β = ***25%*** *(high level of confidence, e.g. detailed characterization, such as calibrated numerical model).*

The tool could be used to prioritize aquifers before conducting a groundwater budget or aquifer characterization project and also after a water budget assessment is completed and all available hydrologic information has been analyzed in more detail.

Appendix C, Table C1 outlines an interim aquifer and groundwater area rating guide, showing the parameters or general criteria involved in assessing the confidence level for a specific aquifer, aquifer system, groundwater region or area. A brief discussion of the parameters, sources of information, scoring and weighting factors for the rating guide is provided in Appendix D. The rating guide provides a semi-quantitative and qualitative measure and is subject to information being readily available for the aquifer or area under consideration.

An example application of the rating guide is provided in Appendix C, Table C2 for the Abbotsford Aquifer indicating an overal confidence factor of 17.5%. Information including aquifer descriptions for the Abbotsford Aquifer from the *Aquifer Classification Database* (Ministry of Environment, 2018a) and data from Ministry of Environment (2014) was used to complete the rating guide form. In terms of an allocation safety factor for the Abbotford Aquifer, the rating indicates a relatively high level of confidence, approaching Level III.

A second example in Appendix C, Table C3 illustrates the guide applied to the Mayne Island bedrock aquifers, showing an overal confidence rating of 14.6%. Information for the Mayne Island bedrock aquifers was obtained from Ministry of Environment (2015). In terms of an allocation safety factor for the Mayne Island bedrock aquifers the rating indicates a moderate level of confidence, close to Level II.

2.9 Environmental Flow Needs (EFN) Methods Used in British Columbia

A provincial EFN policy has been developed to guide the review of water applications in their consideration of environmental flow needs (FLNR and ENV, 2016). The policy outlines an environmental risk management framework and identifies three levels of risk management measures used to assess or mitigate potential effects of withdrawals from a stream.

Hatfield *et al*., (2003) have developed instream flow thresholds as guidelines for reviewing proposed water uses in the province. They are generally referred to as the BCIFN method (Western Water Associates, 2014). These provide seasonally adjusted thresholds for alterations to natural stream flows that are expected to result in low risk to fish, fish habitat, and productive capacity. Lewis *et al*., (2004) describe methods for assessing aquatic habitat and instream flow characteristics in support of applications to dam, or divert water from streams in British Columbia. The assessment methods are a set of endorsed techniques for assessing flow alterations on British Columbia streams, and ultimately for studying their ecological effects (Hatfield *et al.,* 2003). They are used as part of the process to determine environmental flows at a more detailed level.

For fishless streams, Hatfield *et al*., (2003) recommend a flow threshold to be a minimum instream flow release equivalent to the median monthly flow during the low flow month. For fish-bearing streams, Hatfield *et al*., (2003) recommend a flow threshold to be a seasonally-adjusted threshold calculated as percentiles of mean natural daily flows for each calendar month. The percentiles vary through the year to ensure higher protection during low flow months than during high flow months. The maximum diversion rate is determined as the Q_{80} for both stream types (i.e. where flow is exceeded 80% of the time). For fishless streams, the environmental "cut-off" flow is determined as the Q_{50} during the low flow month where the low flow month is defined as the calendar month with the lowest median flow, based on natural mean daily flows. The recommended environmental flow thresholds for fish-bearing streams are adjusted on a monthly basis wherein the environmental flow for the lowest flow month is set as Q_{90}, and for the highest flow month as Q_{20}. For all other months the environmental flow thresholds are calculated as a percentile between Q_{90} and Q_{20} using a weighted function (Hatfield *et al*. 2003).

In the Okanagan Basin of British Columbia, ESSA Technologies Ltd., and Solander Ecological Research (2009) completed an instream flow needs analysis for 38 Okanagan tributary streams using a combination of two peer reviewed methods, 1) the Hatfield and Bruce (2000) meta-analysis approach, and 2) the BC Phase II Instream Flow Guidelines or BCIFN method (Hatfield *et al.,* 2003). In 2014 as part of the *Okanagan Water Allocation Tool Plan*, ESSA Technologies Ltd., recommended using the BCIFN flows developed for the Okanagan Basin and developing specific operational EFNs or OEFNs that are more applicable to drier years (Okanagan Basin Water Board, 2014).

For groundwater dependent ecosystems and in the absence of detailed scientific assessments of environmental flow needs, Gleeson and Richter (2016) suggest that high levels of ecological protection would be provided if groundwater pumping decreases monthly groundwater derived baseflow by less than 10% through time. In terms of an annual groundwater allocation for an aquifer, this presumptive standard suggests that any groundwater allocation for any use should not be allowed to deplete the baseflow quantities of any interconnected streams by more than 10% at any time.

2.10 Quantifying the Groundwater Component for Meeting EFN

As indicated previously in Section 2.3, the groundwater component maintaining environmental flows can be represented as a percentage of the groundwater outflow, αQ^{GW}_{out}, for an aquifer or area as shown in the earlier equation:

$$Q_{AVAIL} = R - Q^{GWpump}_{out} - \alpha Q^{GW}_{out} \qquad \text{(Equation 4)}$$

where Q^{GW}_{out} represents the quantity of groundwater outflow or discharge including the groundwater-derived baseflow component (Q^{GW}_{BF}) for interconnected streams. Q^{GW}_{out} can be expressed as:

$$Q^{GW}_{out} = Q^{GW}_{lat.out} + Q^{GW}_{BF} \qquad \text{(Equation 7)}$$

where:

$Q^{GW}_{lat.out}$ = *quantity of lateral groundwater outflow or discharge, and*

Q^{GW}_{BF} = *quantity of groundwater-derived baseflow.*

These relationships are shown diagrammatically in Figure 4 for an unconsolidated unconfined aquifer, hydraulically interconnected with a stream that flows into a lake. Surface water flowing into the lake is augmented by groundwater discharge into the lower reaches of the stream (i.e. gaining stream). The aquifer is recharged by infiltration of precipitation and leakage from the stream (losing stream) in the upper reaches of the stream.

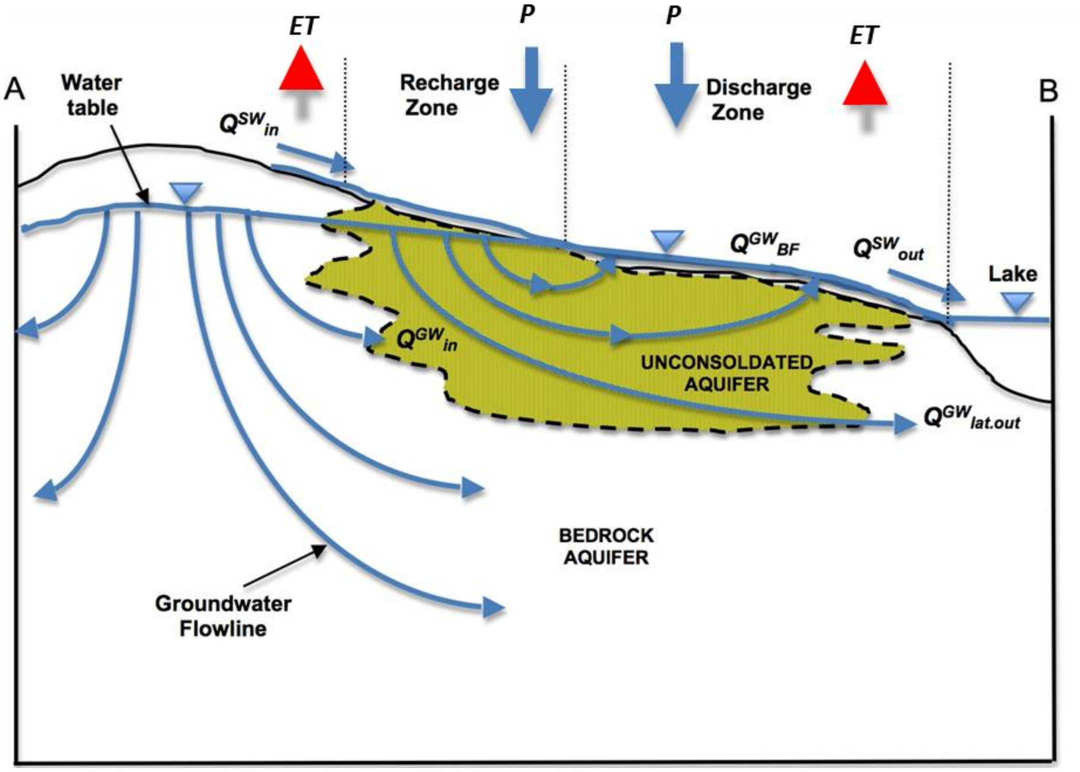


Figure 4: Schematic cross section illustrating relationships between groundwater- derived baseflow (Q^{GW}_{BF})*, lateral groundwater outflow* ($Q^{GW}_{lat.out}$) *and surface water outflow* (Q^{SW}_{out}) *for an unconsolidated aquifer and interconnected aquifer-stream system.*

In terms of environmental flow considerations the groundwater derived baseflow component in this situation at critical times could be a significant portion (up to 100%) of the streamflow in the lower reaches of the stream. Groundwater flow quantities (volume with time) into the stream would depend upon the hydraulic conductivities of the aquifer and stream bed, hydraulic gradients in the aquifer, groundwater pumping and water levels of the stream and the lake. Hydraulic conditions in the underlying bedrock aquifer may also be a contributing factor.

Quantifying the groundwater contributions to EFN from hydraulically interconnected aquifers would not be a simple task given the inherent challenges (complexity of methods, limited data availability and resources required) for determining and setting EFN for streams in British Columbia. Assumptions could be made that groundwater derived baseflow (Q^{GW}_{BF}) is always equal to groundwater outflow (Q^{GW}_{out}) and that groundwater derived baseflow (Q^{GW}_{BF}) is always equal to surface water baseflow (Q^{SW}_{BF}) determined from stream hydrograph analysis methods. These assumptions might be applied on a regional watershed basis but may not be realistic at an aquifer scale.

In some situations, $Q^{GW}_{lat.out}$ could be negligible in which case

$$Q^{GW}_{out} = Q^{GW}_{BF} \qquad \text{(Equation 8)}$$

Figure 5 and Figure 6 illustrate some of the variations that may be found in groundwater-surface water interactions in three different hydrologic situations and the potential effects on groundwater derived baseflow.

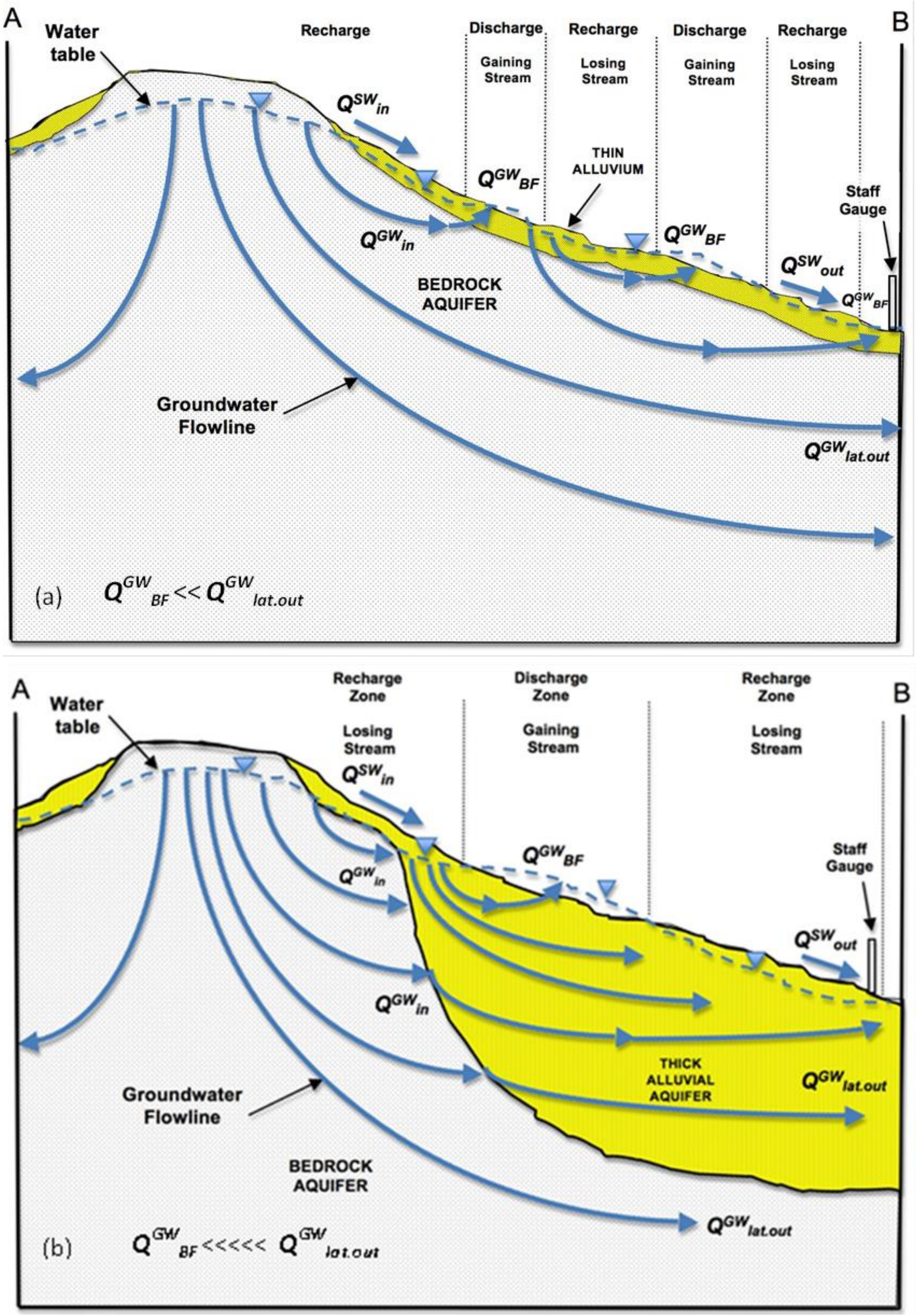


Figure 5: Schematic cross-sections (a) and (b) illustrating variations in GW-SW interactions and potential effects on groundwater derived baseflow.

Figure 5(a) depicts groundwater movement in a bedrock aquifer discharging in places to a stream channel filled with thin alluvial deposits. Groundwater derived baseflow occurs along three reaches of the stream. The stream also loses water along some reaches of the stream, recharging the shallow groundwater regime. A hydrometric station (stream gauge) in the lower reaches of the stream would record the cumulative baseflow constributions upstream. In this situation $Q^{GW}_{BF} << Q^{GW}_{lat.out}$ for the bedrock aquifer.

Figure 5(b) illustrates a a bedrock aquifer overlain by an alluvial aquifer that thickens downgradient along a stream. Groundwater discharge to the stream, occurs in the upper reaches of the alluvial aquifer. Groundwater flow in the alluvial aquifer is then primarily in a lateral direction. A hydrometric station (stream gauge) in the lower reaches of the stream may record only a smaller portion of groundwater baseflow that occurred upstream. In this situation $Q^{GW}_{BF} <<<<< Q^{GW}_{lat.out}$ for the alluvial aquifer.

Figure 6 illustrates a bedrock aquifer overlain by an alluvial aquifer that varies in thickness downgradient along a stream. Groundwater discharge to the stream occurs in zones in the upper reaches of the alluvial aquifer and at downstream reaches immediately above a hydrometric station. The hydrometric station (stream gauge) records a significant portion of the baseflow in the alluvial aquifer. In this situation $Q^{GW}_{BF} = Q^{GW}_{lat.out}$ for the alluvial aquifer.

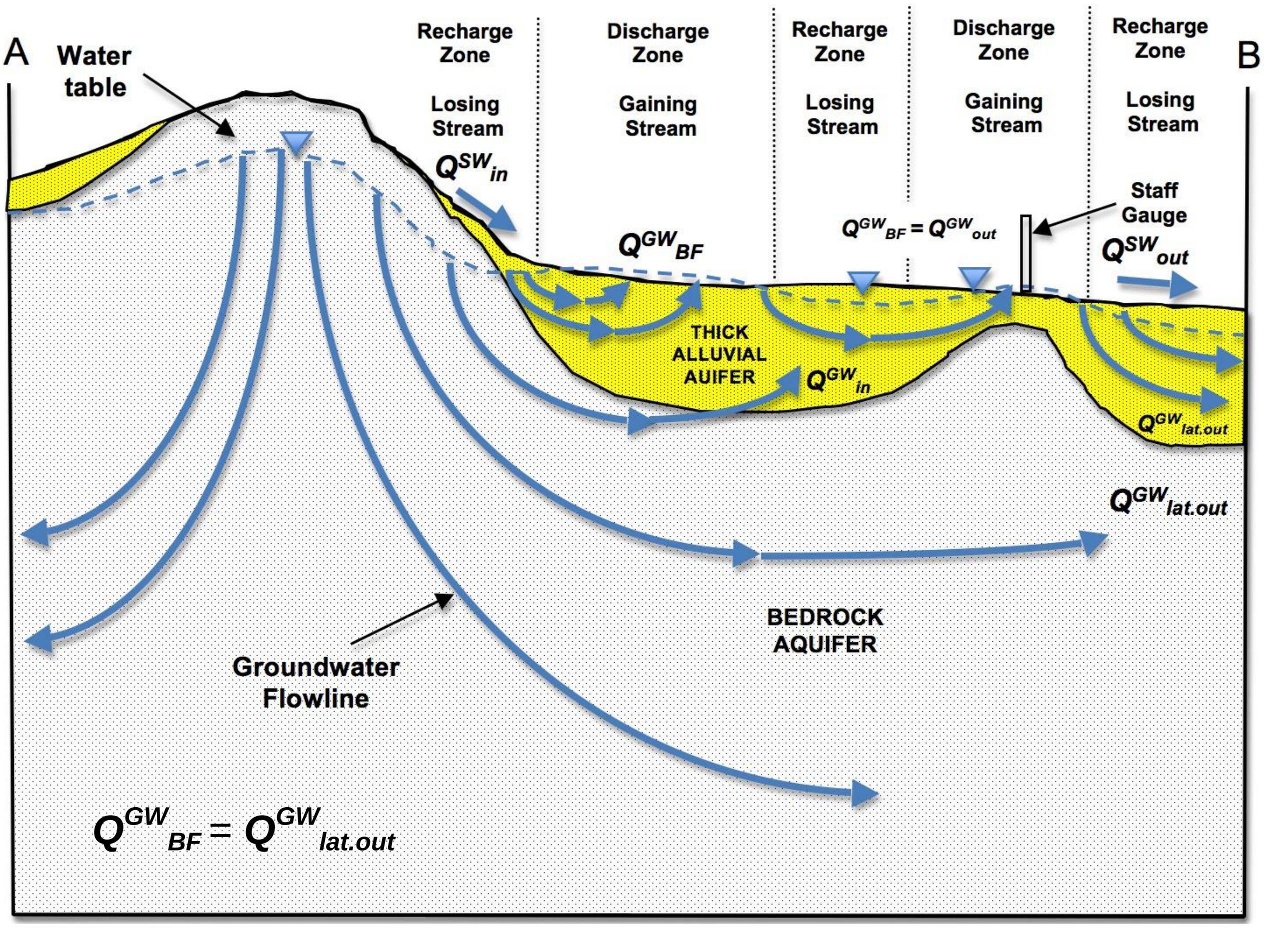


Figure 6: Schematic cross-section illustrating further variations in GW-SW interactions and potential effects on groundwater derived baseflow.

It is not feasible to accurately determine the groundwater contributions to EFN without having the benefits of an EFN assessment, a baseflow analysis of the surface water streams involved and a good understanding of the GW-SW interactions in the aquifer or area under investigation. A suggested interim approach would be to make a subjective, qualitative estimate of the potential significance of groundwater to EFN based on the development of a conceptual aquifer model (CAM) for the aquifer or area of investigation, observed GW-SW relationships as indicated in Appendix B, Table B3 or other evidence available. Based on the most probable degree of groundwater interaction with interconnected surface waters, an interim EFN factor ranging from 10 to 50% could be assigned to the aquifer or area of investigation as follows:

Low EFN factor where α = ***10%*** (low degree of groundwater interaction)
Moderate EFN factor where α = ***25%*** (moderate degree of groundwater interaction)
High EFN factor where α = ***50%*** (high degree of groundwater interaction)

The appropriate factor could then be used in Equation 4 to estimate the quantity of groundwater available for future use (Q_{AVAIL})***.*** These factors should be regarded as interim and subject to further testing, investigations and specific evaluation of the EFN for any interconnected streams involved. Where warranted EFN factors above 50% could be assigned for very sensitve aquatic ecosytems. During critical low flow periods an EFN factor of 100% may be desireable for ecosystem protection.

A low EFN factor (α ***= 10%***) for example, would result in 10% of the total groundwater outflow assigned to meet environmental flow needs. A high EFN factor (α ***= 50%***) for example, would result in 50% of the total groundwater outflow assigned to meet environmental flow needs. Gleeson and Richter (2016), suggest that high levels of ecological protection would be achieved if groundwater pumping decreases monthly baseflow by less than 10% through time. This would be equivalent to an EFN factor of 90% assuming that groundwater-derived baseflow (Q^{GW}_{BF}) is always equal to groundwater outflow (Q^{GW}_{out}).

In terms of applying the water budget approach for determining groundwater available Q_{AVAIL} for a specific aquifer or areas that are connected with surface waters, assigning an EFN quantity as a percentage of Q^{GW}_{out} rather than Q^{GW}_{BF} is suggested for the following reasons:

1. hydrometric stations and data to determine baseflow and groundwater-derived baseflow (Q^{GW}_{BF}) are not available for all surface water streams in British Columbia;
2. baseflow may originate from other sources apart from groundwater-derived baseflow (Q^{GW}_{BF});
3. hydrometric stations specifically record surface flows only and not subsurface flows directly;
4. where available, hydrometric stations may not be suitably located for aquifer analysis;
5. groundwater budgets are generally applied on an aquifer or area basis and not specifically on a watershed basis; and
6. aquifer/area boundaries do not necessarily coincide with watershed boundaries.

In hydrologic situations where good hydrometric data is available and the groundwater-derived baseflow component can be adequately quantified with some confindence, a more accurate estimate of EFN dependent on groundwater may be achievable in comparison to estimating a portion of Q^{GW}_{out}. In assigning an EFN factor on an annual basis, investigators should consider the adequacy of the EFN factor assigned for protecting ecosystems during critical low flow periods. Further discussion on assigning an interim EFN factor is provided in each of the four case examples discussed in Sections 4.3 to 0 of this report.

2.11 Summary for Developing the Equations for the GWAM

A series of fundamental recharge equations were developed for the various aquifer types found in British Columbia by modifying and adapting the water budget equations originally contained in the 2014 Ministry of Environment report entitled, *Preliminary Conceptual Models and Water Budget Methodologies for Aquifers in British Columbia.* Recharge in these equations may represent a portion of the precipitation that percolates through the unsaturated zone to the water table plus any infiltration from surface water sources (losing streams, lakes and wetlands) over the aquifer, plus any irrigation/septic return flow and in the case of confined aquifers, leakage from overlying units. These general equations are meant as a guide and may need to be modified depending upon the conceptual model developed for any particular aquifer and the availability of data on individual components.

An equation was also developed for *groundwater availability* for an aquifer or aquifer system and expressed as the quantity of water (Q_{AVAIL}) that is available for future use over time (t) without causing unacceptable environmental, economic or social consequences. Q_{AVAIL} is derived from the relationship:

$$Q_{AVAIL} = R - Q^{GWpump}_{out} - \alpha Q^{GW}_{out} \qquad \text{(Equation 4)}$$

where:

Q_{AVAIL} = potential quantity available for future use;

R = recharge quantity;

Q^{GWpump}_{out} = quantity of existing groundwater pumping;

Q^{GW}_{out} = quantity of groundwater outflow or discharge including the groundwater-derived baseflow component (Q^{GW}_{BF}) of interconnected streams; and

α = percentage of groundwater outflow needed to meet environmental flow needs (EFN).

In cases where an EFN assessment is not available, an interim EFN factor ranging from 10 to 50% could be assigned to the aquifer or area of investigation based on the conceptual aquifer model (CAM) for the aquifer or area of investigation and any evidence of observed GW-SW relationships as follows:

Low EFN factor	where	α	=	*10%*	(low degree of groundwater interaction)
Moderate EFN factor	where	α	=	*25%*	(moderate degree of groundwater interaction)
High EFN factor	where	α	=	*50%*	(high degree of groundwater interaction)

In light of the potential uncertainties associated with any water budget analysis a confidence factor was developed to evaluate quantities (annual volume) of groundwater for allocation purposes, based on the relationship:

$$Q_{ALLOC} = \beta Q_{AVAIL} \qquad \text{(Equation 6)}$$

where:

Q_{ALLOC} = quantity available for future allocation;

Q_{AVAIL} = potential quantity available for future use; and

β = confidence factor (e.g. percentage).

An interim aquifer rating guide was developed to determine the confidence factor β for an aquifer based on a series of aquifer criteria including aquifer type, availability of meteorological and hydrogeologic data, importance of connected ecosystems, degree of hydrologic complexity, number of watersheds involved, reported water conflicts in the area and other related issues. Three levels of confidence are proposed as follows:

Level I	where	β	=	***10%***	*(low level of confidence)*
Level II	where	β	=	***15%***	*(moderate level of confidence)*
Level III	where	β	=	***25%***	*(high level of confidence, e.g. detailed characterization, such as calibrated numerical model).*

To facilitate the water budget analysis of any aquifer the recharge equations for each aquifer type and the equations for Q_{AVAIL} , Q_{ALLOC} including provision for estimated values for α and β were subsequently incorporated into a user friendly Excel® spreadsheet workbook or GWAM which is discussed in the following section.

3. PART 2 - DEVELOPMENT OF THE GWAM SPREADSHEET WORKBOOK

3.1 User Friendly Spreadsheet for Water Budget Calculations

As part of this project, an Excel® based workbook was developed to facilitate and document water budget calculations for the various types of aquifers found in British Columbia. The workbook template is provided as Appendix G as a separate Excel® file not in this report. It contains the following:

Sheet 1: **Instructions**, outlining procedures for using the spreadsheets and reviewing results.

Sheet 2: **Cover**, which provides for entering information on the aquifer/area under investigation, type of aquifer, date of analysis, name of investigator, precipitation period examined and assigning probable EFN and confindence β factors.

Sheet 3. **Listing of aquifer types and basic water budget equations** for each type.

Sheet 4. **Outline of methods and data sources** used to determine each parameter or component in the water budget analysis.

Sheets 5 to 8. **Spreadsheets for each aquifer type** for entering monthly parameters with formulae imbedded to calculate monthly and annual quantities (m^3) of recharge R, annual Q_{AVAIL}, and ratios of annual recharge/precipitation R/P, $Q^{GWpump}_{out}/Q_{AVAIL}$, and Q^{GWpump}_{out}/R. The annual allocation Q_{ALLOC}, is also determined based on the confidence factor assigned.

Sheet 9. **References** include a listing of key references for data sources.

Note that the workbook is designed to calculate (R) as a residual. Alternatively, if (R) is estimated from alternative methods then other parameters (e.g. ΔS^{GW}) could be set as the residual parameter.

4. PART 3 – APPLICATION OF GWAM TO FOUR TEST AQUIFER AREAS

4.1 Objectives of Test

Objectives for testing each aquifer area were to:

1. Test the facility of the GWAM using water budget data obtained from previous investigations for various aquifer types.
2. Use the GWAM to determine Q_{AVAIL} and Q_{ALLOC} for each test area.

3. Conduct sensitivity analyses of the key parameters to assess to what degree variations in the parameters may affect the overall water budget calculations.
4. Assess the usefulness of the GWAM.
5. Provide recommendations for further investigations that would improve the water budget estimates.

4.2 Areas Investigated

In consultation with FLNR/ENV staff, four test areas with previous water budget studies were selected to apply the water budget methods and relationships outlined in Equations 4 and 6 to determine the groundwater quantity available for future allocation purposes. These areas represent four different types of aquifer regimes situated in three different biogeoclimatic zones (Government of British Columbia, 2018b). The four areas selected were:

1. **Gabriola Island,** along the east coast of Vancouver Island near the city of Nanaimo, representing a fractured sedimentary bedrock aquifer system in a coastal environment. Gabriola Island is underlain by Type 5(a) fractured bedrock Aquifer 706 and Aquifer 709 comprised of Upper Cretaceous sedimentary strata within the Coastal Douglas Fir Zone with a moist maritime climate (Government of British Columbia, 2018c).
2. The **Westwold Valley Aquifer,** between the communities of Westwold and Falkland, situated southeast of Kamloops, representing a Type 1(b) unconfined, unconsolidated sand and gravel aquifer situated within the Salmon River Valley in the southern interior. The Westwold Valley Aquifer comprises two aquifers. Aquifer 98 and Aquifer 289 in the Interior Douglas Fir Zone with a very dry hot climate (Government of British Columbia, 2018d). Aquifer 98 is a confined aquifer which has been included as part of Aquifer 289 for purposes of this report.
3. The **West of Aldergrove Aquifer**, near the community of Aldergrove, representing a Type 4(b) confined, unconsolidated sand and gravel aquifer Aquifer 33, situated in the Hopington area of the Fraser Valley. It is situated in the Coastal Western Hemlock Zone with a very dry maritime climate (Government of British Columbia, 2018e).
4. The **Mill Bay Aquifer,** underlying the community of Mill Bay on Vancouver Island, representing a Type 4(a) unconfined, unconsolidated sand and gravel aquifer. The Mill Bay area is underlain by Aquifer 206 situated within the Coastal Douglas Fir Zone with a moist maritime climate (Government of British Columbia, 2018c).

4.3 Water Budget For Gabriola Island (Type 5a)

4.3.1 General Synopsis

In 2013, SRK Consulting completed a preliminary water budget project for the Regional District of Nanaimo (RDN) for the islands of Gabriola, DeCourcey and Mudge that are underlain by fractured sedimentary bedrock aquifers. The work involved in part:

- development of an updated hydrogeological conceptual model;
- completion of a data gap analysis and suggestions for additional data collection;
- estimation of groundwater and surface water balance components; and
- assessment of the water demand stress in each island water region.

This study was designed to provide a simple accounting of groundwater recharge against residential, commercial, and agricultural demands. The water balance was calculated using the following data sets:

- mean precipitation from historical records for the entire Island (all sub-regions),
- estimated groundwater recharge by water sub-region using high and low recharge scenarios;

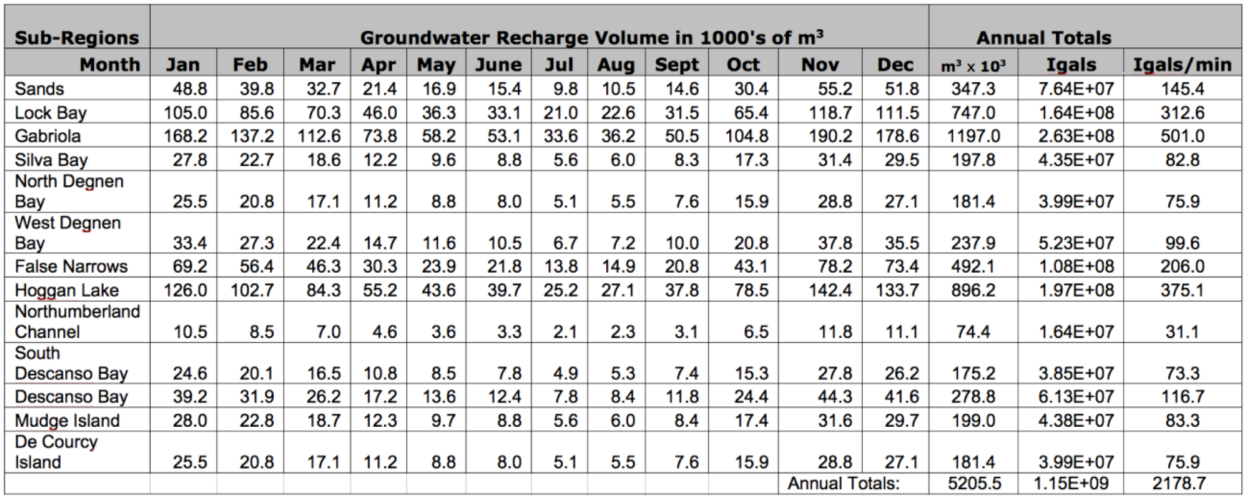
- monthly domestic and non-domestic net demand from domestic and commercial water use surveys; and
- domestic water use values estimated from other published reports.

SRK Consulting (2013) estimated the groundwater recharge rate on the islands to be in the range of 10 and 25% of the annual precipitation rate over an island area of 52.2 km^2. In their assessment, evapotranspiration and runoff values were not estimated and not measured directly. To estimate total recharge volume of water, the precipitation depths were converted to volume of water by multiplying total precipitation by percent recharge and then by the sub-region area. The water demand stress was estimated from the water balance as an indicator of what proportion of the annually replenished groundwater resource was used. Further details on the water budget components evaluated are contained in Appendix D of the SRK Consulting (2013) report.

The water budget method utilized was based on a number of assumptions and the results have large uncertainty in some water balance components. According to SRK Consulting (2013) the "Results of the water budget should be considered indicative of the hydrogeological setting, not absolute. Water budget calculations require a number of assumptions, such as recharge or actual demand. Recharge can only be estimated, not accurately measured."

Table 2, for example, shows the results of the groundwater recharge calculations carried out for the various regions on the islands by SRK Consulting (2013) based on utilizing 10% of 1971-2000 normal monthly and annual precipitation. Volumes originally reported in (m^3) by SRK Consulting have been converted into Imperial gallons (Igals) and Imperial gallons per minute (Igpm) for comparison in Table 2 SRK Consulting (2013) also calculated groundwater recharge based on utilizing 25% of the monthly and annual 1971-2000 normal precipitation amounts.

Table 2: Monthly and annual groundwater recharge calculations based on utilizing 10% of the normal monthly precipitation for Gabriola Island.



Sub-Regions	**Groundwater Recharge Volume in 1000's of m^3**												**Annual Totals**		
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**$m^3 \times 10^3$**	**Igals**	**Igals/min**
Sands	48.8	39.8	32.7	21.4	16.9	15.4	9.8	10.5	14.6	30.4	55.2	51.8	347.3	7.64E+07	145.4
Lock Bay	105.0	85.6	70.3	46.0	36.3	33.1	21.0	22.6	31.5	65.4	118.7	111.5	747.0	1.64E+08	312.6
Gabriola	168.2	137.2	112.6	73.8	58.2	53.1	33.6	36.2	50.5	104.8	190.2	178.6	1197.0	2.63E+08	501.0
Silva Bay	27.8	22.7	18.6	12.2	9.6	8.8	5.6	6.0	8.3	17.3	31.4	29.5	197.8	4.35E+07	82.8
North Degnen Bay	25.5	20.8	17.1	11.2	8.8	8.0	5.1	5.5	7.6	15.9	28.8	27.1	181.4	3.99E+07	75.9
West Degnen Bay	33.4	27.3	22.4	14.7	11.6	10.5	6.7	7.2	10.0	20.8	37.8	35.5	237.9	5.23E+07	99.6
False Narrows	69.2	56.4	46.3	30.3	23.9	21.8	13.8	14.9	20.8	43.1	78.2	73.4	492.1	1.08E+08	206.0
Hoggan Lake	126.0	102.7	84.3	55.2	43.6	39.7	25.2	27.1	37.8	78.5	142.4	133.7	896.2	1.97E+08	375.1
Northumberland Channel	10.5	8.5	7.0	4.6	3.6	3.3	2.1	2.3	3.1	6.5	11.8	11.1	74.4	1.64E+07	31.1
South Descanso Bay	24.6	20.1	16.5	10.8	8.5	7.8	4.9	5.3	7.4	15.3	27.8	26.2	175.2	3.85E+07	73.3
Descanso Bay	39.2	31.9	26.2	17.2	13.6	12.4	7.8	8.4	11.8	24.4	44.3	41.6	278.8	6.13E+07	116.7
Mudge Island	28.0	22.8	18.7	12.3	9.7	8.8	5.6	6.0	8.4	17.4	31.6	29.7	199.0	4.38E+07	83.3
De Courcy Island	25.5	20.8	17.1	11.2	8.8	8.0	5.1	5.5	7.6	15.9	28.8	27.1	181.4	3.99E+07	75.9
											Annual Totals:		5205.5	1.15E+09	2178.7

Data from Table D-9 Appendix D, SRK Consulting (2013).

Burgess and Allen (2016) employing a coupled groundwater-surface water numerical model MIKE SHE (DHI, 2016), computed the mean annual simulation recharge to Gabriola Island at 20% of the 1981-2010 normal precipitation (or 199 mm/year). They report that their model achieves a good match between the averaged simulated and observed WELLS database groundwater levels, the model error is randomly distributed with the model slightly overestimating the groundwater levels, with a mean error of -4.4 m. Burgess and Allen (2016) also used the model to simulate the effects of 2050s and 2080s climate change and report that monthly changes in recharge result in an approximate 8% and 7% reduction in annual recharge for the 2050s and 2080s simulations, respectively.

4.3.2 Water Budget Recharge Equations and Components

The basic water budget recharge equations proposed for a Type 5(a) fractured sedimentary bedrock aquifer are:

$$R = P + Q^{SW}_{in} + Q^{IRRreturn}_{in} - ET - \Delta S^{Lakes} - Q^{SW}_{out} - Q^{SWpump}_{out} \qquad \text{(Equation 9)}$$

and

$$R + Q^{GW}_{in} = \Delta S^{GW} + Q^{GW}_{out} + Q^{GWpump}_{out} \qquad \text{(Equation 10)}$$

where:

P = precipitation (rain and snow)
ET = evapotranspiration
Q^{SW}_{in} = surface water inflow
Q^{SW}_{out} = surface water outflow
Q^{GW}_{in} = groundwater inflow
R = groundwater recharge (from all sources)
ΔS^{Lakes} = change in surface water storage
ΔS^{GW} = change in groundwater storage
$Q^{IRReturn}_{in}$ = irrigation/septic return flow
Q^{GWpump}_{out} = groundwater pumping
Q^{SWpump}_{out} = surface water pumping
Q^{GW}_{out} = groundwater outflow

Recharge is assumed to occur only over the entire area of the island. Since the island is bounded by the sea, groundwater and surface water inflow components (Q^{GW}_{in} and Q^{SW}_{in}) from adjacent areas are non-existent. Saltwater intrusion may occur through up coning or sea water intrusion but these have not been considered as inflow components in this preliminary water budget analysis. Equation 9 for Gabriola Island, therefore, can be rewritten as:

$$R = P + Q^{IRRreturn}_{in} - ET - \Delta S^{Lakes} - Q^{SW}_{out} - Q^{SWpump}_{out} \qquad \text{(Equation 11)}$$

and equation 10 as:

$$R = Q^{GWpump}_{out} + Q^{GW}_{out} + \Delta S^{GW} \qquad \text{(Equation 12)}$$

The SRK Consulting (2013) water budget analysis is based on historic measurements of precipitation (**P**), estimates of recharge (**R**), and estimates of groundwater demand (an indication of potential Q^{GWpump}_{out}). Their analysis did not include any estimates of ET, $Q^{IRRreturn}_{in}$, ΔS^{Lakes}, Q^{SW}_{out}, Q^{SWpump}_{out}, ΔS^{GW} or Q^{GW}_{out}. The numerical model employed by Burgess and Allen (2016) computes estimates of other major components such as ET, ΔS^{Lakes}, Q^{SW}_{out}, ΔS^{GW} and Q^{GW}_{out}. Monthly or annual estimates of these parameters used in the model, however, are not provided in their report.

4.3.3 Testing the GWAM for Gabriola Island

Data on ***P***, ***R*** and groundwater demand (an indication of potential Q^{GWpump}_{out}) from SRK Consulting (2013) was entered into the GWAM workbook. Additional tests of the GWAM spreadsheet were conducted using recharge values of 5% of the annual 1971-2001 normal, and 5, 10 and 25% of the driest year (1985) precipitation amount. A brief discussion of the data input components utilized in the analyses are provided below. For allocation purposes, a confidence factor β of 15% was utilized for the island aquifers based on the aquifer/groundwater area confidence rating guide as shown in Appendix H, Table H1. A maximum confidence factor β of 25% was used for the 20% recharge result of the Burgess and Allen (2016) numerical model. An interim EFN factor α of 0% was assigned for the GWAM analysis as no data was available for the groundwater outflow component (Q^{GW}_{out}).

<u>Precipitation (P)</u>

SRK Consulting (2013) utilized normal precipitation data (Government of Canada, 2018a) for the 1971-2000 period for Climate Station 1023042 located on Gabriola Island. Additional runs of the GWAM spreadsheet were also conducted for this project utilizing precipitation data for the driest year on record (1985) for the same climate station (Figure 7). Annual precipitation for the driest year on record was 630.1 mm or 69 % of the 1971-2000 annual normal of 924 mm. For the 39 year period of record shown in Figure 7, there were 23 years (59%) with precipitation at or below the annual normal amount. Three to four year periods with precipitation below normal occurred during the late 1970s, 1980s, and early 2000s. Burgess and Allen (2016) utilized normal precipitation data (Government of Canada, 2018a) for the 1981-2010 period for Climate Station 1023042 located on Gabriola Island. The annual normal based on 1981-2010 records was 957.5 mm indicating a variance of 3.6% above the 1971-2000 normal.

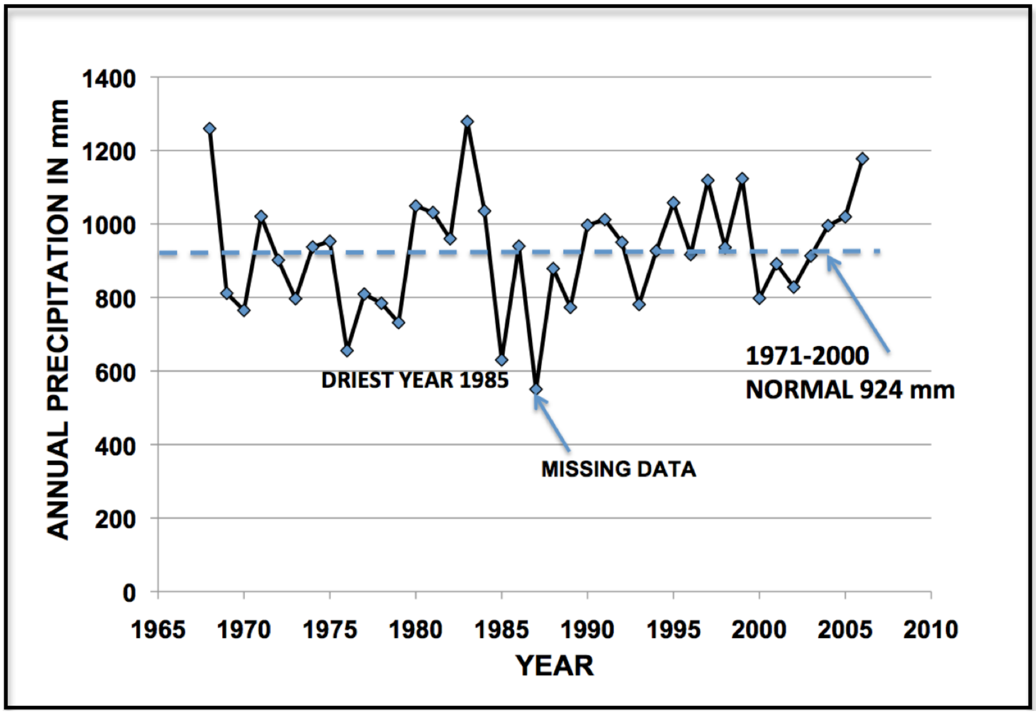


Figure 7: Historic precipitation data for Gabriola climate station 1023042. Data from Government of Canada (2018b).

Uncertainties in Estimating Precipitation: SRK Consulting (2013) attributes an uncertainty of at least 10% for the long-term precipitation mean because of slightly unequal precipitation distribution on Gabriola

Island. Climate Station 1023042 located on Gabriola Island is situated at a relatively low elevation of 46 m, while most of the island lies above the 40 m contour elevation. SRK Consulting (2013) reports that higher than average precipitation may occur in the uplands in central Gabriola Island due to orographic effects, but the elevation difference is only 150 m, so the effect is probably small.

Recharge (R)

SRK Consulting (2013) estimated recharge over the entire island at 10 and 25% of the annual normal (1971-2000) precipitation for two water budget scenarios. SRK Consulting (2013) reported that these rates were estimated using various methods with the lower value of 10% originating from various engineering studies on the Gulf Islands and on the east coast of Vancouver Island in the rain shadow climatic zone. According to SRK Consulting (2013) the higher recharge estimate is larger than the upper limit of recharge values shown by the method of fluctuation in water table and is a typical value for many regional aquifers in southwestern B.C. SRK Consulting (2013) reports that the true recharge rate is not known and is assumed to be in the selected range of 10 to 25%. For water budget planning purposes, they recommend that the conservative (low) recharge volume at 10% mean annual precipitation might be appropriate until the higher recharge rate can be confirmed (SRK Consulting, 2013). Burgess and Allen (2016) employing a coupled groundwater-surface water numerical model MIKE SHE (DHI, 2016), computed the mean annual simulation recharge to Gabriola Island at 20% of the precipitation (or 199 mm/year). They report that their model achieves a good match between the averaged simulated and observed WELLS database groundwater levels, the model error is randomly distributed with the model slightly overestimating the groundwater levels, with a mean error of -4.4 m.

Burgess and Allen (2016) also used the model to simulate the effects of 2050s and 2080s climate change and report that monthly changes in recharge result in an approximate 8% and 7% reduction in annual recharge for the 2050s and 2080s simulations, respectively. Climate change projections from the 1961-1990 baseline normal to the 2050s, reported by the Pacific Climate Impacts Consortium (2013), indicate that mean temperatures in the South Coast Region are likely to increase by a median of 1.7^{o} C (ranging from 1.1 to 2.5^{o} C), while precipitation is expected to increase by approximately 6% in the winter and decrease by approximately 14% in the summer, with an overall increase of 6% over the year.

Uncertainties in Estimating Recharge: SRK Consulting (2013) reports that recharge is variable in space and may be low in some areas and much higher in other areas. They also report that recharge, however, is a highly spatially variable depending on soil type, bedrock geology, vegetation cover, and depth to water table. Near fracture zones, the recharge rate may be significantly higher, while in lower permeability areas, it may be low.

Precipitation recharge was applied by SRK Consulting (2013) for two cases (10% and 25% of precipitation) over the entire island resulting in annual recharge quantities for the two cases. Higher annual recharge quantities may be anticipated if only applied to potential recharge areas. Burgess and Allen (2016) in estimating a 20% recharge rate report that sensitivity analysis results suggest that recharge is most sensitive to the hydraulic conductivity of the fractured bedrock, followed by thickness of the seepage face. Their modeling, however, does not account for potential uncertainties involved in assigning evapotranspiration and surface runoff quantities. Potential groundwater recharge from infiltrating surface water sources also, have also not been considered. Burgess and Allen (2016) have delineated the distribution of average seasonal recharge and discharge areas on Gabriola Island. Their report, however does not quantify these physical areas. Burgess and Allen (2016) base their model on an island area of 57.75 km^2, whereas SRK Consulting (2013) considers an area of 52.2 km^2. A higher recharge rate would be expected if the area is increased. The effect of changing the estimated annual recharge by a factor of 1% was also tested for this project.

Groundwater Demand (Q^{GWpump}_{out})

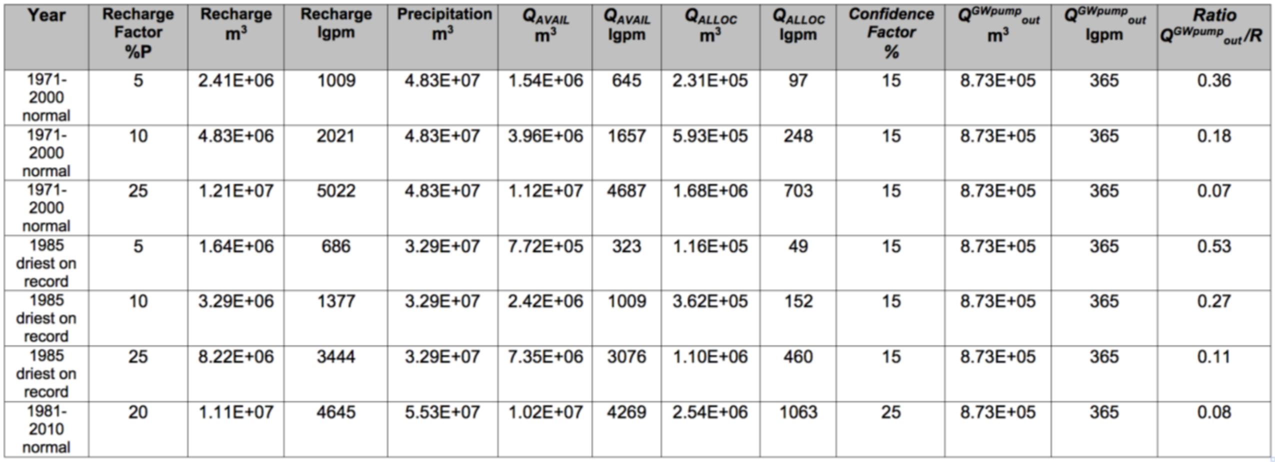
SRK Consulting (2013) reports that water demand was estimated for domestic and non-domestic users from water-use surveys conducted by the Gabriola Groundwater Management Society and the Regional District of Nanaimo in 2012, supplemented from values estimated from previous reports. This survey provided most of the information about pumping water demand used in water budget calculations in their report. Total annual and monthly water demands are the sum of commercial, residential, and agricultural pumping withdrawals for each sub-region. SRK Consulting (2013) estimated the total annual demand at 8.73E+05 m^3 (equivalent to a continuous pumping rate of 365 IGPM). SRK Consulting (2013) reports some 3590 residential properties on the island and there are approximately 2600 water wells reported (Government of British Columbia, 2018f). SRK Consulting (2013) estimated the average total residential water use per household at 193 m^3 per year (equivalent to a pumping rate of 0.08 IGPM). The effect of changing the estimated annual water use, by a factor of 10% was also tested for this project.

Uncertainties in Estimating Groundwater Demand (Q^{GWpump}_{out}): SRK Consulting (2013) reports that the water volumes and rates of use are not necessarily actual water use volumes, as they are not metered accurately or not at all, but they are estimated using the best data available. Many of the numbers used and calculations made require assumptions to simplify the process and to fill in data gaps. The estimated numbers are uncertain and are based on a sample of water users. Only 10.8% of households returned the completed survey questionnaires. In a preliminary assessment of the water budget, these estimates provide a reasonable approximation of the water demands and water stresses for each region (SRK Consulting, 2013). Burgess and Allen (2016) utilized the same annual use data from SRK Consulting (2013).

Results

Results of applying the GWAM utilizing the SRK Consulting (2013) water budget and Burgess and Allen (2016) recharge data are summarized in Table 3. Results based on the 1971-2000 normal and driest year (1985) data for 10 and 25% recharge scenarios are shown in Figure 8. Figure 9and Figure 10 compare various annual recharge rates, $\boldsymbol{Q_{ALLOC}}$ and $\boldsymbol{Q_{AVAIL}}$ expressed in cubic metres per year and IGPM respectively for the 1971-2000 normal and driest year. Figure 11 and Figure 12 illustrate the relationship among various recharge rates, $\boldsymbol{Q_{AVAIL}}$ and $\boldsymbol{Q_{ALLOC}}$ expressed in cubic metres per year and IGPM respectively. An example of the spreadsheet results for calculating recharge utilizing 5% of the normal precipitation is shown in Appendix I, Table I1.

Table 3: Comparison of results for normal and driest precipitation years, Gabriola Island.



Year	Recharge Factor %P	Recharge m^3	Recharge Igpm	Precipitation m^3	Q_{AVAIL} m^3	Q_{AVAIL} Igpm	Q_{ALLOC} m^3	Q_{ALLOC} Igpm	Confidence Factor %	Q^{GWpump}_{out} m^3	Q^{GWpump}_{out} Igpm	Ratio Q^{GWpump}_{out}/R
1971-2000 normal	5	2.41E+06	1009	4.83E+07	1.54E+06	645	2.31E+05	97	15	8.73E+05	365	0.36
1971-2000 normal	10	4.83E+06	2021	4.83E+07	3.96E+06	1657	5.93E+05	248	15	8.73E+05	365	0.18
1971-2000 normal	25	1.21E+07	5022	4.83E+07	1.12E+07	4687	1.68E+06	703	15	8.73E+05	365	0.07
1985 driest on record	5	1.64E+06	686	3.29E+07	7.72E+05	323	1.16E+05	49	15	8.73E+05	365	0.53
1985 driest on record	10	3.29E+06	1377	3.29E+07	2.42E+06	1009	3.62E+05	152	15	8.73E+05	365	0.27
1985 driest on record	25	8.22E+06	3444	3.29E+07	7.35E+06	3076	1.10E+06	460	15	8.73E+05	365	0.11
1981-2010 normal	20	1.11E+07	4645	5.53E+07	1.02E+07	4269	2.54E+06	1063	25	8.73E+05	365	0.08

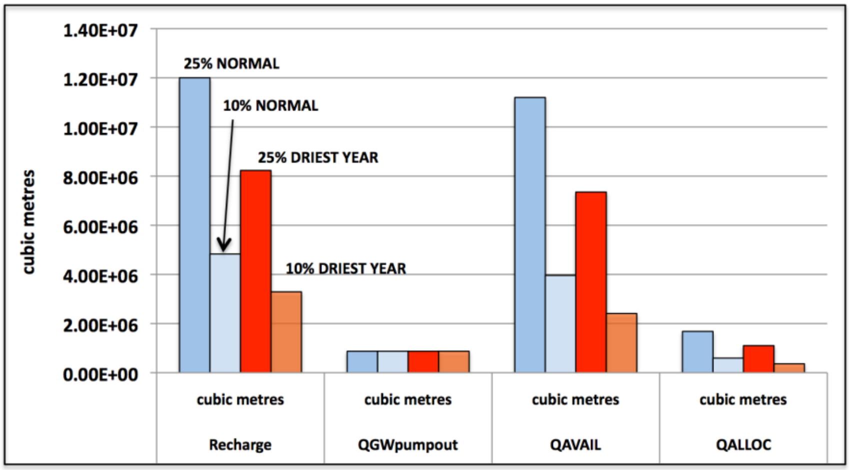


Figure 8: Range of results for annual 1971-2000 normal and driest year (1985) on record, Gabriola Island.

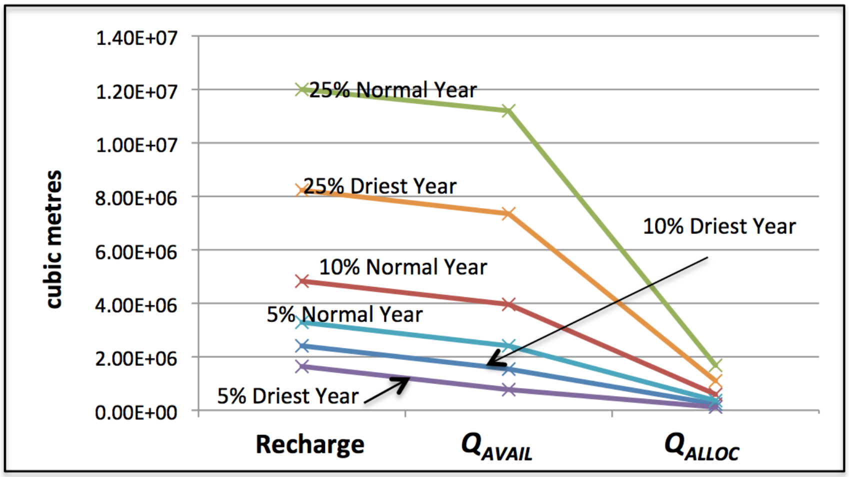


Figure 9: Comparison of various 1971-2000 annual recharge rates, for Gabriola Island, $\mathbf{Q}_{ALLOC}$ and $\mathbf{Q}_{AVAIL}$ expressed in cubic metres per year.

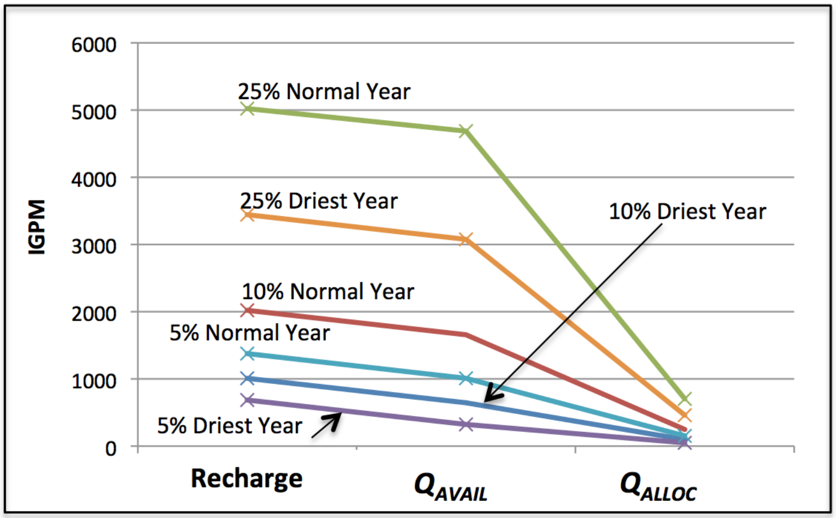


Figure 10: Comparison of various 1971-2000 annual recharge rates for Gabriola Island, $\mathbf{Q}_{ALLOC}$ and $\mathbf{Q}_{AVAIL}$ expressed in IGPM.

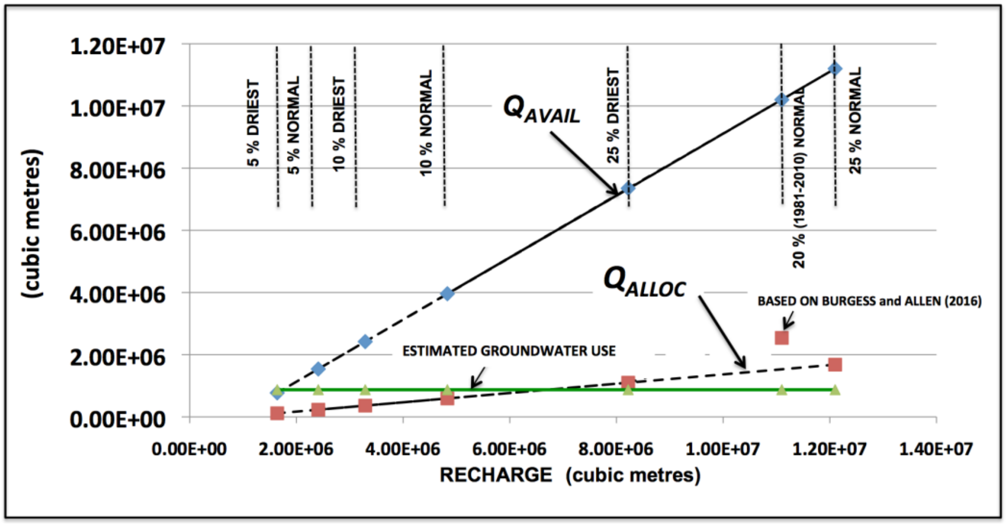


Figure 11: Relationship among various recharge rates, Q_{AVAIL} and Q_{ALLOC} expressed in cubic metres per year. Note that Q_{ALLOC} represents the quantity that may be allocated above the current use.

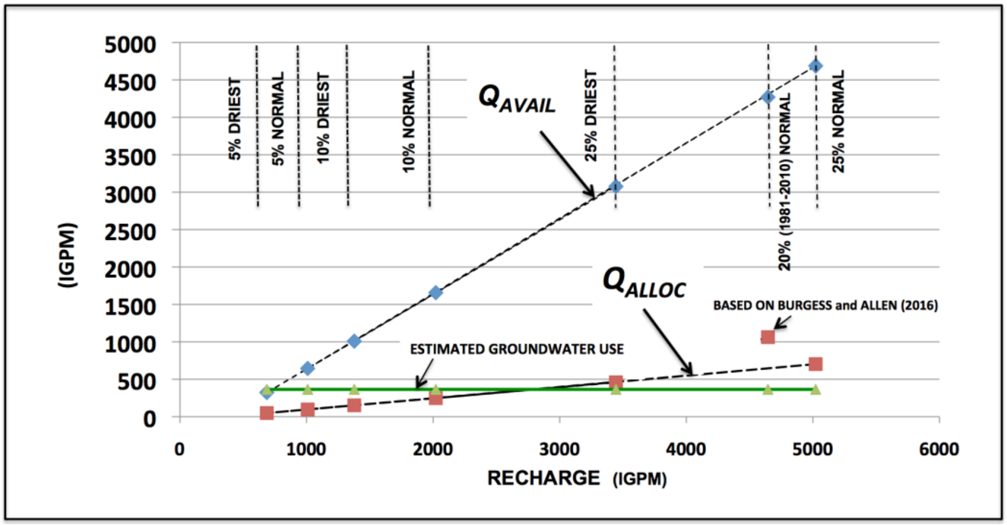


Figure 12: Relationship among various recharge rates for Gabriola Island, Q_{AVAIL} and Q_{ALLOC} expressed in IGPM. Note that Q_{ALLOC} represents the quantity that may be allocated above the current use.

Discussion

In this water budget analysis using the GWAM spreadsheet workbook, the principal parameters considered were only precipitation ***P***, recharge ***R***, and groundwater use Q^{GWpump}_{out}. For any particular annual precipitation amount considered, the recharge rate is the most sensitive parameter affecting the calculation of groundwater availability Q_{AVAIL} and future allocation amounts Q_{ALLOC}. Changing the recharge rate by 1% for example, results in changing Q_{AVAIL} by 12.1% and Q_{ALLOC} by 12.3%. Changing the annual demand (water use) by 10%, for example, results in changing Q_{AVAIL} by 2.2% and Q_{ALLOC} by 2.1%. Results of this simple sensitivity analysis are shown in Table 4.

SRK Consulting (2013) estimated the average total residential water use per household at 193 m^3 per year (equivalent to a pumping rate of 0.08 IGPM). Under Section 22 *Precedence of Rights,* under the *Water Sustainability Act* an excluded groundwater user (i.e. domestic well owner) may utilize up to 2000 litres/day (equivalent to a rate of 0.31 IGPM) or 3.9 times the current estimated use. This raises the question, “In the case of existing domestic well owners, should future allocation decisions consider current water use only or include an allowance for potential water use by existing well owners exercising their full rights?”

Table 4: Results of increasing recharge rate by 1% and pumping rate by 10%, Gabriola Island.

Year	Recharge Factor %P	Recharge m^3	Recharge Igpm	Precipitation m^3	Q_{AVAIL} m^3	Q_{AVAIL} Igpm	Q_{ALLOC} m^3	Q_{ALLOC} Igpm	*Confidence Factor %*	Q^{GWpump}_{out} m^3	Q^{GWpump}_{out} Igpm	*Ratio* Q^{GWpump}_{out}/R
1971-2000 normal	10	4.83E+06	2021	4.83E+07	3.96E+06	1657	5.93E+05	248	15	8.73E+05	365	0.181
1971-2000 normal	10	4.83E+06	2021	4.83E+07	3.87E+06	1620	5.80E+05	243	15	9.60E+05	402	0.199
1971-2000 normal	11	5.31E+06	2222	4.83E+07	4.44E+06	1858	6.66E+05	279	15	8.73E+05	365	0.164

Other key parameters that were not included in the SRK Consulting (2013) recharge estimates and would likely affect the results would be changes in groundwater storage, ΔS^{GW} and groundwater discharge quantities Q^{GW}_{out}. Inclusion of the Q^{GW}_{out} component would significantly reduce the annual Q_{AVAIL} and Q_{ALLOC} estimates. Without an estimate of Q^{GW}_{out} it is moreover, not possible to allow for any environmental flow needs (EFN). Doe (2017 and 2018) has prepared an inventory of wetlands and waterways on Gabriola and assembled some fish data that suggests EFN flows may be significant.

SRK Consulting (2013) reports that water levels in the Provincial observation wells on Gabriola do not appear to be declining from year to year and the aquifer(s) are generally fully recharged during the winter wet seasons. Recent updates of the observation well levels on Gabriola for Aquifer 709 have been documented by GW Solutions (2017).

GW Solutions (2017) reports that over the last five years of data (2012-2016) the water level trend in Observation Wells OW196, OW197, OW316 and OW385 have been declining at -0.04 to -0.32 m per year. This declining water level trend may be reflected in the declining precipitation trend during the period 2004-2014 period (Figure 13) as shown by data from the Entrance Island Climate Station 102BFHH situated off the northeast coast of Gabriola Island some 8.2 km from the Gabriola Island Climate Station 1023042 (Government of Canada, 2018b). Unfortunately, at the time of this report preparation, the climate data for the Gabriola Island Climate Station 1023042, for the period 2000 to 2016, was incomplete or not entirely available from the Government of Canada (2018b).

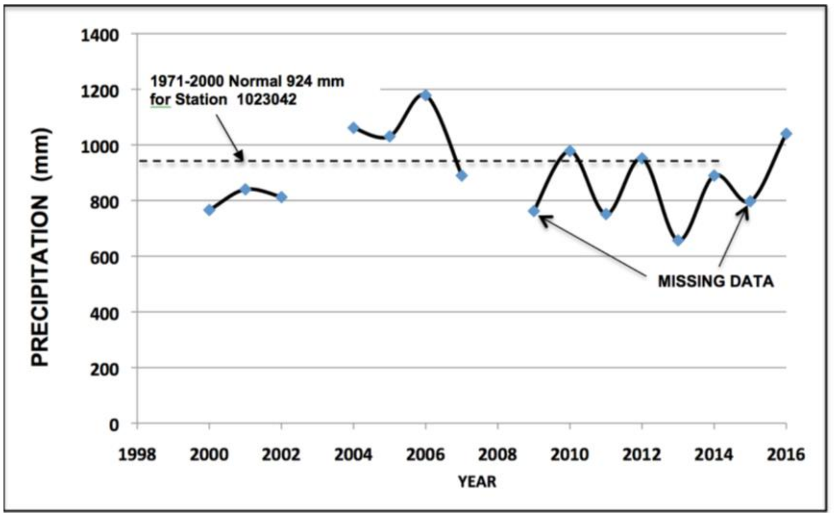


Figure 13: Annual precipitation data for 2000-2016 period at Entrance Island Climate Station 102BFHH. Data from Government of Canada (2018b).

For planning future allocation purposes a reasonable approach would be to consider recharge rates in the range 5 to 10% of normal precipitation or 10% of driest year precipitation. For water budget planning purposes, SRK Consulting (2013) recommends that the conservative (low) recharge volume at 10% mean annual precipitation might be appropriate until the higher recharge rate can be confirmed. In terms of future allocation quantities the GWAM utilizes a conservative confidence factor β with a maximum value of 25% to offset potential uncertainties associated with any water budget analysis.

Recharge rates of 25% as shown in Figure 11 and Figure 12 appear overly optimistic for estimating groundwater availability. Comparisons of the ratio of groundwater pumping (use) to recharge, versus estimated recharge rates are shown in Figure 14. At a recharge rate of 25%, groundwater use would be close to 10% of the annual recharge, suggesting greater use might be readily supported (e.g. 2 to 5 x the current use). However, given the relatively large number of existing wells on the island and high density in some areas, expanding the current use by a factor of 2 or more may lead to compounded water quantity and quality issues such as well interference and quality degradation.

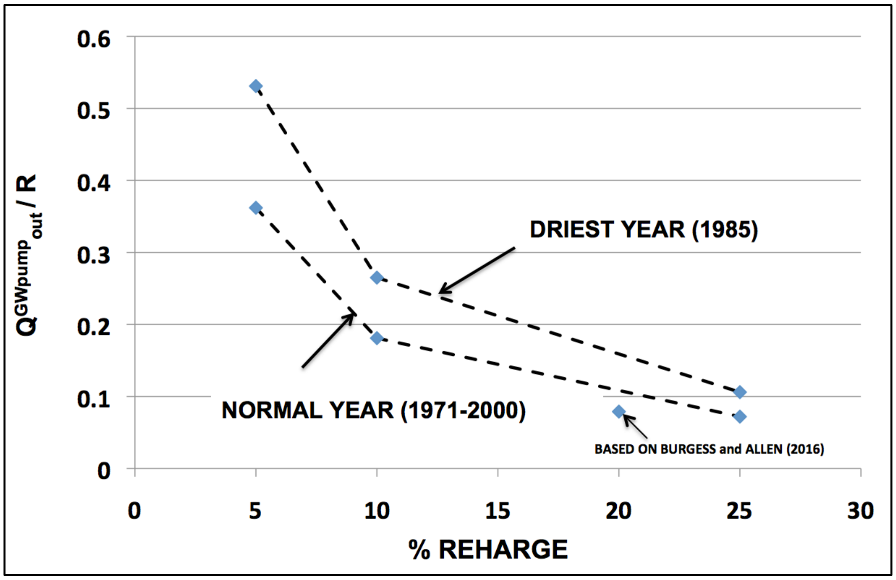


Figure 14: Ratio of pumping (use) versus estimated recharge rates for Gabriola Island.

SRK Consulting (2013) reports that overall water stress on Gabriola is currently low for both high (25%) and low (10%) recharge scenarios. Higher water stress based on the 10% recharge amount was reported for some summer months for the Sands, Lock Bay, North Degnen Bay, West Degnen Bay, False Narrows, South Descanso Bay sub-regions. SRK Consulting (2013) defines water stress for an aquifer as a relative measure, which compares the total demand of groundwater to the amount of natural recharge to the aquifer. Water stress is calculated as the ratio of volumes of total pumping demand to the total recharge, as a percentage value. For the various regions on Gabriola, SRK Consulting (2013) categorized water stress as:

- Lower stress: demand < 50% of recharge (large excess of recharge);
- Moderate stress: demand > 50% of recharge; and
- Higher stress: recharge deficit where demand > recharge.

Potential effects of higher stress conditions during the summer months when withdrawals may be excessive may be reflected in water quantity and quality issues such as wells going dry, well interference and quality degradation including seawater intrusion.

Conclusions (Gabriola Island)

In applying the GWAM to the available water budget information from SRK Consulting (2013) and from Burgess and Allen (2016), the following conclusions are made:

1. The water budget reports by SRK Consulting (2013) and Burgess and Allen (2016), provided limited parameter data for testing the GWAM spreadsheet workbook. The SRK Consulting (2016) water budget was based on only three parameters namely: historic measurements of precipitation (P), estimates of recharge (R), and estimates of groundwater demand (an indication of potential Q^{GWpump}_{out}). A similar situation existed for the Burgess and Allen (2016) report, although other parameters not available were included in their numerical model.
2. By utilizing the GWAM spreadsheet workbook, it was possible to compare the recharge estimates of SRK Consulting (2013) and Burgess and Allen (2016) with additional estimates for the driest year (1985) on record.
3. For any particular annual precipitation amount considered, the recharge rate is the most sensitive parameter affecting the calculation of groundwater availability Q_{AVAIL} and future allocation amounts Q_{ALLOC}. Changing the recharge rate by 1% for example results in changing Q_{AVAIL} by 12.1% and Q_{ALLOC} by 12.3%.
4. Based on the current levels of hydrologic information available, an interim approach for planning future allocation purposes would be to consider recharge rates in the range 5 to 10% of normal precipitation or 10% of driest year precipitation. Annual recharge rates much above 10% of the annual normal precipitation maybe overly optimistic for estimating groundwater availability for allocation purposes for Gabriola Island.
5. For aquifer areas such as Gabriola Island where domestic wells are most prevalent, it may be prudent to include an allowance for potential water use by existing well owners exercising their full rights in the future.
6. Based on a recharge rate of 10% of the driest year (1985) precipitation, the potential amount of Q_{AVAIL} would be 1.54E+06 m^3/ yr (645 Igpm) with a suggested future allocation quantity Q_{ALLOC} of 2.31E+05 m^3 / yr (97 Igpm) considering a conservative confidence factor β of 15%.
7. The GWAM is useful as a preliminary assessment tool for compiling, interpreting and comparing the results of one or more water budgets that may have been conducted for any particular aquifer or area and providing conservative estimates of groundwater availability (Q_{AVAIL}) and quantities for future allocation (Q_{ALLOC}).
8. The GWAM proved useful for examining a range of water budgets for an unconfined fractured bedrock Type 5a aquifer.

Recommendations (Gabriola Island)

Based on the analysis conducted of the available water budgets for Gabriola Island the following recommendation is suggested:

1. Further investigate the higher stress regions on Gabriola to identify and assess the magnitude and potential causes of any quantity and quality issues that may be occurring. Hodge (1978) for example, reported saltwater intrusion in some of the coastal areas of the island 40 years ago. One or two pilot studies in higher stress regions may be particularly beneficial for understanding the relationship among, recharge, water use, water quality and saltwater intrusion. It would be beneficial if the pilot region selected, included one with an observation well and one or more streams or discharge areas (e.g. springs) that could be monitored.

4.4 Water Budget For Westwold Valley Aquifer (Type 1b)

4.4.1 General Synopsis

In 2012, Bennett developed an empirical water budget for the Westwold Valley Aquifer southeast of Kamloops, to assess the feasibility of using a simplified spreadsheet water budget to quantitatively determine the primary components of groundwater recharge and discharge to an unconsolidated sand and gravel aquifer. The Westwold Valley actually contains two aquifers, namely Aquifer 289 and Aquifer 98. Aquifer 289 is classified as an unconfined IIB (12) aquifer and Aquifer 98 is a confined IIC (12) aquifer (Government of British Columbia, 2018f). Bennett's conceptual aquifer model as a linear reservoir treats both aquifers as one unconfined aquifer unit occupying a valley bottom area of 37 km^2. The aquifer can be categorized as a Type 1(b) predominantly unconfined aquifer along rivers of moderate stream order (Wei *et al*., 2014). An additional goal of the 2012 project was to have the water budget model function as a tool to examine allocation (licensing) options and their general impact on the groundwater resource.

The project included establishing four hydrometric stations on the Salmon River and installing groundwater monitoring wells to examine surface water and groundwater hydrographs in order to quantify water budget inputs and outputs. The conceptual water budget for the aquifer is shown schematically in Figure 15 representing the fundamental equation:

> *Precipitation infiltration + Groundwater inflow + River and stream leakage + Irrigation return = Groundwater extraction + Surface water extraction + Evapotranspiration + Groundwater discharge to river + Groundwater outflow +/- Change in storage in the aquifer.*

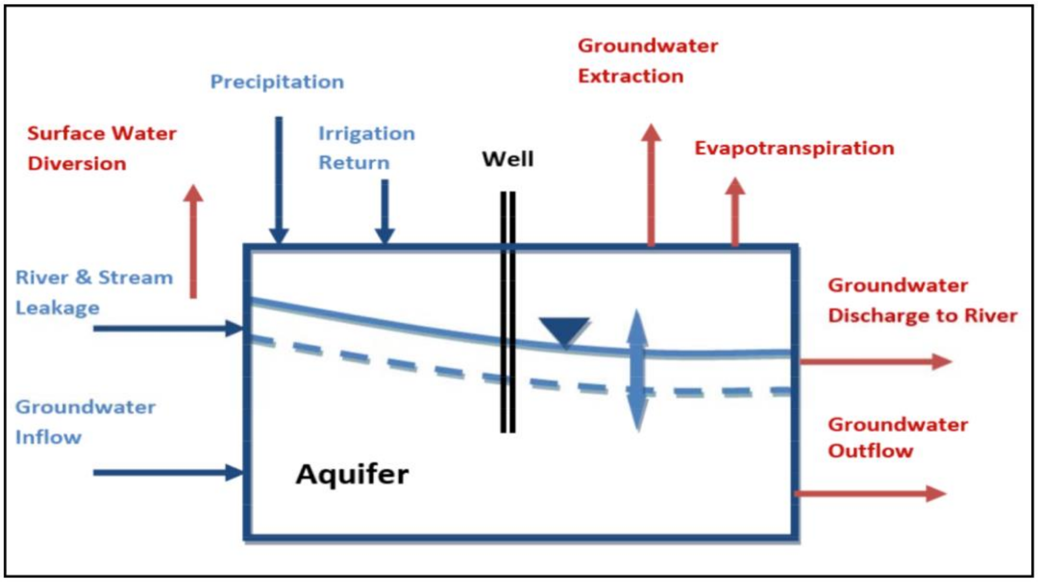


Figure 15: Conceptual water budget components for Westwold Valley Aquifer, from Bennett (2012).

Bennett (2012) utilized a spreadsheet to develop the water budget for 2010 and 2011 where monthly recharge to and discharge from the aquifer was quantified along with a resulting monthly surplus or deficit. Monthly data were totaled into annual volumes. Parameters used to calculate volumetric inflow and outflow components included: irrigated area, precipitation infiltration, irrigation duty, theoretical crop requirements, irrigation return, aquifer specific yield and groundwater inflow and outflow at the study boundaries. Some parameters were based on field work and desktop review such as irrigated area while other parameters were assigned values such as aquifer specific yield (assumed to be 0.25 for an unconfined sand and gravel aquifer), the percentage of annual precipitation that enters the aquifer and irrigation return. Other parameters were also inferred from hydrometric, topographical and water well information such as the volume of groundwater flowing into and out of the study area along the valley floor. Further details on determining other components of the water budget can be found in Bennett (2012). Figure 16 shows the results of the recharge and discharge calculations as percentages of total inflow (blue) and outflow (red).

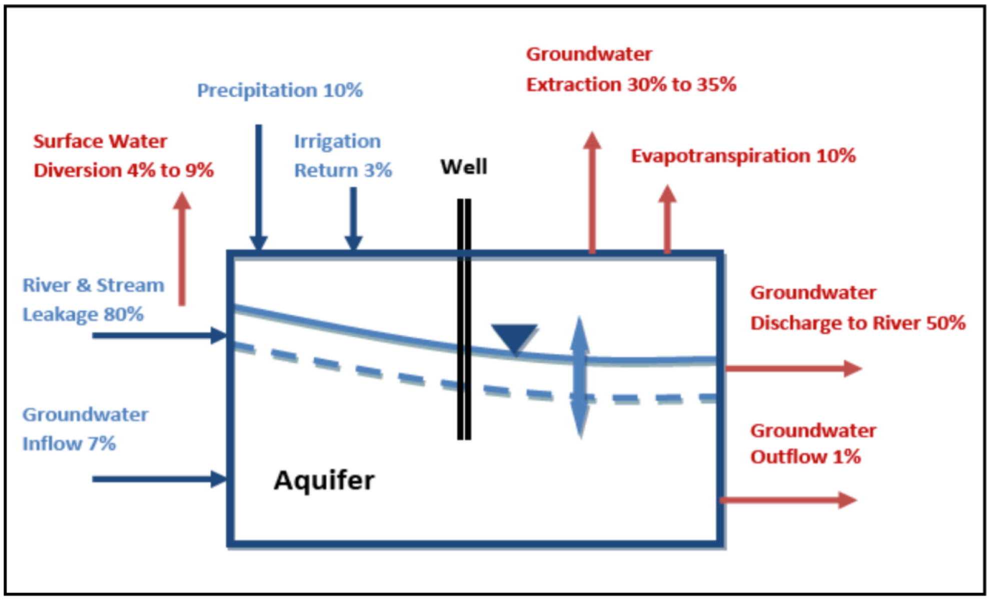


Figure 16: Inflow and outflow percentages for Westwold Valley Aquifer, from Bennett (2012).

For this particular example, Bennett (2012) makes a number of important conclusions that are noted as follows:

1. The water budget indicates that groundwater and surface water must be managed conjunctively to achieve sustainable water use in the Westwold Valley.
2. Predicting and measuring river loss is the most crucial **inflow** parameter to predict and assess the likelihood of a water deficit.
3. The duration of freshet may be more influential on aquifer recharge than the intensity of the freshet by providing a longer period for river loss.
4. The water budget reveals that a difference of 10% to 20% between total inflow and total outflow will result in a notable rise or decline in the groundwater table.
5. Natural outflow into the river is the largest **outflow** parameter in the water budget comprising approximately 50% to 60% of the total annual outflow.
6. The second largest outflow was irrigation use of surface water and groundwater pumping representing approximately of 35% to 40% of the annual outflow. It should be noted that although irrigation use of water is the second largest outflow parameter, actual use of water is not known and not monitored.
7. River loss during the freshet period provides approximately 55% or more of the estimated annual recharge to the aquifer.

4.4.2 Water Budget Recharge Equations and Components

The basic water budget recharge equation proposed for a Type 1(b) predominantly unconfined aquifer along rivers of moderate stream order is:

$$R = P + Q^{SW}_{in} + Q^{IRReturn}_{in} - ET - \Delta S^{SW} - Q^{SW}_{out} - Q^{SWpump}_{out} \qquad \text{(Equation 13)}$$

Bennett (2012) qualifies the recharge from precipitation to be 10% of the annual amount and adds components for groundwater inflow Q^{GW}_{in} , Q^{GW}_{out} and a recharge component for mountain block recharge (MBR). Adapting Equation 13 to include the components of Bennett (2012) results in:

$$R_{TOT} = P_p + (Q^{SW}_{in} - Q^{SW}_{out} + Q^{SWpump}_{out}) + Q^{GW}_{in} + Q^{IRReturn}_{in} + \Delta S^{GW} \qquad \text{(Equation 14)}$$

and

$$\begin{aligned}\Delta S^{GW} = P_p + (Q^{SW}_{in} - Q^{SW}_{out} + Q^{SWpump}_{out}) + Q^{GW}_{in} + Q^{IRReturn}_{in} - \\ (ET + Q^{SW}_{out} + Q^{SWpump}_{out} + Q^{GW}_{in} + Q^{GWpump}_{out})\end{aligned} \qquad \text{(Equation 15)}$$

where;

P_p = a portion of the annual precipitation (rain and snow)
ET = evapotranspiration
Q^{SW}_{in} = surface water inflow
Q^{SW}_{out} = surface water outflow
Q^{GW}_{in} = lateral groundwater inflow + MBR inflow
R_{TOT} = groundwater recharge (from all sources)
ΔS^{GW} = change in groundwater storage
$Q^{IRReturn}_{in}$ = irrigation/septic return flow
Q^{GWpump}_{out} = groundwater pumping
Q^{SWpump}_{out} = surface water pumping
Q^{GW}_{out} = groundwater outflow ($Q^{GW}_{lat.out} + Q^{GW}_{BF}$), and

where,

$Q^{GW}_{lat.out}$ = quantity of lateral groundwater outflow or discharge, and
Q^{GW}_{BF} = quantity of groundwater-derived baseflow, a component of surface water outflow Q^{SW}_{out}, and

$$(Q^{SW}_{in} - Q^{SW}_{out} + Q^{SWpump}_{out}) = \text{river loss or leakage} \qquad \text{(Equation 16)}$$

Rathfelder (2016) describes the Westwold Valley as an area characteristic of a snowmelt dominated climatic region. Recharge to the aquifer can be expected to be highly influenced by the stage and flows of the Salmon River.

4.4.3 Testing the GWAM for the Westwold Valley Aquifer

Bennett (2012) provides an Excel® spreadsheet that contains monthly parameter input data and results obtained for 2010 and 2011. The monthly results compare the sums of the water budget inflows versus the water budget outflows and whether there is a net surplus or deficit. A surplus or deficit reflects a positive or negative water level change in the aquifer, which can be compared to available observation well data.

2011 monthly inflow and outflow data for each parameter from Bennett (2012) was entered into the GWAM spreadsheet workbook. Data available from Bennett (2012) for 2010, only included monthly totals and annual summary figures. The 2010 data therefore could not be tested for each parameter. A brief discussion of the data input components utilized in the analyses is provided below. For allocation purposes, a confidence factor β of 21.7% was estimated for Aquifer 289 using the aquifer /groundwater area confidence rating guide as shown in Appendix H, Table H2. Given the importance of fisheries interests on the Salmon River (Obedkoff, 1976) and historic conflicts with other water uses during low flow periods, a high EFN factor α of 50% was assigned for the GWAM analysis. A discussion of the various inflow and outflow components estimated by Bennett (2012) is as follows:

Precipitation (P_p)

In his water budget analysis Bennett (2012) utilized a percentage of the monthly 1971-2000 normal precipitation data for Westwold available from Government of Canada (2018a). The valley bottom infiltration area was estimated at 3,700 hectares (37 km^2) with 10% of the precipitation assumed to infiltrate past the rooting zone and recharge the aquifer. Infiltration as a percentage of precipitation is a modifiable parameter in the Bennett (2012) spreadsheet. For purposes of testing the GWAM spreadsheet, the input units for $\boldsymbol{P_p}$ needed to be changed from mm over the aquifer area to m^3.

Bennett (2012) also estimated precipitation on the valley sides and upland area that would provide deep seated lateral recharge through the aquifer-bedrock contact along the valley sides. The inflow from the surrounding bedrock was estimated by multiplying a flux rate (50 mm/year) multiplied by the valley length (21 km x 2 sides) multiplied by the valley aquifer thickness (100 m). This inflow was also assumed to occur uniformly throughout the year. This was based on numerical hydrogeological modeling of conceptual mountainous watersheds by Neilson-Welch and Allen (2007). Their modeling results suggest that recharge to the saturated zone in an upland area would partition into surface runoff, stream base flow (via deep groundwater discharge at stream valleys) and deep-seated groundwater flow that replenishes valley bottom aquifers via *Mountain Block Recharge* (MBR). It is believed this deep groundwater recharge would provide a continuous flux of MBR to a valley bottom aquifer through the bedrock-valley sediment contact along the valley bottom sides. Neilson-Welch and Allen (2007) determined that the rate of flux was primarily controlled by the mountain geology rather than climate (annual precipitation). They also estimated that 35 to 50 mm/year of available precipitation across their conceptual watersheds could migrate as deep groundwater flow through the mountain bedrock to a valley bottom aquifer. While Bennett (2012) regards this MBR component as precipitation recharge from valley sides and uplands it was regarded as part of the groundwater inflow component $\boldsymbol{Q^{GW}_{in}}$ in Equation 13 for purposes of testing the GWAM spreadsheet.

Uncertainties in Estimating Precipitation: Bennett (2012) reports that the precipitation infiltration component at 10% may be variable based on local knowledge. The rationale for considering only 10% of the precipitation in the water budget is not presented in the report. Presumably the remainder of the precipitation is integrated into the river flows or lost to evapotranspiration processes. Total precipitation data for the years 2010 and 2011 were not used in the analysis.

Groundwater Inflow (Q^{GW}_{in})

Bennett (2012) reports that groundwater was assumed to flow into the upstream study boundary through the valley bottom alluvium alongside the Salmon River and calculated the inflow using Darcy's Equation Q = K x i x A where:

- Q = volumetric flow rate,
- K= hydraulic conductivity (e.g. 10^{-2} m/s assumed for sand and gravel),
- i = hydraulic gradient (2.5m/km based on ground topography), and

- A = saturated cross-sectional area (estimated at 400 m wide by 8 m deep, based on the width of the mapped aquifer and known thickness from well logs).

As discussed previously, for purposes of testing the GWAM spreadsheet, the MBR component as precipitation recharge from valley sides and uplands was added to the groundwater inflow component $\boldsymbol{Q^{GW}_{in}}$.

Uncertainties in Estimating Groundwater Inflow: The groundwater inflow component estimate is largely dependent upon estimates of hydraulic conductivity that may vary by an order of magnitude.

Irrigation/Septic Return Flow ($Q^{IRReturn}_{in}$)

Bennett (2012) used an irrigation return of 5% for his estimates based on groundwater and Salmon River sources for the months of April through September.

Uncertainties in Estimating Irrigation/Septic Return Flow: Bennett (2012) notes that the irrigation use of water is the second largest outflow parameter, and the actual use of water is not known and not monitored. This uncertainty would be reflected in any estimates of irrigation return flow. Quantifying return flow from irrigation and domestic water use is difficult to estimate without adequate monitoring data. Scibek (2005) estimated return flows of approximately 25% of the amount of irrigation water used for the Grand Forks Aquifer. He based this on consultation with experts in irrigation practices for the types of crops present. In other areas,

Le Breton (1976a) calculated return flows of 20 to 30% from irrigation of alfalfa and potato crops for a monitored site in the Salmon River Valley. Based on these studies, it is possible that return flows from irrigation may be 4 to 5 times higher than estimated.

Evapotranspiration (ET)

Bennett (2012) utilized estimates of evapotranspiration (***ET***) based on Farmwest's climate web site tool (Farmwest, 2018). Farmwest (2018) reports that ***ET*** is calculated for a grass reference crop using a modified Penman Monteith equation, which is the standard method recommended by the UN Food and Agriculture Organization (Allen *et al.,* 1998). The budget assumes that during the irrigation season all ***ET*** in irrigated areas is satisfied by the applied irrigation water, so there is no ***ET*** outflow in the irrigation season. The exception to this is the east end of the study area where there is a high groundwater table that supplies the crops with water and no surface application of water occurs. The theoretical ***ET*** in this area is 750 mm/year. The budget assumes that no ***ET*** occurs during periods of snow cover, December through February. ***ET*** is also considered a discharge from the aquifer in the non-irrigation season where the groundwater table is < 2m below surface. For purposes of testing the GWAM spreadsheet, the input units for ***ET*** needed to be changed from mm over the area to m^3 in order to enter the data from Bennett (2012).

Uncertainties in Estimating Evapotranspiration: Some researchers using different approaches for estimating evaporation on a global scale, for example, (Droogers and Allen, 2002) indicate potential errors of 30%. Uncertainties associated with estimating evapotranspiration can be considered to be significant.

River Losses, Surface Water Inflow (Q^{SW}_{in}), and Surface Water Outflow (Q^{SW}_{out})

Based on river flow measurements, Bennett (2012) reports river losses and river gains presumably based on the differences between $\boldsymbol{Q^{SW}_{in}}$ and $\boldsymbol{Q^{SW}_{out}}$ as monitored at various hydrometric stations along the valley. The main surface water gauging stations (automatic and manual) are shown in Figure 17.

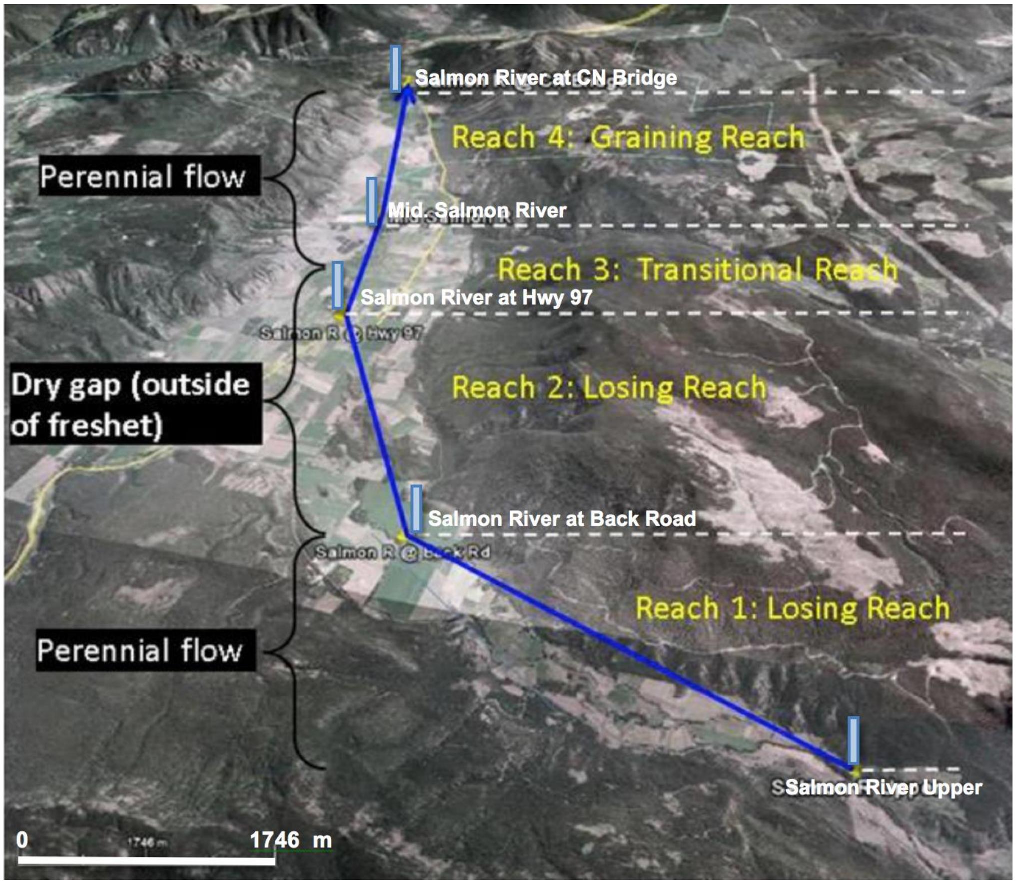


Figure 17: Westwold Valley looking easterly with location of manual and automatic surface water gauging stations. Original figure from Bennett (2012), modified by Rathfelder (2016) and adapted for this report.

For entering into the GWAM spreadsheet, the flow loss data from Bennett (2012) was used to calculate the surface water inflow parameter (Q^{SW}_{in}) based on the relationship;

$$\text{River loss or leakage} = (Q^{SW}_{in} - Q^{SW}_{out} + Q^{SWpump}_{out}) \qquad \text{(Equation 17)}$$

In determining river losses, changes in flow between hydrometric stations were adjusted for estimated surface water diversions and tributary flow, Bennett (2012). Hence the inclusion of the parameter (Q^{SWpump}_{out}) in Equation 16. A positive value for Q^{SWpump}_{out} was also required for this parameter to calculate Q^{SW}_{in}, in the GWAM spreadsheet in order to replicate the water balance figures of ΔS^{GW} calculated by Bennett (2012).

Bennett (2012) reports that river gain in the two reaches downstream of "Salmon R @ Hwy 97" is due to groundwater discharge to the river as base flow. The reach from Mid Salmon River to Salmon River at CN Bridge, is a gaining reach year round including freshet. Monthly base flow estimates in 2010 and 2011 ranged from 40,000 to 60,000 m^3/day.

Uncertainties in River Losses, Surface Water Inflow, and Surface Water Outflow: Bennett (2012) reports that uncertainty in a river loss measurement is the product of the uncertainty in the flow measurement at the beginning and end of each reach, compared to the measured river loss, and the uncertainty in a single river loss measurement can be up to 50%. Hydrometric data for the individual gauging stations was not included in the Bennett (2012) report.

Groundwater Pumping (Q^{GWpump}_{out})

Bennett (2012) assumes that the volume of groundwater pumped from the aquifer for irrigation is the irrigated area multiplied by the estimated application rate. The domestic and livestock groundwater consumption was estimated based on 5,000 head of cattle eight months per year (October through May) consuming 70 L/day (15 gallons/day each) and 300 residents consuming 340 L/day (75 gallons/day) each.

Uncertainties in Estimating Groundwater Pumping: Bennett (2012) reports that the actual use of water is not known and not monitored. Estimated quantities might vary perhaps in the range of + or – (25% to 50%). It is also assumed that groundwater pumping would not be drawing any portion of water from the river or interfering with river flows to any significant degree.

Groundwater Outflow (Q^{GW}_{out})

In a similar method for estimating groundwater inflow, Bennett (2012) estimated groundwater outflow using Darcy's Equation Q = K x i x A where:

- Q = volumetric flow rate,
- K= hydraulic conductivity of 5×10^{-5} m/s assumed for silty sand,
- i = hydraulic gradient (2 m/km based on ground topography), and
- A = saturated cross-sectional area estimated at 750 m wide by 30 m deep, based on the width of the mapped aquifer and known thickness from well logs.

The groundwater outflow component estimated by Bennett (2012) can be considered as the lateral component of groundwater outflow ($\boldsymbol{Q^{GW}_{lat.out}}$) and does not include the groundwater baseflow component to the river, which is integrated within the surface water outflow ($\boldsymbol{Q^{SW}_{out}}$).

Uncertainties in Estimating Groundwater Outflow: Again, the groundwater outflow component estimate is largely dependent upon estimates of hydraulic conductivity that may vary by an order of magnitude.

Surface Water Pumping (Q^{SWpump}_{out})

Bennett (2012) estimated the volume of surface water diverted for irrigation in 2011 based on the irrigated area multiplied by the application rate of 0.76 m per acre.

Uncertainties in Estimating Surface Water Pumping: Bennett (2012) reports that the actual use of water is not known and not monitored. Estimated quantities might vary perhaps in the range of + or – (25% to 50%).

Results

Results of applying the GWAM utilizing the 2011 spreadsheet data from Bennett (2012) are summarized in Table 5 and Table 6 and also shown in Appendix I, Table I2. Table 5 summarizes the inflow and outflow components estimated by Bennett (2012) and Table 6 summarizes the inputs and output components in the GWAM spreadsheet analysis. **A similar annual ΔS^{GW} value of -3,847,217 m^3 was calculated for each spreadsheet.** Figure 18 and Figure 19 show the relative percentage of each component in the Bennett (2012) water budget and the percentage of each component in the GWAM. Comparison of Figure 18 and Figure 19 show similar percentages of the main budget components. In Figure 18 and Figure 19, SW inflow represents the sum of the adjusted surface water loss components in Figure 18.

Sensitivity of the parameters was also tested in the GWAM spreadsheet by increasing each parameter by 10 to 20% and calculating effects on ΔS^{GW}, ***R***, $\boldsymbol{Q_{AVAIL}}$ and $\boldsymbol{Q_{ALLOC}}$. Results for this exercise are shown in Table 7 and discussed in the following section.

Table 5: Summary of water budget estimates for the Westwold Valley Aquifer for 2011 from Bennett (2012).

Water Budget Component INFLOWS	**Annual 2011 m^3**	**Annual 2011 Igpm**	**Water Budget Component OUTFLOWS**	**Annual 2011 m^3**	**Annual 2011 Igpm**
Precipitation	1,450,030	607	Evapotranspiration in non-irrigation season	928,370	389
MBR Inflow	420,000	176	Evapotranspiration & sub-irrigation	2,245,510	940
GW Inflow	2,520,225	1055	SW Irrigation	1,572,745	658
River Loss – Salmon R Upper to Back Road	19,310,950	8082	GW Irrigation	7,817,468	3272
River Loss – Hwy 97 Bridge to Salmon R mid	2,245,000	940	Domestic and Livestock watering	122,393	51
Monte Lake diversion (ditch loss)	489,600	205	GW Outflow	73,050	31
Ingram Creek (stream loss & hyporeic flow)	1,189,000	498	Surface Outflow	18,701,500	7827
SW Irrigation loss	-566,651	-237			
Irrigation Return	555,665	233			
Totals:	27,613,819	11,559		31,461,036	13168
ΔS^{GW} =	-3,847,217				

Table 6: Summary of water budget estimates for the Westwold Valley Aquifer for 2011 based on the GWAM spreadsheet.

Water Budget Inflow Parameters	**Annual 2011 m^3**	**Annual 2011 Igpm**	**Water Budget Outflow Parameters**	**Annual 2011 m^3**	**Annual 2011 Igpm**
Precipitation (P_p)	1,450,030	607	Evapotranspiration (*ET*)	3,173,882	1328
GW Inflow including MBR (Q^{GW}_{in})	2,940,225	1231	SW Pumping (Q^{SWpump}_{out})	1,572,745	658
Surface Water Inflow (Q^{SW}_{in})	39,796,655	16655	GW Pumping (Q^{GWpump}_{out})	7,939,862	3323
Irrigation Return ($Q^{IRReturn}_{in}$)	555,665	233	GW Outflow ($Q^{GW}_{lat.out}$)	73,050	31
			Surface Outflow (Q^{SW}_{out})	18,701,500	7827
Totals:	44,742,575	18,726		31,461,039	13167
ΔS^{GW} =	$P_p + (Q^{SW}_{in} - Q^{SWout} + Q^{SWpump}_{out}) + Q^{GW}_{in} + Q^{IRReturn}_{in} - ET - Q^{SW}_{out} - Q^{SWpump}_{out} - Q^{GWpump}_{out} - Q^{GW}_{out}$				
ΔS^{GW} =	-3,847,219				
Q_{AVAIL} = 1.62E+07 m^3 (6774 Igpm)					
Q_{ALLOC} = 3.51E+06 m^3 (1470 Igpm)					
Ratios of $Q^{GWpump}_{out} / Q_{AVAIL}$, and Q^{GWpump}_{out} / R = 49 and 33% respectively.					

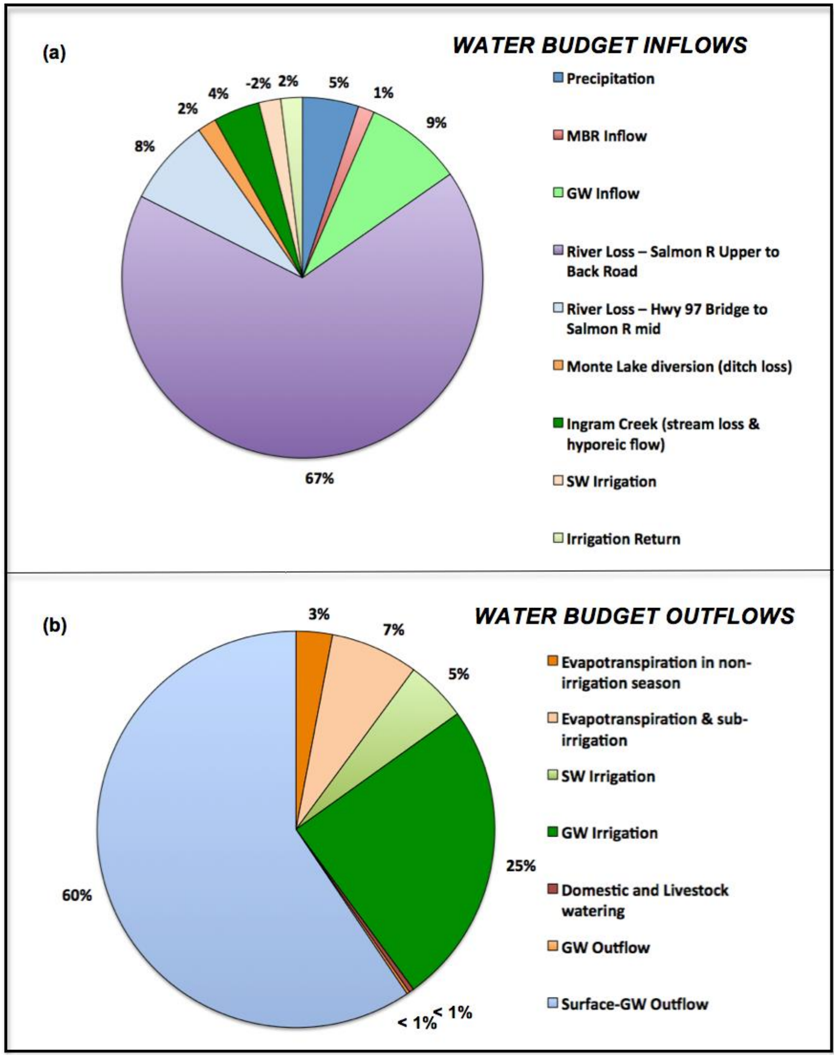


Figure 18: Percentages of each water budget component in 2011 for the Westwold Valley Aquifer. Data from Bennett (2012).

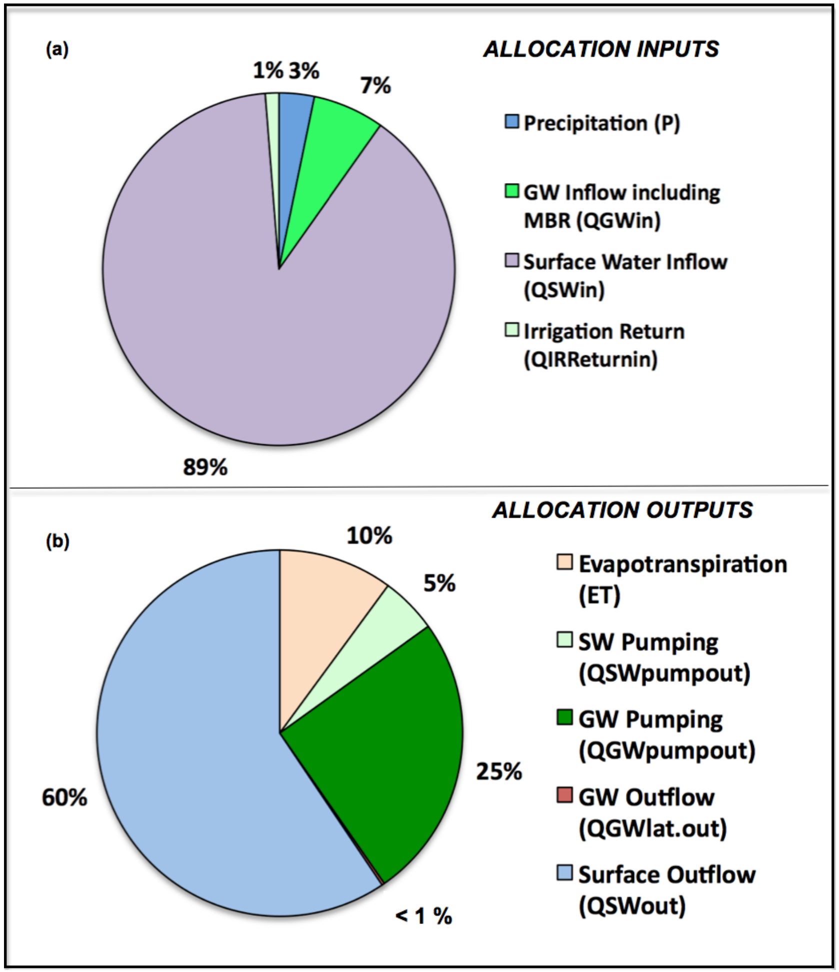


Figure 19: Percentages of each water budget component in 2011 for the Westwold Valley Aquifer from the GWAM spreadsheet.

Table 7: Results of sensitivity analysis of various parameters for the Westwold Valley Aquifer. All values in m^3 except for %.

Parameter	Modified by %	Initial Value ΔS^{GW}	Changed Value ΔS^{GW}	Net Change %	Initial Value R	Changed Value R	Net Change %	Initial Value Q_{AVAIL}	Changed Value Q_{AVAIL}	Net Change %	Initial Value Q_{ALLOC}	Changed Value Q_{ALLOC}	Net Change %
Q^{SW}_{in}	10	-3847219	132447	103.4	24162305	31725932	31.3	16184918	23749545	46.7	3512344	5153651	46.7
Q^{SW}_{out}	10	-3847219	-7587519	-97.2	24162305	19731881	-18.3	16184918	11755494	-27.4	3512344	2550942	-27.4
Q^{GWpump}_{out}	20	-3847219	-5435191	-41.3	24162305	23002044	-4.8	16184918	13437685	-17.0	3512344	2915978	-17.0
Q^{GW}_{in}	20	-3847219	-3259174	15.3	24162305	25139275	4.0	16184918	17162888	6.0	3512344	3724347	6.0
ET	10	-3847219	-4164607	-8.2	24162305	23853481	0.4	16184918	15877094	1.9	3512344	3445329	1.9
P_p	10	-3847219	-3702216	3.8	24162305	24401399	1.0	16184918	16425012	1.5	3512344	3564228	1.5
$Q^{IRReturn}_{in}$	20	-3847219	-3736086	2.9	24162305	24384571	0.9	16184918	16408184	1.4	3512344	3560576	1.4
Q^{SWpump}_{out}	20	-3847219	-3847219	0	24162305	24476854	1.3	16184918	16500467	1.9	3512344	3580601	1.9
$Q^{GW}_{lat.out}$	20	-3847219	-3861829	-0.4	24162305	24150175	-0.1	16184918	16166483	-0.1	3512344	3508127	-0.1

In terms of calculating recharge (***R***), groundwater availability (Q_{AVAIL}) and an allocation quantity (Q_{ALLOC}) for 2011, the GWAM spreadsheet (Appendix I, Table I2) resulted in the following:

- R/P_p of 1666%,
- Q_{AVAIL} of 1.62E+07 m^3 (6774 Igpm) based on Equation 4, and
- Q_{ALLOC} of 3.51E+06 m^3 (1470 Igpm) based on Equation 6.
- Q_{AVAIL} was based on a relatively high EFN factor α of 0.5 or 50%.
- Q_{ALLOC} was based on a relatively high confidence factor β, of 21.7%.
- Ratios of $Q^{GWpump}_{out}/Q_{AVAIL}$, and Q^{GWpump}_{out}/R were 49 and 33%, respectively.

Discussion

Entering the water budget data from Bennett (2012) into the GWAM spreadsheet required a review, interpretation and clarification of each budget component. There were, for example, some differences in component terminology that needed to be reconciled. Budget equations in the GWAM spreadsheet also needed to be adjusted to utilize the Bennett (2012) data. The GWAM spreadsheet was originally set up to calculate the recharge (***R***) quantity as a residual, based on entering the other parameters. The Bennett (2012) water budget was set up to calculate monthly changes in groundwater storage (ΔS^{GW}) quantities as a residual. Data from Bennett (2012) was first utilized in the GWAM to calculate values of ΔS^{GW} using Equation 15**.** Values of ΔS^{GW} obtained were then utilized to calculate values of R_{TOT} in the GWAM using Equation 14.

Bennett (2012) reports that the simulated (or predicted) change in the water level in the aquifer (based on 2009, 2010 and 2011 river and creek flow data) was compared to 2010 and 2011 hydrographs to validate or calibrate the water budget model. The report provides no further details on how the calibration was conducted. Calculated ΔS^{GW} quantities for 2011 closely matched the equivalent average monthly and annual water level changes in the observation wells for that year. For 2010, the calculated ΔS^{GW} quantities closely matched the equivalent average water level changes in the observation wells for the first part of the year until August, thereafter falling short to the end of the year.

Bennett (2012) reports a notable rise or recovery in the groundwater table in the fall of 2010 as compared to the fall of 2011 and river flow in the upper (losing) reach of the Salmon River was at least 50% higher in fall 2010 than fall 2011. He reports that the 2010 hydrograph and longer term hydrograph data for the provincial observation well (Obs. Well 45) suggest that groundwater extraction for irrigation may be influencing groundwater levels at the provincial observation well and contributing to groundwater recovery in late September after irrigation has ended. He further adds that “a comparison of historical and recent data suggests that river flow in the losing reaches of the Salmon River has a larger influence on groundwater recovery than shutting off irrigation wells.” A comparison of the water level data for 2010 in Observation Well 45 with the stage of the Salmon River at Falkland (STN. 08LE020) shows fall groundwater levels rising above the earlier effects of the annual freshet of May-June (Figure 20). This suggests that both factors, a curtailment of groundwater pumping and relatively higher river flows in the early fall contributed to higher groundwater levels at that time. A similar but smaller rise of the water level in Observation Well 45 also occurred during the fall of 2011 (Figure 21).

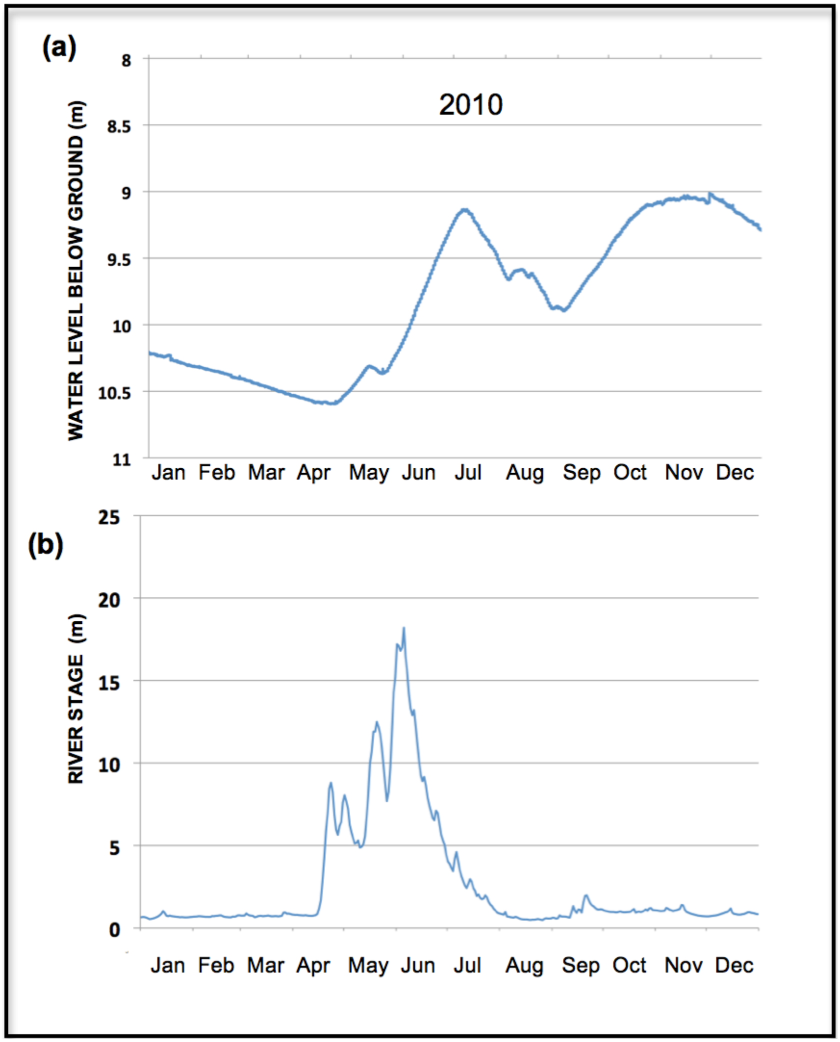


Figure 20: Comparison of water levels in Observation Well 45 and stage of the Salmon River at Falkland in 2010. Data from Government of British Columbia (2018g) and Government of Canada (2018c).

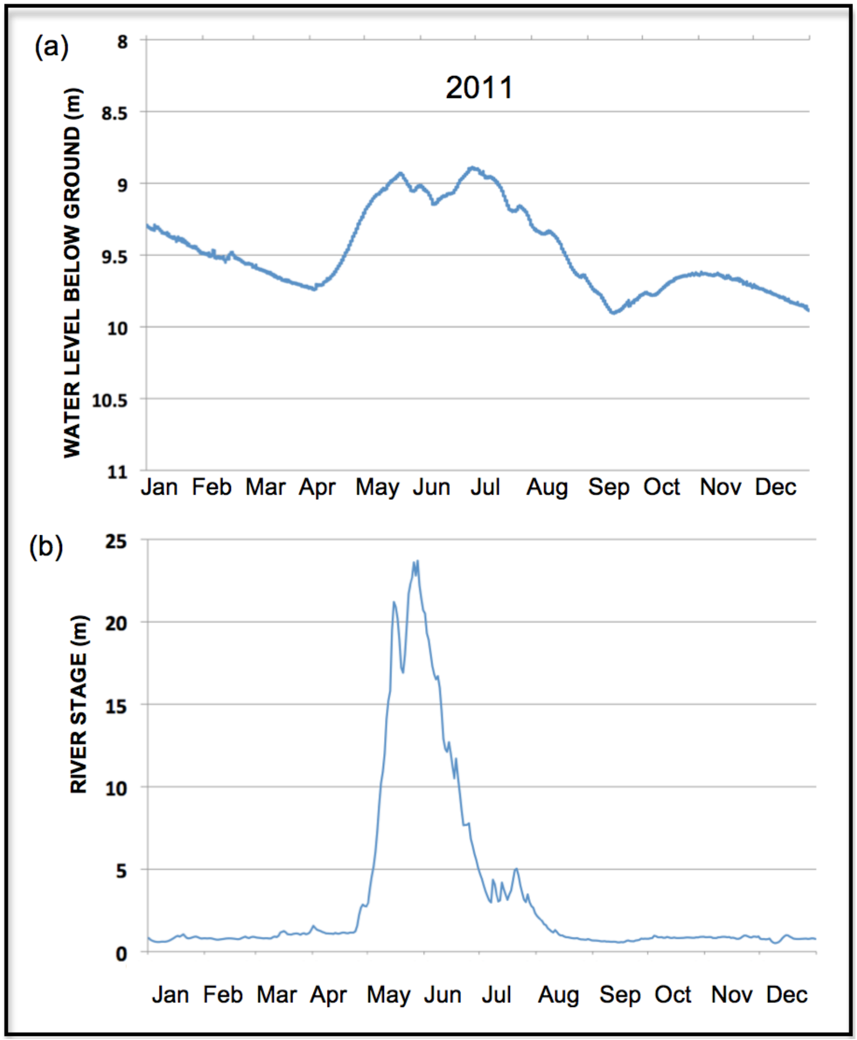


Figure 21: Comparison of water levels in Observation Well 45 and stage of the Salmon River at Falkland in 2011. Data from Government of British Columbia (2018g) and Government of Canada (2018c).

The 2011 results of the GWAM spreadsheet analysis for recharge (***R***), groundwater availability (Q_{AVAIL}), allocation quantity (Q_{ALLOC}), $Q^{GWpump}_{out}/Q_{AVAIL}$, and Q^{GWpump}_{out}/R all appear to be reasonable values for a normal flow year when compared to estimates of current groundwater use and reported water issues in the valley. The R/P_p value of 1666% is, however, not very meaningful given the fact that the main source of recharge is from river losses and not precipitation. Stream-driven recharge is likely the dominant recharge mechanism in the southern interior region for many aquifers in river valleys. Precipitation input to the water budget was limited to 10% of the annual 1971-2000 normal. While 2011 pumping was only 33% of the recharge, it is unlikely that future groundwater availability would be sufficient to accommodate a doubling of the 2011 groundwater pumping quantity.

Sensitivity analysis (Table 7) indicates that variations in surface water losses (Q^{SW}_{in}) and outflow (Q^{SW}_{out}) have the largest effect on the water budget and hence the importance of hydrometric measurements. A 10% increase in (Q^{SW}_{in}), for example results in a 103% increase in groundwater storage (ΔS^{GW}) and a 31% increase in recharge (***R***). A 10% increase in (Q^{SW}_{out}), for example results in a 97% decrease in groundwater storage (ΔS^{GW}) and an 18% decrease in recharge (***R***). These surface water parameters also have a high degree of uncertainty as individual measurement errors can be as high as 50%. The budget is also sensitive to variations in groundwater pumping (Q^{GWpump}_{out}) and groundwater inflow (Q^{GW}_{in}). A 20% increase in groundwater pumping (Q^{GWpump}_{out}), for example, results in a 41% decrease in groundwater storage (ΔS^{GW}) and a 5% decrease in recharge (***R***).

Since the Bennett (2012) water budget was applied to two relatively normal years for flows of the Salmon River, Q_{AVAIL} and Q_{ALLOC} estimates may be considered optimistic. While the water budget demonstrates the interconnection between the groundwater and surface water regimes in the Westwold Valley, its application based on 2011 data for making future water allocation decisions should be used with caution. Obedkoff (1976) reports that historically the Salmon River has been the object of vital concerns to irrigation and fisheries interests, two major conflicting users of a very limited water resource during the low flow period. Obedkoff (1976) provides some preliminary estimates of surplus surface flow for future restricted water licences, based on critical minimum depths required for salmon swimming downstream of the spawning reach (i.e. downstream of Westwold). While recommending future licensing of groundwater, Obedkoff (1976) does not discuss potential implications for licensing groundwater and any potential effects on groundwater-streamflow interactions.

Conclusions (Westwold Valley Aquifer)

In applying the GWAM to the available water budget information from Bennett (2012), the following conclusions are made:

1. Entering the water budget data from Bennett (2012) into the GWAM spreadsheet required a review, interpretation and clarification of each budget component and reconciliation of differences in component terminology. Budget equations in the GWAM spreadsheet also needed to be adjusted to utilize the Bennett (2012) data.
2. The GWAM spreadsheet was originally set up to calculate the recharge (***R***) quantity as a residual, based on entering the other parameters. The Bennett (2012) water budget was set up to calculate monthly changes in groundwater storage (ΔS^{GW}) quantities as a residual. Similar monthly values and an annual ΔS^{GW} value of -3,847,217 m^3 were calculated for 2011 for both spreadsheets.
3. River losses and gains are the most sensitive parameters affecting the calculation of groundwater availability Q_{AVAIL} and future allocation amounts Q_{ALLOC} (Table 7). A 10% increase in Q^{SW}_{in}, for example, doubles the change in groundwater storage (ΔS^{GW}), and increases Q_{AVAIL} and Q_{ALLOC} by about 47%. Conversely, and 10% increase in Q^{SW}_{out}, reduces groundwater storage by

97%, and reduces Q_{AVAIL} and Q_{ALLOC} by about 27%. This highlights the importance of accurate hydrometric measurements to support groundwater allocation for stream-driven recharge systems common in the interior areas of British Columbia.

4. Based on the GWAM analysis for a relatively normal flow year (2011), the quantity of groundwater available Q_{AVAIL} was determined at 1.62E+07 m^3 (6774 Igpm) with an estimated future allocation quantity Q_{ALLOC} of 3.51E+06 m^3 (1470 Igpm) utilizing a conservative confidence factor β of 21.7%. Ratios of $Q^{GWpump}_{out}/Q_{AVAIL}$, and Q^{GWpump}_{out}/R were 49 and 33%, respectively.
5. The 2011 results of the GWAM spreadsheet analysis for recharge (R), groundwater availability (Q_{AVAIL}), allocation quantity (Q_{ALLOC}), ($Q^{GWpump}_{out}/Q_{AVAIL}$), and ($Q^{GWpump}_{out}/R$) all appear to be reasonable values for a normal flow year when compared to estimates of current groundwater use and reported water issues in the valley. Individual component data was not available to calculate the above parameters for 2010.
6. While 2011 pumping was only 33% of the estimated total recharge, it is apparent from the GWAM that future groundwater availability would be insufficient to accommodate a doubling of the 2011 groundwater pumping quantity of 7,939,862 m^3 (3272 Igpm) since the ratio of $Q^{GWpump}_{out}/Q_{AVAIL}$ would approach 100%.
7. Since the Bennett (2012) water budget was applied to relatively normal year (2011) flows of the Salmon River, Q_{AVAIL} and Q_{ALLOC} estimates may be considered optimistic. While the water budget demonstrates the interconnection between the groundwater and surface water regimes in the Westwold Valley, its application based on 2011 data for making future water allocation decisions should be used with caution, particularly for low surface flow years.
8. The GWAM proved useful for examining the Bennett (2012) water budget data for an unconfined unconsolidated Type 1b aquifer and interacting surface water regime for a normal flow year.

Recommendations (Westwold Valley Aquifer)

Based on the analysis conducted of the 2011 water budgets for the Westwold Valley Aquifer the following recommendations are suggested:

1. As indicated by Bennett (2012), in the future it will be necessary to manage groundwater and surface water conjunctively to achieve sustainable water use in the Westwold Valley.
2. Given the historic water use stresses during low flow periods, better data should be obtained on both surface water and groundwater use, points of abstraction and potential interactions. Licensing of groundwater provides an opportunity to refine the water use estimates that have been made to date.
3. Existing observation wells along the Westwold Valley should be maintained and low flow hydrometric monitoring carried out during periods of drought to enable examination of water budgets for these periods. Given the importance of the streamflow components and potential measurement errors up to 50%, improvement to hydrometric monitoring network should be
4. Site specific EFN studies in the Westwold Valley should be conducted to assess the validity of utilizing an EFN factor of 50% for normal year flows and appropriate EFN factors for below normal and drought year flow conditions.
5. As better data is obtained the Bennett (2012) water budget and GWAM analysis should be updated and refined to improve the groundwater availability estimates.

4.5 Water Budget For The West Of Aldergrove Aquifer (Type 4b)

4.5.1 General Synopsis

In 2016, Golder Associates Ltd., developed a series of groundwater budgets for seven aquifers in the Hopington Aquifer – Salmon River area in the Fraser Valley. One of 5 confined aquifers in the area, the West of Aldergrove Aquifer, Aquifer 33, is an unconsolidated, confined sand and gravel aquifer, underlying the Hopington Aquifer (Figure 22). It is classified as a confined IIC (12) aquifer under the *BC Aquifer Classification System* (Government of British Columbia, 2018f) and occupies an area of 73 km^2. The aquifer can be categorized as a Type 4(b), predominantly confined sand and gravel aquifer of glacial or pre-glacial origin (Wei *et al*., 2014). This aquifer area was selected to test the GWAM in a confined aquifer setting.

Golder Associates Ltd (2016) used a previously developed numerical groundwater model termed the Township of Langley groundwater model, as a basis for the delineation of hydraulic connections between aquifers and for input and output parameters used in the water budgeting. Inputs and outputs were disaggregated to a monthly basis using various assumptions.

4.5.2 Water Budget Recharge Equations and Components

The basic water budget recharge equations proposed for a Type 4(b) predominantly confined sand and gravel aquifer of glacial or pre-glacial origin can be expressed as:

$$R = Q^{GWLeak}_{in} = (Q^{GW}_{out} + Q^{GWpump}_{out}) - (Q^{GW}_{in}) + \Delta S^{GW} \qquad \text{(Equation 18)}$$

where,

$$\Delta S^{GW} = (Q^{GW}_{in} + Q^{GWLeak}_{in}) - (Q^{GWpump}_{out} + Q^{GW}_{out}) \qquad \text{(Equation 19)}$$

and:

Q^{GW}_{in} = groundwater inflow from other aquifers

Q^{GWLeak}_{in} = leakage from overlying less permeable units (aquitards)

ΔS^{GW} = change in groundwater storage

Q^{GWpump}_{out} = groundwater pumping

Q^{GW}_{out} = groundwater outflow to aquitards and other aquifers

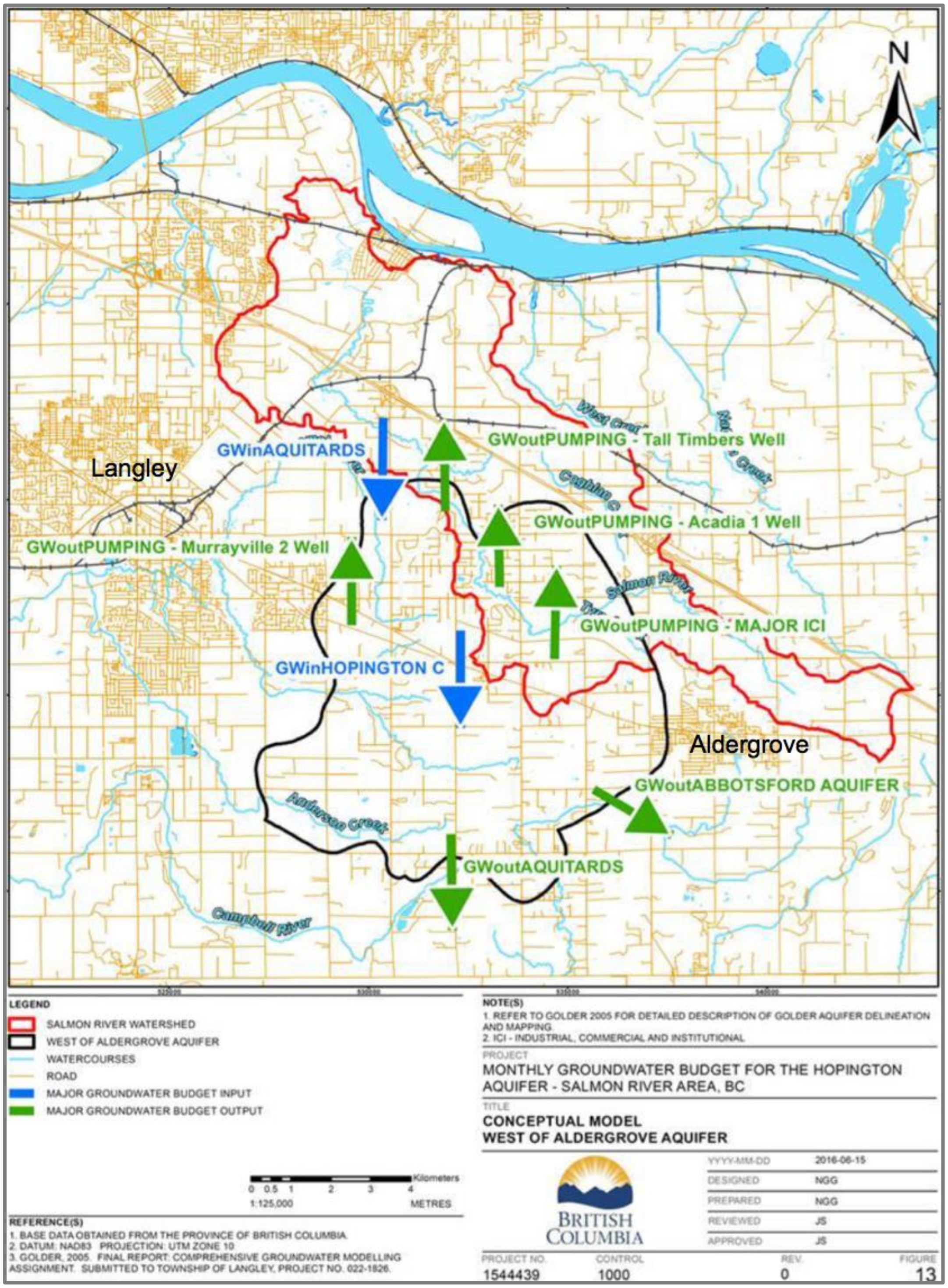
R = groundwater recharge (from all sources)

4.5.3 Testing the GWAM for the West of Aldergrove Aquifer

Golder Associates Ltd (2016) provides an Excel® spreadsheet that contains monthly parameter input data and results obtained for average annual (1945-2012) meteorological conditions and 2011/2012 conditions in the Township of Langley (pumping rates, water demand, etc.). As the confined aquifer was regarded as generally hydraulically isolated from changes in recharge, inputs and results for dry and wet years were deemed to be consistent with the average year.

The monthly results compare the sums of the water budget inflows versus the water budget outflows and whether there is a net surplus or deficit. A surplus or deficit reflects a positive or negative water level change in the aquifer, which can be compared to available observation well data.

The monthly inflow and outflow data for each parameter from Golder Associates Ltd (2016) was entered into the GWAM spreadsheet workbook. A brief discussion of the data input (inflow and outflow) components utilized in the analyses are provided below. For allocation purposes, a confidence factor β of 20.8% was estimated for Aquifer 33 using the aquifer/groundwater area confidence rating guide as shown in Appendix H, Table H3. As the confined aquifer does not appear to discharge to any surface water sources the EFN factor α, was set at 0% for the GWAM analysis. A discussion of the various inflow and outflow components estimated by Golder Associates Ltd (2016) is as follows:



REFERENCE(S)
1. BASE DATA OBTAINED FROM THE PROVINCE OF BRITISH COLUMBIA.
2. DATUM: NAD83 PROJECTION: UTM ZONE 10
3. GOLDER, 2005. FINAL REPORT: COMPREHENSIVE GROUNDWATER MODELLING ASSIGNMENT. SUBMITTED TO TOWNSHIP OF LANGLEY, PROJECT NO. 022-1826.

NOTE(S)
1. REFER TO GOLDER 2005 FOR DETAILED DESCRIPTION OF GOLDER AQUIFER DELINEATION AND MAPPING.
2. ICI - INDUSTRIAL, COMMERCIAL AND INSTITUTIONAL

PROJECT
MONTHLY GROUNDWATER BUDGET FOR THE HOPINGTON AQUIFER - SALMON RIVER AREA, BC

TITLE
CONCEPTUAL MODEL
WEST OF ALDERGROVE AQUIFER

YYYY-MM-DD 2016-06-15
DESIGNED NGG
PREPARED NGG
REVIEWED JS
APPROVED JS

PROJECT NO. 1544439
CONTROL 1000
REV. 0
FIGURE 13

Figure 22: Conceptual model of the West of Aldergrove Aquifer. Adapted from Golder Associates Ltd (2016).

Groundwater Inflow (Q^{GW}_{in})

Groundwater inflows for aquifers and aquitards were derived from the numerical model (Golder Associates Ltd., 2005 and 2014) and apportioned monthly using a constant linear distribution. Seasonal and monthly variations in inter-aquifer fluxes and aquitards were assumed to be minor as a result of relatively small changes in observed hydraulic head gradients and varying degrees of hydraulic isolation from seasonal forcings. Golder Associates Ltd (2016) calibrated the numerical model against the measured average annual groundwater levels at available monitoring wells. The predicted head distributions from the calibrated model were used to estimate average annual groundwater fluxes to/from aquifers and aquitards.

Uncertainties in Estimating Groundwater Inflow: Golder Associates Ltd (2016) estimates that the overall uncertainty in groundwater fluxes between individual aquifers as predicted by the Township of Langley groundwater model is expected to be similar to the uncertainty in baseflow predictions or plus or minus 30 to 50%.

Groundwater Leakage (Q^{GWLEAK}_{in})

Golder Associates Ltd (2016) reports groundwater leakage from surrounding aquitards as one of the groundwater inflow components as derived from the numerical model.

Uncertainties in Groundwater Leakage: As discussed under uncertainties in estimating groundwater inflow, similar errors of plus or minus 30 to 50% would be anticipated.

Groundwater Pumping (Q^{GWpump}_{out})

Groundwater pumping for municipal purposes was derived from monthly municipal pumping records from the Township of Langley. Pumping from private industrial, commercial and institutional sources was originally derived from metered water records from the Township of Langley and extracted from the groundwater model. Large volume industrial, commercial and institutional water users were extracted from the model and have their own groundwater budget term. Uses from private agricultural and private domestic sources were not specifically identified as being significant for the West of Aldergrove Aquifer.

Uncertainties in Groundwater Pumping: Golder Associates Ltd (2016) estimates uncertainty in estimating major groundwater users to be in the range of plus or minus 50 to 100%.

Groundwater Outflow (Q^{GW}_{out})

Groundwater outflows for aquifers and aquitards were derived from the numerical model (Golder Associates ltd., 2005 and 2014) and apportioned monthly using a constant linear distribution. Seasonal and monthly variations in inter-aquifer fluxes and aquitards were assumed to be minor as a result of relatively small changes in observed hydraulic head gradients and varying degrees of hydraulic isolation from seasonal forcings. Groundwater average annual fluxes to/from aquifers and aquitards were used to identify the presence and magnitude of hydraulic connections and hydraulic head fluctuations were used for calibration.

Uncertainties in Groundwater Outflow: Golder Associates Ltd (2016) estimates the overall uncertainty in groundwater fluxes between individual aquifers as predicted by the Township of Langley groundwater model is expected to be similar to the uncertainty in baseflow predictions, or plus or minus 30 to 50%.

Results

Results of applying the GWAM utilizing the spreadsheet data from Golder Associates Ltd (2016) are summarized in Table 8 and

Table 9, and are also shown in Appendix I, Table I3. Table 8 summarizes the inflow and outflow components estimated by Golder Associates Ltd (2016) and

Table 9 summarizes the inputs and output components in the GWAM spreadsheet analysis. **Similar annual ΔS^{GW} (surplus or deficit) values of -365 m^3 and -370 m^3 were calculated for each spreadsheet respectively.** The difference between the two is likely due to number rounding differences in the two spreadsheets. Figure 23 and Figure 24 show the relative percentage of each component in the Golder Associates Ltd (2016) water budget and the percentage of each component in the GWAM water budget. Comparison between Figure 23 and Figure 24 show similar percentages for the main budget components. Sensitivity of the parameters was also tested in the GWAM spreadsheet by increasing each parameter by 5 to 20% and calculating effects on ΔS^{GW}, ***R***, Q_{AVAIL} and Q_{ALLOC}. Results for this exercise are shown in Table 10 and discussed in the following section.

In terms of calculating recharge (***R***), groundwater availability (Q_{AVAIL}) and an allocation quantity (Q_{ALLOC}), the GWAM spreadsheet resulted in the following:

- ***R*** of 2.84E+07 m^3 or 11,884 Igpm,
- Q^{GWpump}_{out} of 1.48E+06 m^3 or 619 Igpm,
- Q_{AVAIL} of 2.69E+07 m^3 or 11,258 Igpm based on an EFN factor α = 0%, and
- Q_{ALLOC} of 5.60+06 m^3 or 2244 Igpm based on a confidence factor β of 20.8%.
- Ratios of $Q^{GWpump}_{out}/Q_{AVAIL}$, and Q^{GWpump}_{out}/R were 5.5 and 5.2%, respectively.

Table 8: Summary of water budget estimates for the West of Aldergrove Aquifer from Golder Associates Ltd (2016).

Water Budget Component INFLOWS (Q^{GW}_{in})	**Average Year (1945-2012) m^3**	**Average Year (1945-2012) Igpm**	**Water Budget Component OUTFLOWS (Q^{GW}_{out}) including pumping**	**Average Year (1945-2012) m^3**	**Average Year (1945-2012) Igpm**
From surrounding aquitards	28,395,905	11884	To surrounding aquitards	27,602,760	11552
From Abbotsford Aquifer	251,485	105	To Abbotsford Aquifer	2,048,745	857
From Brookswood Aquifer	151,840	64	To Hopington Aquifer	540,930	226
From Hopington AB Aquifer	123,370	52	To South of Hopington Aquifer	21,535	9
From Hopington C Aquifer	2,744,435	1149	To Langley Upland Intertill Aquifer	39,785	17
From South of Hopington Aquifer	161,330	68	To South of Murrayville Aquifer	98,185	41
			From Murrayville wells	454,425	190
			From Tall Timbers well	22995	10
			From Acadia well	9125	4
			From Britco, Poppy Est and Spring Valley wells	990245	414
Totals:	31,828,365	13,322		31,828,730	13,320
$\Delta S^{GW} = \Sigma (Q^{GW}_{in}) - \Sigma (Q^{GW}_{out})$					
$\Delta S^{GW} =$	**-365**				

Table 9: Summary of water budget estimates for the West of Aldergrove Aquifer based on GWAM spreadsheet.

Water Budget Component INFLOWS	Average Year (1945-2012) m^3	Average Year (1945-2012) Igpm	Water Budget Component OUTFLOWS	Average Year (1945-2012) m^3	Average Year (1945-2012) Igpm
GW Leakage from aquitards Q^{GWLeak}_{in}	28,395,905	11,884	**GW Pumping** (Q^{GWpump}_{out})	1,476,795	619
GW Inflow (Q^{GW}_{in})	3,432,460	1,437	**GW Outflow** (Q^{GW}_{out})	30,351,940	12,703
Totals:	31,828,365	13,321		31,828,735	13,322
$Q^{GW}_{in} + Q^{GWLeak}_{in} = Q^{GWpump}_{out} + Q^{GW}_{out} + \Delta S^{GW}$					
$\Delta S^{GW} =$	**-370**				
R = 2.84E+07 m^3 or 11,884 Igpm, Q^{GWpump}_{out} = 1.48E+06 m^3 or 619 Igpm, Q_{AVAIL} = 2.69E+07 m^3 or 11,258 Igpm based on EFN factor α = 0%, and Q_{ALLOC} = 5.60E+06 m^3 or 2244 Igpm based on, confidence factor β of 20.8%. Ratios of $Q^{GWpump}_{out}/Q_{AVAIL}$, and Q^{GWpump}_{out}/R = 5.5 and 5.2%, respectively.					

Discussion

Entering the water budget data from Golder Associates Ltd (2016) into the GWAM spreadsheet required a review, interpretation and clarification of each budget component. There were, for example, some differences in component terminology that needed to be reconciled. Golder Associates Ltd (2016) for example, lists each inflow component whereas the GWAM lumps components into Q^{GW}_{in} or Q^{GWLeak}_{in}. Budget equations in the GWAM spreadsheet also needed to be adjusted to utilize the Golder Associates Ltd (2016) data. Inflow and outflow data from Golder Associates Ltd (2016) was also aggregated and separated in some cases into lumped parameters. The GWAM was originally set up to calculate the recharge (***R***) quantity as a residual, based on entering the other parameters. The Golder Associates Ltd (2016) water budget was set up to calculate monthly changes in groundwater storage (ΔS^{GW}) quantities as a residual. Data from Golder Associates Ltd (2016) was first utilized in the GWAM to calculate values of ΔS^{GW} using Equation 19. ***R*** was determined from Equation 18 where $R = Q^{GWLeak}_{in}$, based on the data from Golder Associates Ltd (2016).

The calculated ΔS^{GW} quantities from Golder Associates Ltd (2016) for the average 1945-2012 period closely match the (2.5 m) range of water level fluctuations that have been historically recorded in Observation Well 415 completed in the aquifer (Figure 25). The results of the GWAM analysis for recharge (***R***), groundwater availability (Q_{AVAIL}), allocation quantity (Q_{ALLOC}), ($Q^{GWpump}_{out}/Q_{AVAIL}$), and ($Q^{GWpump}_{out}/R$) all appear to be reasonable values based on the estimates of current groundwater use and historic observation well trends which suggest the aquifer is not being adversely stressed at current pumping rates. 2017 and 2018 water level data (Figure 25), however, indicates levels near historic minimum levels. Further investigations of this recent trend would be warranted.

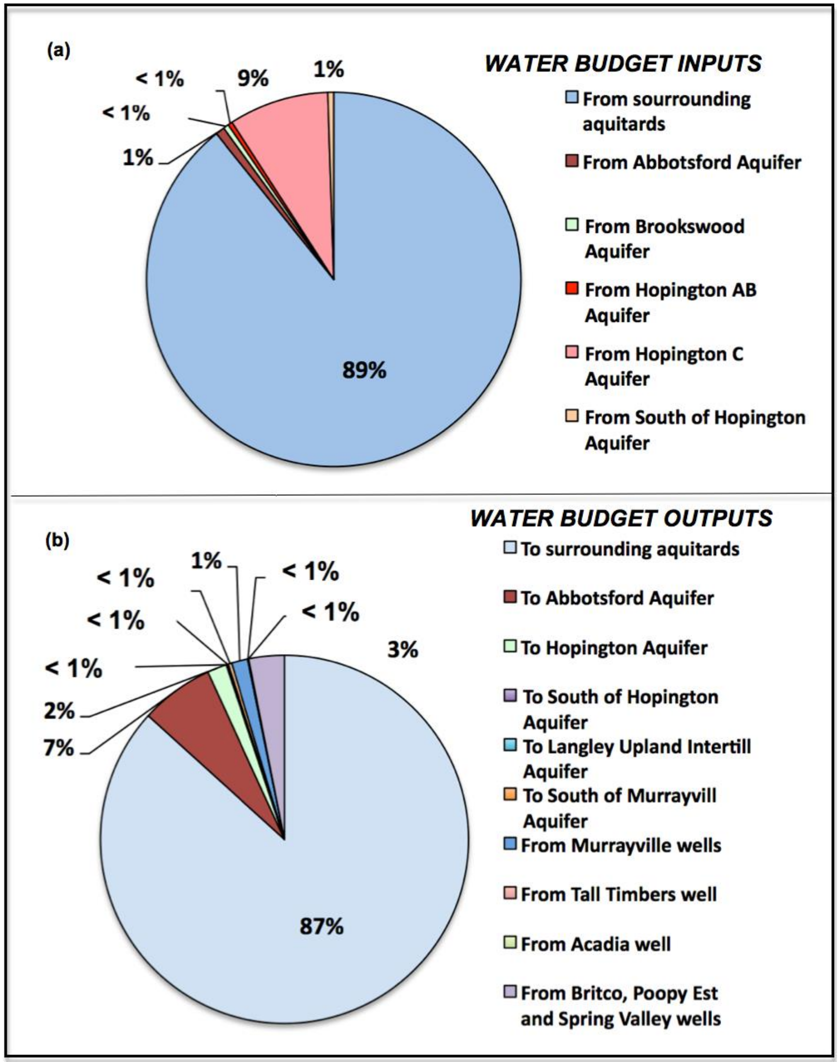


Figure 23: Percentages of each water budget component for the West of Aldergrove Aquifer. Data from Golder Associates Ltd (2016).

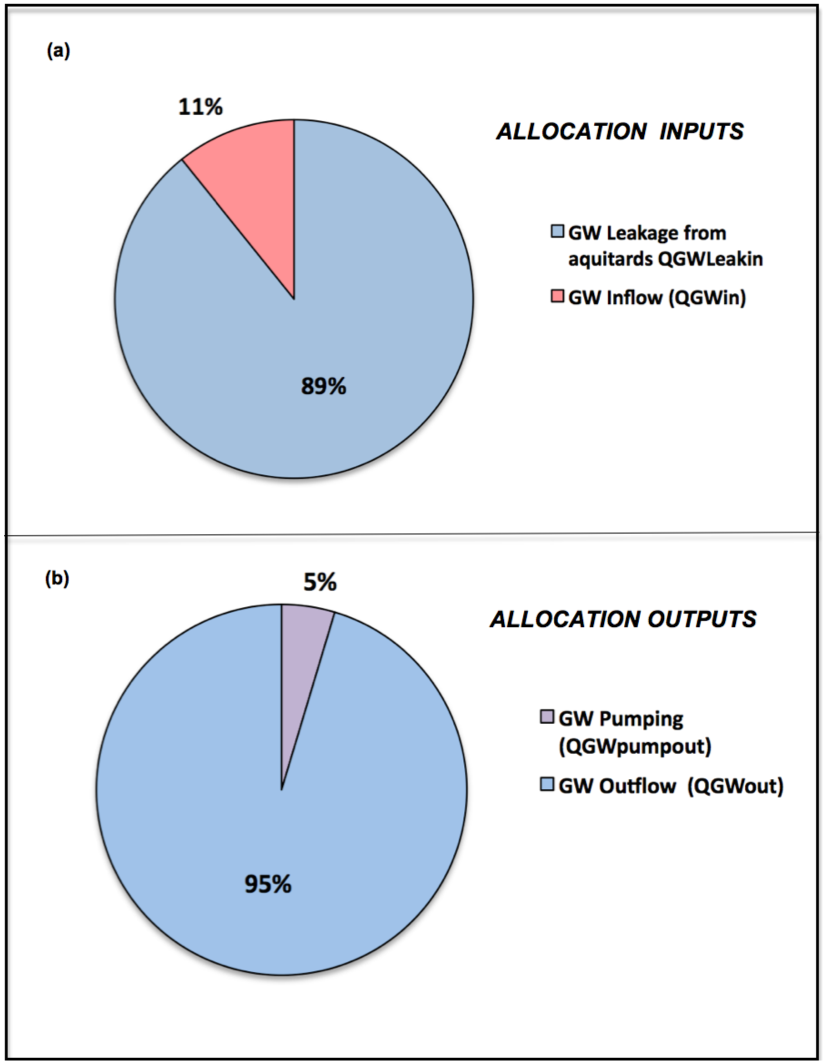


Figure 24: Percentages of each water budget component for the West of Aldergrove Aquifer from the GWAM spreadsheet.

Table 10: Results of sensitivity analysis of various parameters for the West of Aldergrove Aquifer. All values in m³ except for %.

Parameter	**Modified by %**	**Initial Value ΔS^{GW}**	**Changed Value ΔS^{GW}**	**Net Change %**	**Initial Value R**	**Changed Value R**	**Net Change %**	**Initial Value Q_{AVAIL}**	**Changed Value Q_{AVAIL}**	**Net Change %**	**Initial Value Q_{ALLOC}**	**Changed Value Q_{ALLOC}**	**Net Change %**
Q^{GW}_{in}	10	-370	-370	0	28395905	28309821	-0.3	26919110	26833026	-0.3	5599175	5581269	-0.3
Q^{GWleak}_{in}	5	-370	1419425	383728	28395905	29815700	5.0	26919110	28338905	5.3	5599175	5894492	5.3
Q^{GWpump}_{out}	20	-370	-370	0	28395905	28948425	1.9	26919110	27176272	1.0	5599175	5652665	1.0
Q^{GW}_{out}	10	-370	-370	0	28395905	31688261	11.6	26919110	30211466	12.2	5599175	6283985	12.2

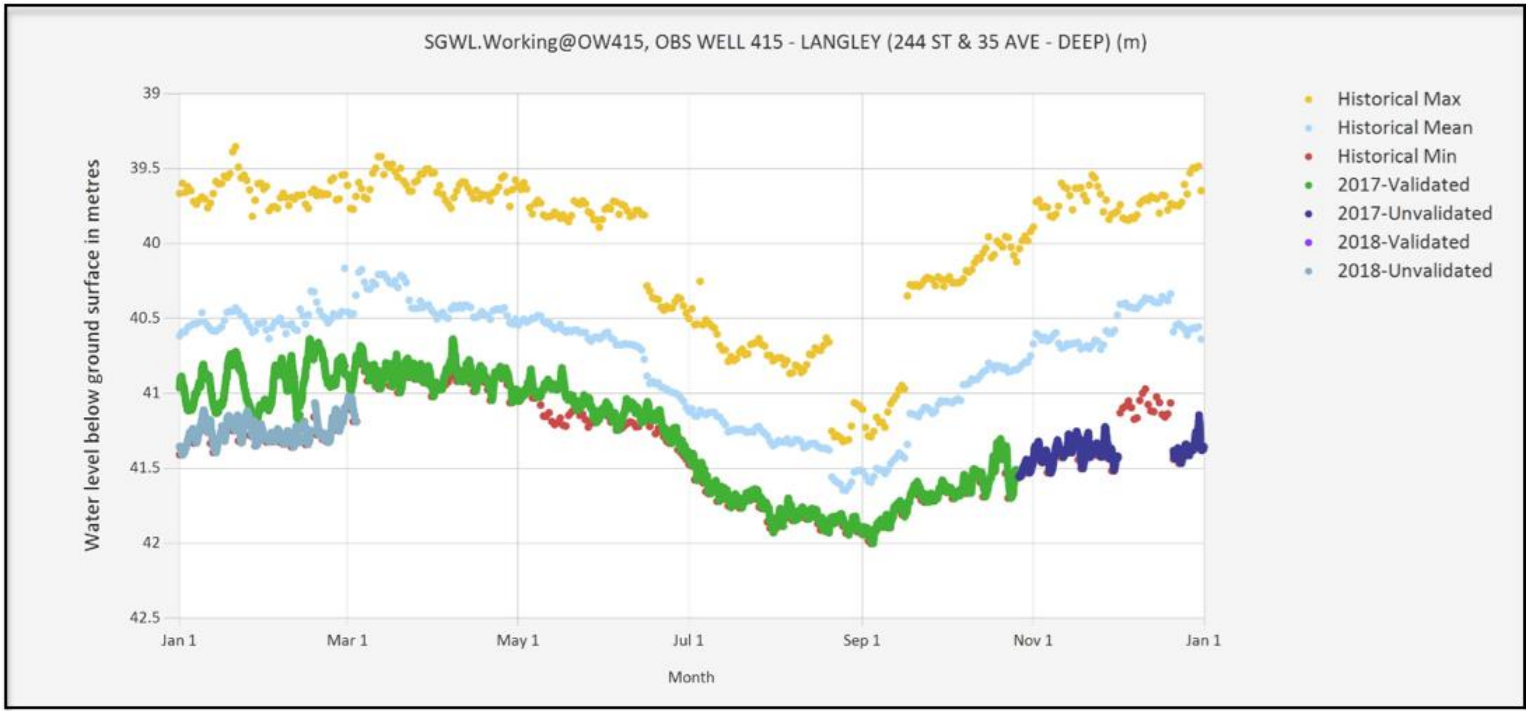


Figure 25: Current and historic water level fluctuation in Observation Well 415. From Government of British Columbia (2018g).

Groundwater leakage from surrounding aquitards is the largest inflow component while groundwater outflow to other aquifers and aquitards is the largest outflow component. In cases where a numerical model is not employed estimates of these components could be made, for example, using Darcy's Law and assuming a range of hydraulic conductivity values for the aquitard layers. Sensitivity analysis (Table 10) indicates that variations in leakage from aquitards (Q^{GWLeak}_{in}) and outflow (Q^{GW}_{out}) have the largest effect on the water budget. A 5% increase in (Q^{GWLeak}_{in}), for example, results in a 5% increase in recharge (R), and 5.3% increases in Q_{AVAIL} and Q_{ALLOC}. A 20% increase in groundwater pumping (Q^{GWpump}_{out}), for example, results in a 1.9 % increase in recharge (R) and 1% increases in Q_{AVAIL} and Q_{ALLOC} if ΔS^{GW} is held constant. A 10% increase in outflow (Q^{GW}_{out}) results in a 11.6% increase in recharge (R), and 12.2% increases in Q_{AVAIL} and Q_{ALLOC} , if ΔS^{GW} is held constant. It is apparent that variations in leakage from aquitards (Q^{GWLeak}_{in}) and outflow (Q^{GW}_{out}) examined individually have a profound effect on groundwater storage (ΔS^{GW}). In reality these two components for a confined aquifer are likely inter-dependent and maintain a relatively constant ratio. Golder Associates Ltd (2016) report that prolonged periods of drier than average conditions could result in reductions in inflows from aquitards in response to reduction in recharge to overlying units.

Based on the current water budget estimates groundwater pumping from the West of Aldergrove aquifer appears to be a relatively low percentage of the potential availability (Q_{AVAIL}) and allocation quantities (Q_{ALLOC}).

While the GWAM suggests that further allocation could be increased substantially above current pumping rates, significant errors (in the range of 30 to 50%) are inherent in the estimates for both groundwater inflow and outflow. Confined aquifer systems, with low storativity values can also be especially sensitive to increased changes in pumping rates that could lead to well interference issues as drawdown cones can spread more quickly and more widely than in unconfined systems. Recent 2017/18 observation well data indicates levels at or near historical minimums. Future groundwater allocations for large capacity (> 50 IGPM) wells should be based on long duration (minimum 24 hour) pumping tests including monitoring of neighbouring wells. Continued monitoring of the aquifer with a number of additional strategically placed observation wells would be warranted.

Conclusions (West of Aldergrove Aquifer)

In applying the GWAM to the available water budget information from Golder Associates Ltd (2016) the following conclusions are made:

1. Entering the water budget data from Golder Associates Ltd (2016) into the GWAM spreadsheet required a review, interpretation and clarification of each budget component and reconciliation of differences in component terminology. Golder Associates (2016) for example, lists each inflow component whereas the GWAM lumps components into Q^{GW}_{in} or Q^{GWLeak}_{in}. Inflow and outflow data from Golder Associates Ltd (2016) was also aggregated and separated in some cases into lumped parameters. Budget equations in the GWAM spreadsheet also needed to be adjusted to utilize the Golder Associates Ltd (2016) data.
2. The GWAM spreadsheet was originally set up to calculate the recharge (R) quantity as a residual, based on entering the other parameters. The Golder Associates Ltd (2016) water budget was set up to calculate monthly changes in groundwater storage (ΔS^{GW}) quantities as a residual. A similar annual ΔS^{GW} value of -365 m^3 was calculated for both spreadsheets.
3. Estimates for the leakage rate through aquitards (Q^{GWLeak}_{in}) and groundwater outflow (Q^{GW}_{out}) have the largest effect on the estimates for groundwater availability Q_{AVAIL} and future allocation amounts Q_{ALLOC} (Table 10). For example, a 5% increase in Q^{GWLeak}_{in} results in 5.3% increases in Q_{AVAIL} and Q_{ALLOC}, and a 10% increase in (Q^{GW}_{out}) results in 12.2% decreases in estimates for Q_{AVAIL} and Q_{ALLOC}. The aquitard leakage rate and groundwater outflow are the most important

parameters in developing groundwater availability estimates for confined aquifer systems. However, these parameters cannot be measured directly and must generally be inferred through calibration. The availability of representative and long-term water level monitoring data is important for groundwater allocation of confined systems.

4. Based on the GWAM analysis for average annual (1945-2012) meteorological conditions, the quantity of groundwater available Q_{AVAIL} was determined at 2.69E+07 m^3 (11,258 Igpm) with an estimated future allocation quantity Q_{ALLOC} of 5.60E+06 m^3 (2244 Igpm) utilizing a conservative confidence factor β of 20.8%. The GWAM suggests that the current annual pumping of 1.48E+06 m^3 (619 Igpm) could be increased by a factor of 4.6 times to a total annual pumping of about 6.84E+06 m^3 (2863 Igpm).
5. The results of the GWAM analysis for recharge (R), groundwater availability (Q_{AVAIL}), allocation quantity (Q_{ALLOC}) , $Q^{GWpump}_{out}/Q_{AVAIL}$, and Q^{GWpump}_{out}/R all appear to be reasonable values based on the estimates of current groundwater use and historic observation well trends which suggest the aquifer is not being adversely stressed at current pumping rates. Recent 2017/18 observation well data, however, indicates levels at or near historical minimums, the cause of which has not been investigated.
6. While the GWAM suggests that further allocation could be increased substantially above current pumping rates, significant errors (in the range of 30 to 50%) are inherent in the estimates for both groundwater inflow and outflow. Groundwater availability and allocation quantities are also based on results from a numerical model that does not consider effects of extended dry periods on recharge.
7. The GWAM proved useful for examining the water budget data for a confined unconsolidated Type 4b aquifer. The water budget and model are most sensitive to estimates of the aquitard and inter-aquifer fluxes that may be difficult to quantify in the absence of regional groundwater modeling.

Recommendations (West of Aldergrove Aquifer)

Based on the analysis conducted of the water budgets for the West of Aldergrove Aquifer, the following recommendations are suggested:

1. Given the large degree of uncertainties in estimating various components of the water budget and current data limitations, efforts to refine the estimates of groundwater use should be considered. Licensing of groundwater use and annual reporting requirements provide an opportunity to improve the water use estimates that have been made to date.
2. Investigations should be carried out to determine possible causes for the historic minimum water levels observed at Observation Well 415 during 2017/18.
3. Future groundwater allocations for large capacity (> 50 IGPM) wells should be based on long duration (minimum 24 hour) pumping tests including monitoring of neighbouring wells to assess potential interference effects.
4. Continue monitoring of the aquifer with a number of additional strategically placed observation wells would be warranted.
5. Extend the use of the numerical model to look at how additional pumping and variations in inflow and outflow components may affect the hydraulic head distribution in the aquifer. The numerical model could also be extended to investigate transient conditions in order to examine/consider more longer-term seasonal effects, such as extended droughts.

4.6 Water Budget For The Mill Bay Aquifer (Type 4a)

4.6.1 General Synopsis

In 2017, Harris and Usher, developed a series of groundwater budgets for eleven aquifers in the South Cowichan region of Vancouver Island. One of 5 overburden aquifers in the area, the Mill Bay Aquifer, Aquifer 206, is an unconsolidated, unconfined sand and gravel aquifer (Figure 26). It is classified as a confined IIA (11) aquifer under the *BC Aquifer Classification System* (Government of British Columbia, 2018f). The aquifer is relatively small (2.6 km^2) in area and can be categorized as a Type 4(a), predominantly unconfined sand and gravel aquifer of glaciofluvial origin (Wei *et al*., 2014).

Harris and Usher (2017) largely followed the general methodology outlined by the Ministry of Environment (2014) to determine the groundwater budget. Their study employed the method of MOEE (1995) wherein partitioning relationships are calculated based on recharge factors, and applied in a GIS platform discretized on a 50 m grid. Further details of their overall water budget approach are provided by Harris and Usher (2017).

4.6.2 Water Budget Recharge Equations and Components

The basic water budget recharge equations proposed for a Type 4(a), predominantly unconfined sand and gravel aquifer of glaciofluvial origin can be expressed as:

$$R = P + Q^{SW}_{in} + Q^{IRRreturn}_{in} - ET - \Delta S^{Lakes} - Q^{SW}_{out} - Q^{SWpump}_{out} \qquad \text{(Equation 20)}$$

and,

$$R + Q^{GW}_{in} = \Delta S^{GW} + Q^{GW}_{out} + Q^{GWpump}_{out} \qquad \text{(Equation 21)}$$

where:

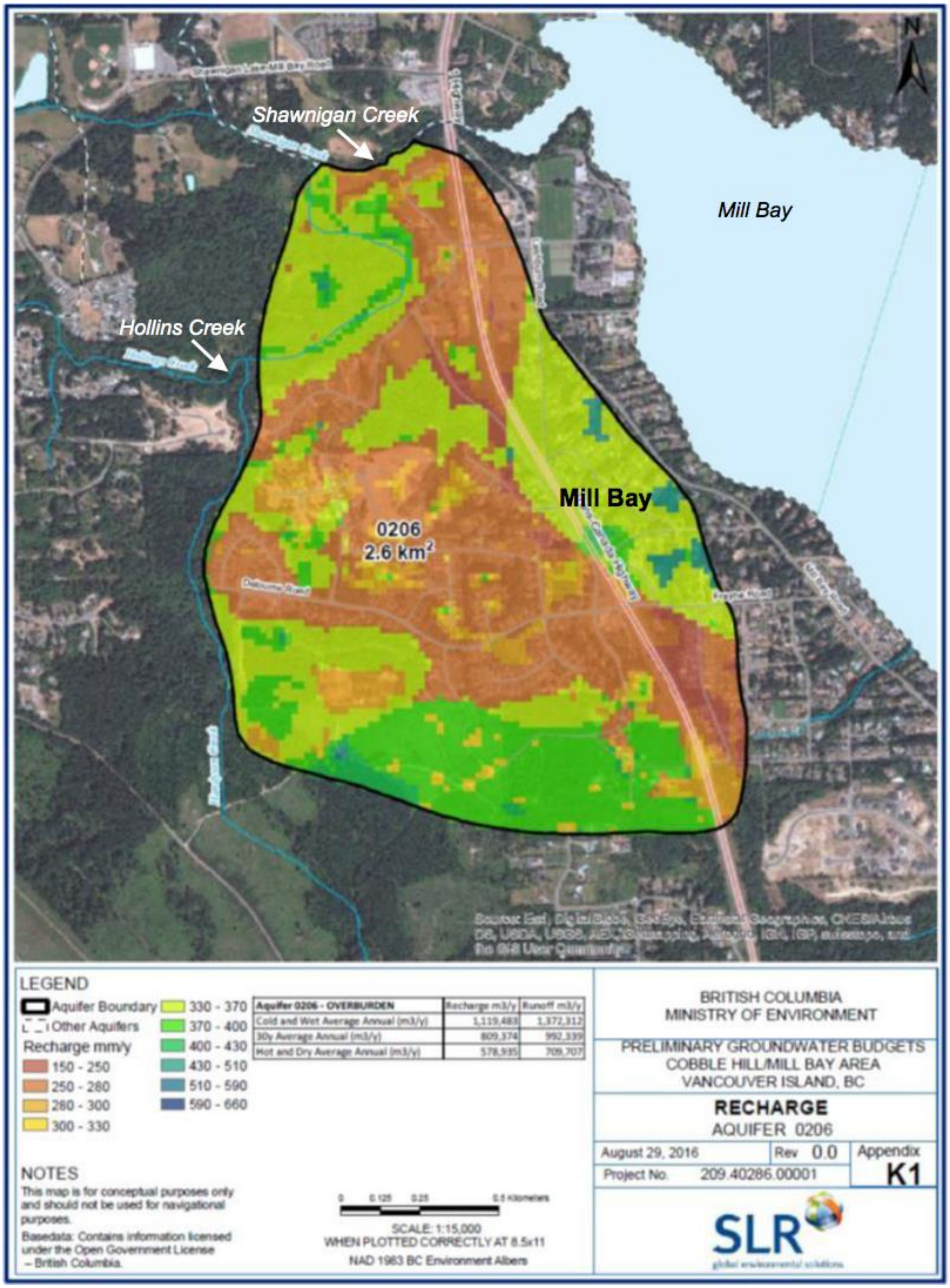
P = precipitation (rain and snow)
ET = evapotranspiration
Q^{SW}_{in} = surface water inflow
Q^{SW}_{out} = surface water outflow
Q^{GW}_{in} = groundwater inflow
R = groundwater recharge (from all sources)
ΔS^{Lakes} = change in surface water storage
ΔS^{GW} = change in groundwater storage
$Q^{IRReturn}_{in}$ = irrigation/septic return flow
Q^{GWpump}_{out} = groundwater pumping
Q^{SWpump}_{out} = surface water pumping
Q^{GW}_{out} = groundwater outflow

4.6.3 Testing the GWAM for the Mill Bay Aquifer

Harris and Usher (2017) provide an Excel® spreadsheet that contains monthly parameter input (inflow and outflow) data and results obtained for:

(a) an average year based on a 30 year (1977-2006) meteorological record;
(b) the driest 3 consecutive years (1987-1989); and
(c) the wettest 3 consecutive years (1997-1999).

The monthly results compare the sums of the water budget inflows versus the water budget outflows and whether there is a net surplus or deficit. A surplus or deficit reflects a positive or negative water level change in the aquifer, which can be compared to available observation well data.



Aquifer 0206 - OVERBURDEN	Recharge m3/y	Runoff m3/y
Cold and Wet Average Annual (m3/y)	1,119,483	1,372,312
30y Average Annual (m3/y)	809,374	992,339
Hot and Dry Average Annual (m3/y)	578,935	709,707

Figure 26: General location of the Mill Bay Aquifer 206. Adapted from Harris and Usher (2017).

The monthly inflow and outflow data for key parameters from Harris and Usher (2017) was entered into the GWAM spreadsheet workbook. A brief discussion of the data input (inflow and outflow) components utilized in the analyses are provided below. The Harris and Usher (2017) water budget has also been calibrated to historic observation well records and revised by Rathfelder (2018). Data from Rathfelder (2018) was also entered into the GWAM spreadsheet workbook for analysis.

For allocation purposes, a confidence factor β of 19.2% was estimated for Aquifer 206 using the aquifer/groundwater area confidence rating guide as shown in Appendix H, Table H4. Given that the aquifer discharges in part to Shawnigan Creek via Hollins Creek, a high EFN factor α, of 50% was assigned for the GWAM analysis. Hollins Creek is known to support salmonids during low flow periods during the summer months (Anonymous, 2000).

A discussion of the various inflow and outflow components estimated by Harris and Usher (2017) is as follows:

Recharge (R)

Harris and Usher (2017) estimated direct recharge from precipitation by:

1. Calculating water surplus available for infiltration and runoff from local long term meteorological records, on a monthly basis using the method of Thornthwaite and Mather (1957);
2. Partitioning surplus into runoff and infiltration volumes by the calculation of the infiltration factor; and
3. Extracting the recharge distribution for each aquifer area for input into the water balance.

Recharge was then determined by multiplying the infiltration factors by the surpluses on a cell-by-cell basis in the GIS platform. Other potential sources of recharge such as groundwater inflow ($\boldsymbol{Q^{GW}_{in}}$) was deemed to be zero due to the presence of only a thin saturated zone in the overburden above the bedrock near surface at the up gradient western boundary of the aquifer (Harris and Usher, 2017). Irrigation/septic return flows ($\boldsymbol{Q^{IRReturn}_{in}}$) were not estimated. The aquifer also receives inflows from Handysen Creek losses although this component was not included as part of the recharge calculations by Harris and Usher (2017).

Uncertainties in Recharge: Based on the methods utilized by Harris and Usher (2017) to determine recharge quantities, potential errors in estimating recharge appear to be within plus or minus 10%.

Groundwater Outflow (Q^{GW}_{out})

Harris and Usher (2017) report that groundwater either discharges to Shawnigan Creek via Hollins Creek or ultimately to Saanich Inlet or exits by leakage out of the aquifer to the underlying bedrock aquifer, Aquifer 207. Estimates of lateral and vertical contributions were estimated based on Darcy's Law and assigning appropriate hydraulic conductivity, gradients and seepage areas.

Uncertainties in Groundwater Outflow: Uncertainties in estimating groundwater outflow largely depend upon estimates of hydraulic conductivity and are likely within plus or minus one order of magnitude.

Surface Water Losses and Gains, Surface Water Inflow (Q^{SW}_{in}), and Surface Water Outflow (Q^{SW}_{out})

Harris and Usher (2017) report that for streams that cross over the aquifer, a review of the nearby potentiometric surface (as defined by shallow wells) with respect to the elevation of the stream was conducted to see if there were upward hydraulic gradients. This was further checked by examining provincial records through ENV staff to determine if the stream in question was cool water (implying a mix of cold and warm water) or cold water, and also to see if there were records of cold water fish in the streams. If these factors agreed and a stream was determined to have groundwater input, a simple calculation of specific flux times streambed area, described below, was undertaken to estimate groundwater discharge. As a gross approximation, losses from groundwater to the stream may be calculated as the streambed area (length x width) times the specific discharge times 10%. To approximate losses from the creek to the aquifer, Harris and Usher (2017) assumed the streambed condition will be the same as for the upward flowing streams (10% permeable coverage) and simply reversed that calculation.

For entering into the GWAM spreadsheet, the flow gain and loss data from Harris and Usher (2017) were set as the surface water inflow parameter ($\boldsymbol{Q^{SW}_{in}}$) and the surface water outflow parameter ($\boldsymbol{Q^{SW}_{out}}$) respectively. They represent surface water infiltration into the aquifer and groundwater discharge to surface water.

Uncertainties in Surface Water Inflow and Surface Water Outflow: Without seasonal streamflow data against which to calibrate the surface water inflow and outflow quantities, there is a high degree of uncertainty associated with these estimates. Errors in the range plus or minus 50% may be anticipated.

Groundwater Pumping (Q^{GWpump}_{out})

Harris and Usher (2017) used groundwater usage values reported by Hatfield (2015) and adjusted these through consultation with the Cowichan Valley Regional District and the Mill Bay Waterworks District to produce a more realistic consumptive water use impact on the groundwater. As a conservative approach, they also assumed 100% consumptive use for all water takings, including commercial and irrigation uses. For agricultural takings, Ministry of Agriculture data were used for withdrawal from groundwater for irrigation based on van der Gulik *et al*. (2013). No industrial water takings were recorded for the aquifer area. Seventy percent of the rural population relies on wells and septic beds and 30% rely on a sewer collection system, which then discharges the treated water to infiltration basins. The largest water taking is that of the Mill Bay Waterworks District well fields, where the peak year (2014) pumping data were used (Thurber, 2016).

Uncertainties in Groundwater Pumping: Harris and Usher (2017) report using an overly conservative approach to estimating groundwater use and assuming no returns from irrigation or septic disposal fields. Actual use could be 25 to 50% less than estimated. They report that over half the population is on rural septic systems, which returns the water to the ground and so are likely only 10% consumptive.

Results

Results of applying the GWAM utilizing the average year spreadsheet data from Harris and Usher (2017) are summarized in Table 11 and Table 12. Copies of the spreadsheet results are provided in Appendix I, Table I4. Table 11 summarizes the inflow and outflow components estimated by Harris and Usher (2017) and Table 12 summarizes the inputs and output components in the GWAM spreadsheet analysis. **Slightly different annual ΔS^{GW} (surplus or deficit) values of - 789,567 m^3 and - 632,390 m^3 were calculated for each spreadsheet respectfully.** The difference between the two is due to differing interpretations when monthly recharge estimates are negative values. For the GWAM spreadsheet, negative recharge values are treated as zero values (i.e. no recharge). Some number rounding differences also occur in the two spreadsheets. Figure 27 and Figure 28 show the relative percentage of each component in the Harris and Usher (2017) water budget and the percentage of each component in the GWAM water budget. Comparison of Figure 27 and Figure 28 show similar percentages for the outflow budget components and slightly different percentages for the inflow components.

Table 11: Summary of water budget estimates for the Mill Bay Aquifer from Harris and Usher (2017) for average year precipitation (1977-2006).

Water Budget Component INFLOWS	Average Year (1977-2006) m^3	Average Year (1977-2006) Igpm	Water Budget Component OUTFLOWS	Average Year (1977-2006) m^3	Average Year (1977-2006) Igpm
Direct Recharge (R)	912,946	382	Surface Water Loss (Q^{SW}_{out})	208,138	87
Surface Water Gain (Q^{SW}_{in})	226,969	95	Water Usage (Q^{GWpump}_{out})	575,588	241
			Lateral Groundwater Loss + *Leakage down to Aquifer 207* (Q^{GW}_{out})	1,145,756	480
Totals:	1,139,915	477		1,929,482	808
ΔS^{GW} =	$R + (Q^{SW}_{in}) - (Q^{SW}_{out}) - (Q^{GWpump}_{out}) - (Q^{GW}_{out})$				
ΔS^{GW} =	-789,567				

Table 12: Summary of water budget estimates based on GWAM spreadsheet for the Mill Bay Aquifer for average year precipitation (1977-2006).

Water Budget Component INFLOWS	Average Year (1977-2006) m^3	Average Year (1977-2006) Igpm	Water Budget Component OUTFLOWS	Average Year (1977-2006) m^3	Average Year (1977-2006) Igpm
Precipitation Recharge (R_P)	1,070,123	448	Surface Water Outflow (Q^{SW}_{out})	208,138	87
Surface Water Infiltration (Q^{SW}_{in})	226,969	95	Groundwater Pumping (Q^{GWpump}_{out})	575,588	241
			Groundwater outflow including *leakage down to Aquifer 2017* (Q^{GW}_{out})	1,145,756	480
Totals:	1,297,092	543		1,929,482	808
ΔS^{GW} =	$R_P + (Q^{SW}_{in}) - (Q^{SW}_{out}) - (Q^{GWpump}_{out}) - (Q^{GW}_{out})$				
ΔS^{GW} =	-632,390				

R_{TOT} = 1.30E+06 m^3 or 543 Igpm,
Q^{GWpump}_{out} = 5.76E+05 m^3 or 241 Igpm,
Q_{AVAIL} = 1.49E+05 m^3 or 62 Igpm based on EFN factor α = 50%, and
Q_{ALLOC} = 2.85E+04 m^3 or 12 Igpm based on, confidence factor β, of 19.2%.
Ratios of $Q^{GWpump}_{out} / Q_{AVAIL}$, and $Q^{GWpump}_{out} / R_{TOT}$ = 387.3 and 44.4%, respectively.

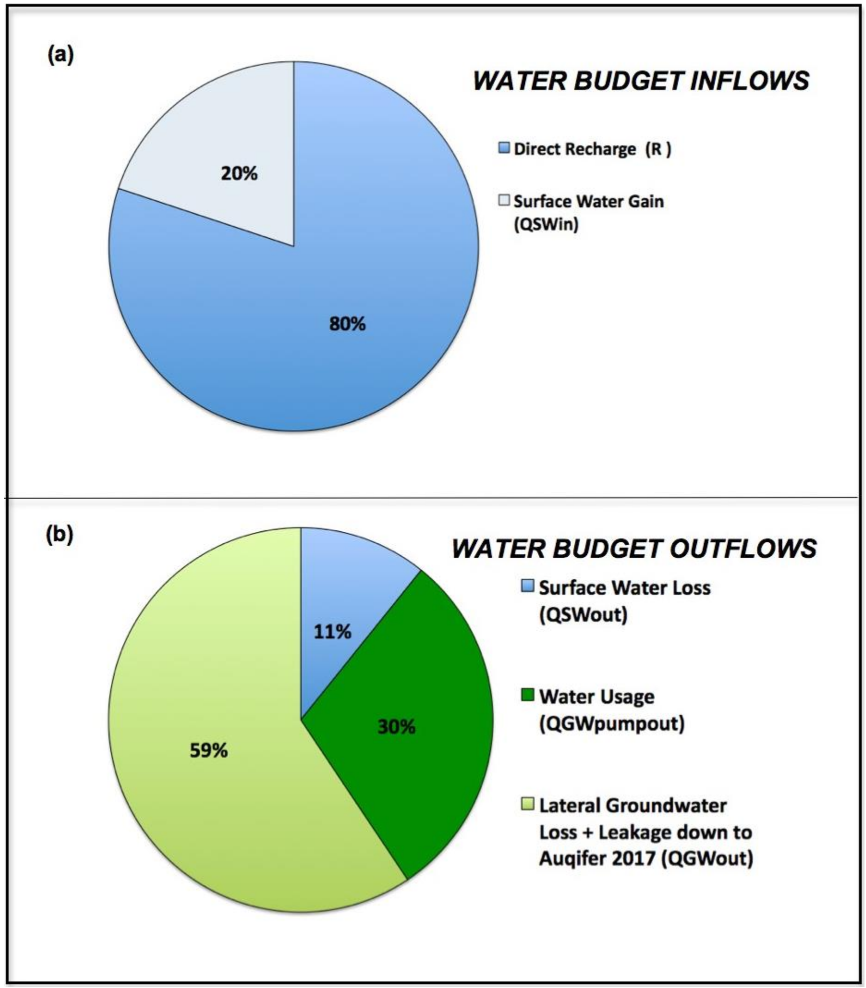


Figure 27: Percentages of each water budget component for the Mill Bay Aquifer based on data from Harris and Usher (2017) for average year precipitation.

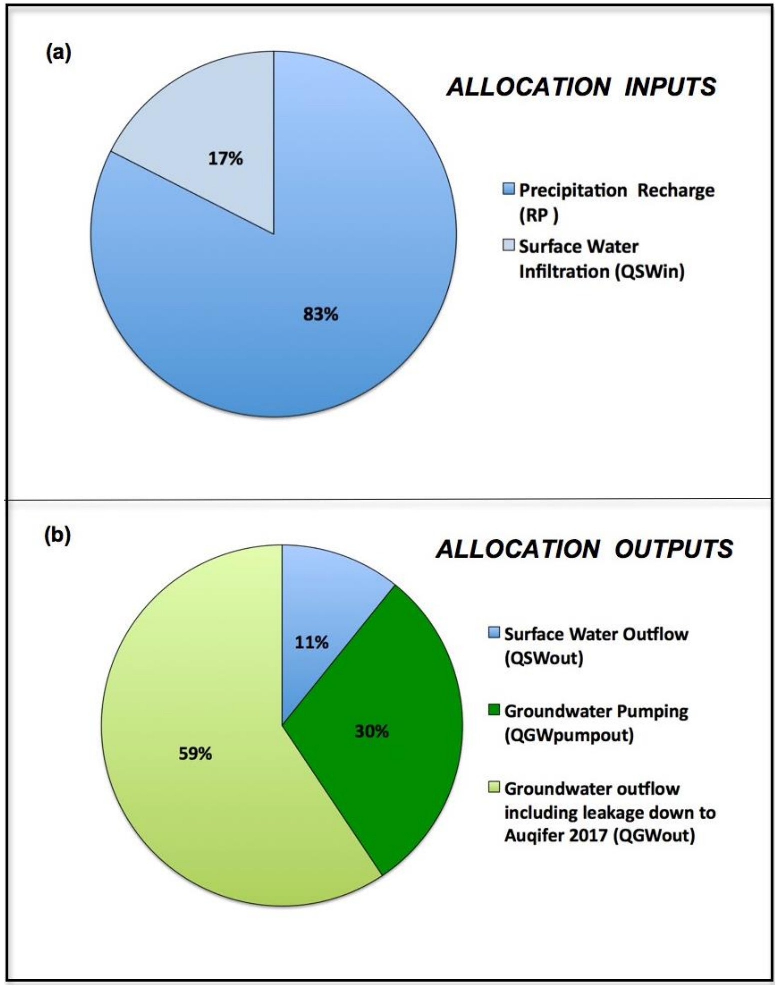


Figure 28: Percentages of each water budget component for the Mill Bay Aquifer based on the GWAM spreadsheet for average year precipitation.

Results of applying the GWAM utilizing the dry year (1999) spreadsheet data from Harris and Usher (2017) are summarized in Table 13 and Table 14. Copies of the spreadsheet results are provided in Appendix I, Table I5. Table 13 summarizes the inflow and outflow components estimated by Harris and Usher (2017) and Table 14 summarizes the inputs and output components in the GWAM spreadsheet analysis. **Slightly different annual ΔS^{GW} (surplus or deficit) values of - 1,088,635 m^3 and - 925,461 m^3 were calculated for each spreadsheet respectfully.** The difference between the two results is due to differing interpretations when monthly recharge estimates are negative values as discussed above. Some number rounding differences also occur in the two spreadsheets. Figure 29 and Figure 30 show the relative percentage of each component in the Harris and Usher (2017) water budget and the percentage of each component in the GWAM water budget. Comparison of Figure 29 and Figure 30 show similar percentages for the outflow budget components and slightly different percentages for the inflow components.

Table 13: Summary of water budget estimates for the Mill Bay Aquifer from Harris and Usher (2017) for driest period (1987-1989) precipitation.

Water Budget Component INFLOWS	**Driest Period (1987-1989) m^3**	**Driest Period (1987-1989) Igpm**	**Water Budget Component OUTFLOWS**	**Driest Period (1987-1989) m^3**	**Driest Period (1987-1989) Igpm**
Direct Recharge ($\boldsymbol{R}$)	614,176	257	Surface Water Loss ($\boldsymbol{Q^{SW}_{out}}$)	208,138	87
Surface Water Gain ($\boldsymbol{Q^{SW}_{in}}$)	226,969	95	Water Usage ($\boldsymbol{Q^{GWpump}_{out}}$)	575,588	241
			Lateral Groundwater Loss + *Leakage down to Aquifer 207* ($\boldsymbol{Q^{GW}_{out}}$)	1,146,054	480
Totals:	841,145	352		1,929,780	808
ΔS^{GW} =	$R_P + (Q^{SW}_{in}) - (Q^{SW}_{out}) - (Q^{GWpump}_{out}) - (Q^{GW}_{out})$				
ΔS^{GW} =	-1,088,635				

Table 14: Summary of water budget estimates based on GWAM spreadsheet for driest period (1987-1989) precipitation.

Water Budget Component INFLOWS	**Driest Period (1987-1989) m^3**	**Driest Period (1987-1989) Igpm**	**Water Budget Component OUTFLOWS**	**Driest Period (1987-1989) m^3**	**Driest Period (1987-1989) Igpm**
Precipitation Recharge ($\boldsymbol{R_P}$)	777,350	325	Surface Water Outflow ($\boldsymbol{Q^{SW}_{out}}$)	208,138	87
Surface Water Infiltration ($\boldsymbol{Q^{SW}_{in}}$)	226,969	95	Groundwater Pumping ($\boldsymbol{Q^{GWpump}_{out}}$)	575,588	241
			Groundwater outflow including *leakage down to Aquifer 2017* ($\boldsymbol{Q^{GW}_{out}}$)	1,146,054	480
Totals:	1,004,319	420		1,929,780	808
ΔS^{GW} =	$R_P + (Q^{SW}_{in}) - (Q^{SW}_{out}) - (Q^{GWpump}_{out}) - (Q^{GW}_{out})$				
ΔS^{GW} =	-925,461				

$\boldsymbol{R_{TOT}}$ = 1.00E+06 m^3 or 420 Igpm,
$\boldsymbol{Q^{GWpump}_{out}}$ = 5.76E+05 m^3 or 241 Igpm,
$\boldsymbol{Q_{AVAIL}}$ = -1.44E+05 m^3 based on EFN factor α = 50%, and
$\boldsymbol{Q_{ALLOC}}$ = -2.77E+04 m^3 based on, confidence factor β, of 19.2%.
Ratios of $\boldsymbol{Q^{GWpump}_{out} / Q_{AVAIL}}$, and $\boldsymbol{Q^{GWpump}_{out} / R_{TOT}}$ = -398.9 and 57.3%, respectively.

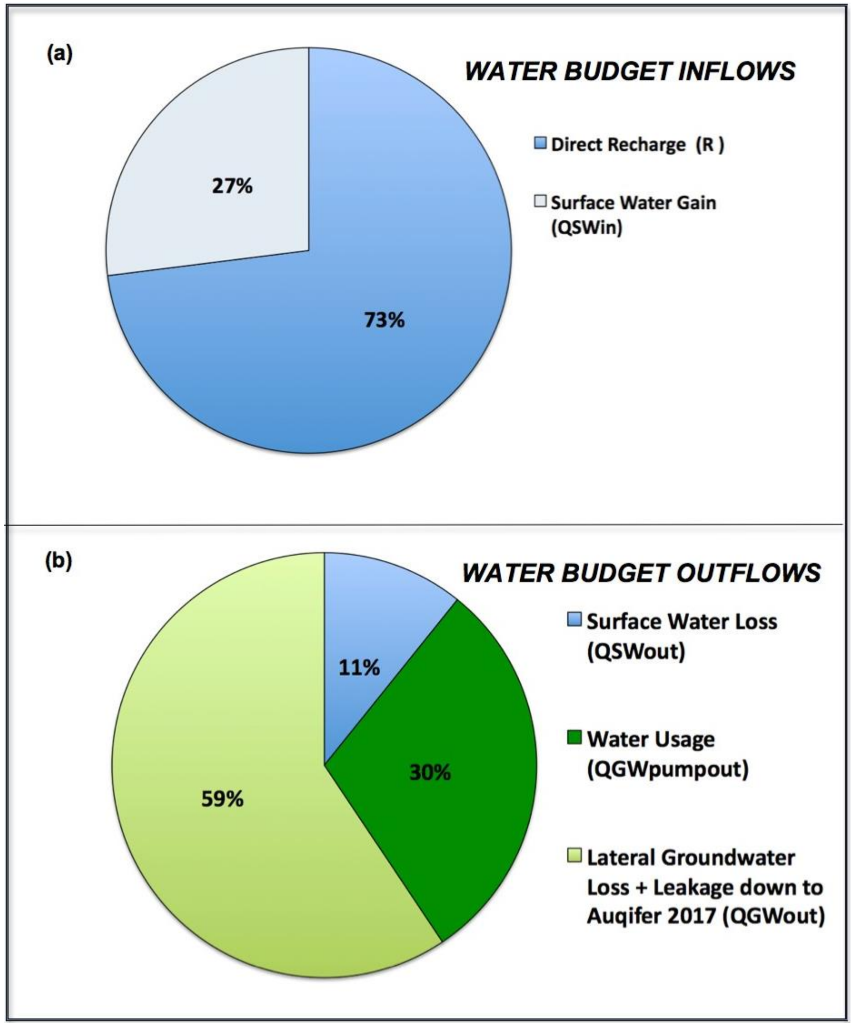


Figure 29: Percentages of each water budget component for the Mill Bay Aquifer based on data from Harris and Usher (2017) for driest period (1987-1989) precipitation.

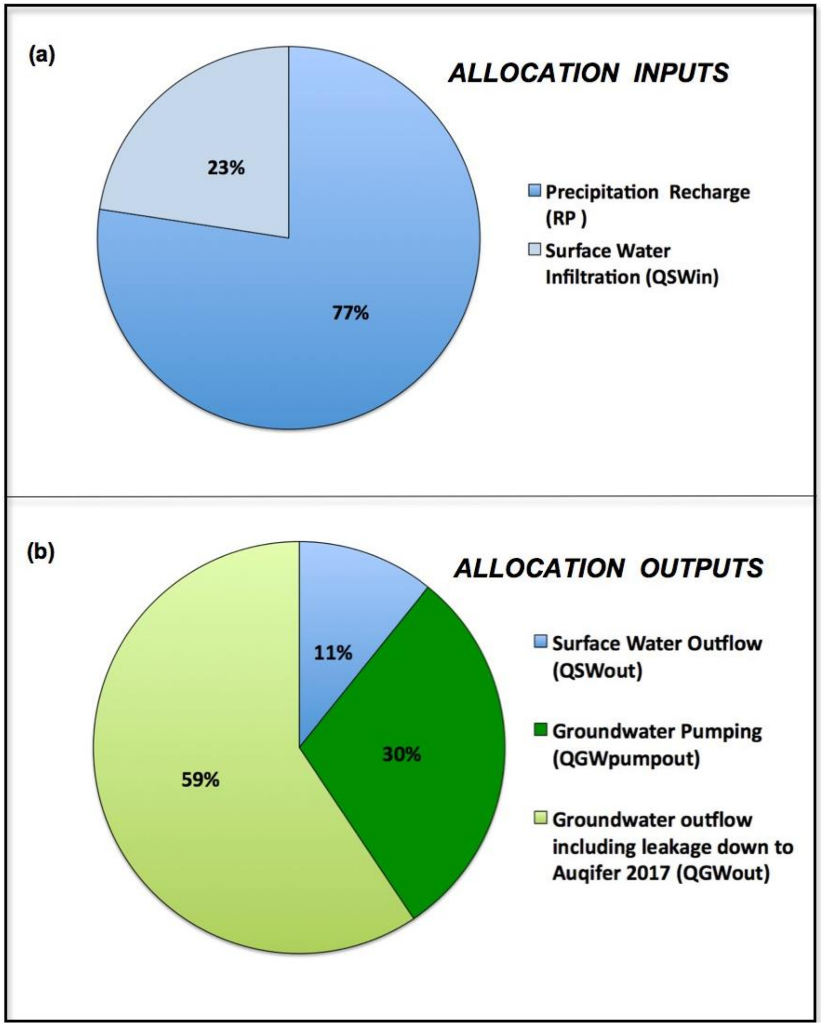


Figure 30: Percentages of each water budget component for the Mill Bay Aquifer based on the GWAM spreadsheet for the driest period (1987-1989) precipitation.

Table 15: Summary of water availability and allocation estimates for the Mill Bay Aquifer.

Water Budget	**R_P/P %**	**Q_{AVAIL} m^3**	**Q_{ALLOC} m^3**	**$Q^{GWpump}_{out}/Q_{AVAIL}$ %**	**Q^{GWpump}_{out}/R_{TOT} %**	**ΔS^{GW} m^3**	**Q^{GWpump}_{out} m^3**	**Q^{GW}_{out} m^3**	**R_{TOT} m^3**
Average Year (Harris and Usher, 2016)	28.6	-2.36E+05	-4.52E+04	-244.4	50.5	-7.90E+05	5.76E+05	1.15E+06	1.14E+06
Average Year (GWAM) spreadsheet	33.6	1.49E+05	2.85E+04	387.3	44.4	-6.32E+05	5.76E+05	1.15E+06	1.30E+06
Average Year (Rathfelder (2018) after Harris and Usher, 2016)	33.5	4.06E+05	7.80E+04	93.1	29.8	-7.79E+04	3.78E+05	9.68E+05	1.27E+06
Average Year Rathfelder (2018) and (GWAM) spreadsheet	33.5	5.63E+05	1.08E+05	67.1	26.5	7.92E+04	3.78E+05	9.68E+05	1.43E+06
Driest Period 1987-1989 (Harris and Usher, 2016)	25.1	-3.07E+05	-5.90E+04	-187.2	68.4	-1.09E+06	5.76E+05	1.15E+06	8.41E+05
Driest Period 1987-1989 (GWAM) spreadsheet	31.8	-1.44E+05	-2.77E+04	-398.9	57.3	-9.25E+05	5.76E+05	1.15E+06	1.00E+06
Driest Period 1987-1989 (Rathfelder (2018) after Harris and Usher, 2016)	25.1	1.07E+05	2.06E+04	351.7	39.0	-3.76E+05	3.78E+05	9.68E+05	9.70E+05
Driest Period 1987-1989 Rathfelder (2018) and (GWAM) spreadsheet	31.7	2.71E+05	5.19E+04	139.7	33.4	-2.13E+05	3.78E+05	9.68E+05	1.13E+06

Table 16: Results of sensitivity analysis of key water budget parameters for the Mill Bay Aquifer. All values in m^3 except for %.

Parameter	Modified by %	Initial Value ΔS^{GW}	Changed Value ΔS^{GW}	Net Change %	Initial Value R_{TOT}	Changed Value R_{TOT}	Net Change %	Initial Value Q_{AVAIL}	Changed Value Q_{AVAIL}	Net Change %	Initial Value Q_{ALLOC}	Changed Value Q_{ALLOC}	Net Change %
R_P	10	-632390	-525378	16.9	1297092	1404104	8.3	148626	255638	72.0	28536	49083	72.0
Q^{GWpump}_{out}	10	-632390	-689949	-9.1	1297092	1297092	0.0	148626	91067	-38.7	28536	17485	-38.7
Q^{GW}_{out}	10	-632390	-746966	-18.1	1297092	1297092	0.0	148626	91338	-38.5	28536	17537	-38.5
Q^{SW}_{in}	10	-632390	-609693	3.6	1297092	1319789	1.7	148626	171323	15.3	28536	32894	15.3
Q^{SW}_{out}	10	-632390	-653204	-3.3	1297092	1297092	0.0	148626	148626	0.0	28536	28536	0.0

A similar approach was used to examine the revised water budget estimates prepared by Rathfelder (2018) for the average year and driest period (1987-1989) data. Copies of the spreadsheet results for this review are provided in Appendix I, Tables I6 and I7.

Table 15 provides a summary of the water availability and allocation estimates obtained from testing the various data sets.

Sensitivity of the parameters was also tested in the GWAM spreadsheet by increasing key parameters by 10% and calculating effects on ΔS^{GW}, R_{TOT}, Q_{AVAIL} and Q_{ALLOC}. Results for this exercise are shown in Table 16 and discussed in the following section.

Discussion

Entering the water budget data from Harris and Usher (2017) into the GWAM spreadsheet required a review, interpretation and clarification of each budget component. There were, for example, some differences in component terminology that needed to be reconciled. Budget equations in the GWAM spreadsheet also needed to be adjusted to utilize the Harris and Usher (2017) data. Outflow data from Harris and Usher (2017) was also aggregated and separated in some cases into lumped parameters. The GWAM spreadsheet was originally set up to calculate the recharge (R) quantity as a residual, based on entering the other parameters. The Harris and Usher (2017) water budget was set up to calculate monthly changes in groundwater storage (ΔS^{GW}) quantities as a residual.

The calculated ΔS^{GW} quantities from Harris and Usher (2017) for the average and driest periods as shown in Table 15 are all deficit values. Calculated Q_{AVAIL} and Q_{ALLOC} values are also negative indicating that groundwater use is currently not sustainable at rates of 51% of the estimated total recharge. While indicating a slightly lower deficit in ΔS^{GW} the GWAM analysis for the average period indicates some additional groundwater, albeit a very small amount, (2.85E+04 m^3 or 12 Igpm) may be available for future allocation. This is the result of the higher recharge figures used in the GWAM analysis as discussed previously. The GWAM analysis for the driest period also indicates a deficit in ΔS^{GW} and negative values for Q_{AVAIL} and Q_{ALLOC} as would be expected.

The calculated ΔS^{GW} quantities from Harris and Usher (2017) for the average 1945-2012 period were not calibrated with any observation well data. Rathfelder (2018) was able to revise the water budget data from Harris and Usher (2017) and calibrate the monthly ΔS^{GW} quantities with historic water level fluctuations for the inactive Observation Well 350.

The water budget results produced by Rathfelder (2018) as shown in Table 15 likely provide the most reasonable estimates for future groundwater availability (Q_{AVAIL}) and allocation (Q_{ALLOC}) quantities. They indicate a surplus value for ΔS^{GW} for average conditions and a deficit ΔS^{GW} for the driest period. Based on the Rathfelder (2018) water budget estimates, some additional groundwater water allocations in the range of 5.19E+04 to 1.08E+05 m^3 (22 to 45 Igpm) may be warranted, based on the driest and average periods, respectively. The question arises, however, should further groundwater allocations be approved if ΔS^{GW} is indicating a deficit situation? Q_{AVAIL} and Q_{ALLOC} are dependent upon the total recharge (R_{TOT}), groundwater pumping (Q^{GWpump}_{out}) and groundwater outflow (Q^{GW}_{out}). From the various water budget analyses conducted, ΔS^{GW} appears related to the ratio of groundwater pumping to the total recharge ($Q^{GWpump}_{out} / R_{TOT}$) as shown in Figure 31. As groundwater pumping begins to exceed about 25% of the total recharge, ΔS^{GW} begins to shift towards deficit values. In reality it is possible that increases in groundwater pumping may be offset by decreases in groundwater outflow. Nevertheless, deficit ΔS^{GW} values suggest that a cautionary approach should be taken before allocating additional quantities of groundwater and additional investigations and monitoring undertaken to understand reasons for the estimated deficit ΔS^{GW} condition.

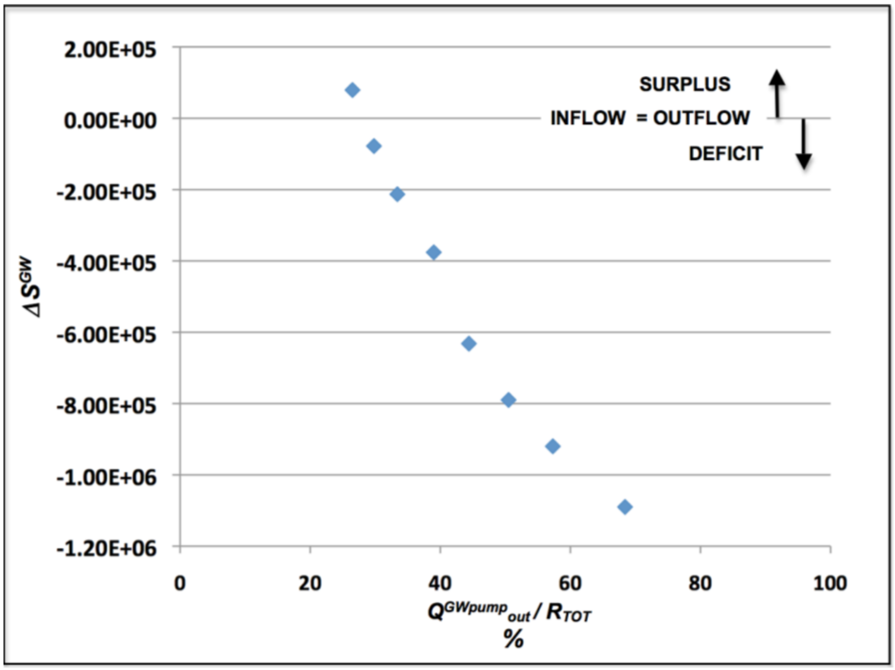


Figure 31: Relationship between ΔS^{GW} and ($Q^{GWpump}{}_{out} / R_{TOT}$) for the Mill Bay Aquifer based on various water budget analyses.

For the Mill Bay Aquifer, a relatively high EFN factor α of 50% was assigned for the GWAM analysis based on little available information. Total groundwater outflow ($Q^{GW}{}_{out}$) from the aquifer for the average period was reported by Harris and Usher (2017) at 1.15E+06 m^3 with leakage of 7.72E+05 m^3 (67%) to the underlying bedrock and a lateral groundwater flow component of 3.74E+05 m^3 (33%). Given that the majority of the estimated outflow is to the bedrock aquifer the assigned EFN factor appears conservative. Further EFN investigation of the surface sources and springs in the region down gradient of the aquifer would be needed to provide a more definitive assessment of the EFN factor.

Precipitation is the largest inflow component while groundwater pumping and outflow to other aquifers, streams and the ocean are the largest outflow components. Sensitivity analysis (Table 16) indicates that variation in precipitation recharge has the largest effect on the water budget. A 10% increase in R_P, for example, results in a 72% increase Q_{AVAIL} and Q_{ALLOC}. A 10% increase in groundwater pumping ($Q^{GWpump}{}_{out}$), for example, results in a 38.7% decrease in Q_{AVAIL} and Q_{ALLOC}. Similarly a 10% increase in ($Q^{GW}{}_{out}$) results in a 38.5% decrease in Q_{AVAIL} and Q_{ALLOC}.

Conclusions (Mill Bay Aquifer)

In applying the GWAM to the available water budget information from Harris and Usher (2017) the following conclusions are made:

1. Entering the water budget data from Harris and Usher (2017) into the GWAM spreadsheet required a review and clarification of each budget component and reconciliation of differences in component terminology. Outflow data from Harris and Usher (2017) was also aggregated and separated in some cases into lumped parameters. Budget equations in the GWAM spreadsheet also needed to be adjusted to utilize the Harris and Usher (2017) data.
2. The GWAM spreadsheet was originally set up to calculate the recharge (**R**) quantity as a residual, based on entering the other parameters. The Harris and Usher (2017) water budget was set up to calculate monthly changes in groundwater storage (ΔS^{GW}) quantities as a residual. Slightly different annual ΔS^{GW} (surplus or deficit) values were calculated for each spreadsheet.

The difference between the two is due to differing interpretations when monthly recharge estimates are negative values. For the GWAM spreadsheet, negative recharge values are treated as zero values (i.e. no recharge).

3. The calculated ΔS^{GW} quantities from Harris and Usher (2017) for the average and driest periods were all deficit values and calculated Q_{AVAIL} and Q_{ALLOC} values are also negative indicating that groundwater use is currently not sustainable at rates of 51% of the estimated total recharge.
4. The water budget results produced by Rathfelder (2018) that were calibrated with historic observation well data, likely provide more reasonable estimates for future groundwater availability (Q_{AVAIL}) and allocation (Q_{ALLOC}) quantities. They indicate a surplus value for ΔS^{GW} for average conditions and a deficit ΔS^{GW} for the driest period**.** Deficit ΔS^{GW} values suggest that a cautionary approach should be taken before allocating additional quantities of groundwater and additional investigations and monitoring undertaken to understand reasons for the estimated deficit ΔS^{GW} conditions.
5. Based on the Rathfelder (2018) water budget estimates, some additional groundwater water allocations in the range of 5.19E+04 to 1.08E+05 m^3 (22 to 45 Igpm) may be warranted based on the driest and average periods respectively.
6. Based on the GWAM analysis for driest period (1987-1989) meteorological conditions, and modifications of the water budget by Rathfelder (2018), the quantity of groundwater available Q_{AVAIL} was determined at 2.71E+05 m^3 (113 Igpm) with an estimated future allocation quantity Q_{ALLOC} of 5.19E+04 m^3 (22 Igpm) utilizing a conservative confidence factor β of 19.2%.
7. Precipitation is the largest inflow component while groundwater pumping and outflow to other aquifers, streams and the ocean are the largest outflow components. Sensitivity analysis indicates that variation in precipitation recharge has the largest effect on the water budget. A 10% increase in R_P, for example, results in a 72% increase in Q_{AVAIL} and Q_{ALLOC}. A 10% increase in groundwater pumping (Q^{GWpump}_{out}), for example, results in a 38.7% decrease in Q_{AVAIL} and Q_{ALLOC}. Similarly a 10 % increase in (Q^{GW}_{out}) results in a 38.5% decrease in Q_{AVAIL} and Q_{ALLOC}.
8. The GWAM proved useful for examining a range of water budgets for an unconfined unconsolidated Type 4a aquifer.

<u>Recommendations (Mill Bay Aquifer)</u>

Based on the analysis conducted of the water budgets for the Mill Bay Aquifer, the following recommendations are suggested:

1. Given the large degree of uncertainties in estimating various components of the water budget and current data limitations, efforts to refine the estimates of groundwater use should be considered. Licensing of groundwater use and annual reporting requirements provide an opportunity to improve the water use estimates that have been made to date.
2. Consideration should be given to re-establishing an observation well in Aquifer 206 to enable future calibration of water budget analyses conducted of the aquifer and assess whether deficit changes in groundwater storage (ΔS^{GW}) are prevalent.
3. As groundwater pumping is a significant component of the Mill Bay Aquifer and the underlying Aquifer 207, it may be beneficial to compile and analyze any available long-term pumping records for both aquifers in conjunction with available observation well data to determine any significant trends.
4. Further EFN investigations of the surface sources and springs in the region down gradient of the aquifer should be undertaken to provide a more definitive assessment of the EFN factor.

5. PART 4 – OVERALL CONCLUSIONS

5.1 Use of GWAM

Based on the results of testing the GWAM in four aquifer areas where previous water budgets have been completed, the following conclusions are made:

1. The GWAM is a useful preliminary assessment tool for compiling, interpreting and comparing the results of one or more water budgets that may have been conducted of any particular aquifer or area.
2. The GWAM proved useful for examining a range of water budgets covering a range of different aquifer types including unconfined Type 1(b) and Type 4(a) unconsolidated aquifers, a confined Type 4(b) unconsolidated aquifer and a Type 5(a) fractured bedrock aquifer.
3. The GWAM can be used as a stand-alone spreadsheet for conducting a water budget analysis of an aquifer or for incorporating data and documenting methods from previously prepared water budgets.
4. Given the variety of terms that may be assigned by investigators to various components and sub-components in any water budget analysis, the allocation methodology provides a framework for reducing terms to key water budget parameters for comparative purposes. It may be used, therefore, to compare the results of any number of water budgets prepared for an aquifer.
5. The GWAM provides conservative estimates for groundwater availability ($\boldsymbol{Q_{AVAIL}}$) above current estimated use and quantities available for future allocation ($\boldsymbol{Q_{ALLOC}}$), including consideration of EFN. In cases where water budgets indicate deficit changes in groundwater storage ($\boldsymbol{\Delta S^{GW}}$) and some future allocation is indicated, a cautionary approach should be taken before allocating additional quantities of groundwater and additional investigations and monitoring undertaken to understand reasons for the estimated deficit $\boldsymbol{\Delta S^{GW}}$ conditions.
6. As a potential allocation tool, the GWAM should be viewed as a preliminary decision support tool and not utilized in isolation. Results of using the methodology are dependent on the availability and accuracy of the data sets examined, the validity and specifications of the conceptual model of the aquifer developed and assumptions made in the water budget. A high degree of uncertainty, lack of key data and imprecise estimates are often associated with any analysis of hydrologic systems. The degree of certainty can be improved by using the GWAM to focus characterization and data collection on the most sensitive components, employing more than one methodology and comparing results for consistency.
7. Given the large degree of uncertainties in estimating various components of water budgets, efforts to refine the estimates of groundwater use should be considered before allocating any significant groundwater quantities for future us. Efforts to improve the accuracy of current groundwater use would be especially beneficial. Licensing of groundwater use and annual reporting of monthly usage would provide an opportunity to improve the water use estimates that have been made to date.
8. For aquifer areas where domestic wells are the most prevalent type of groundwater use, e.g. Gabriola Island and other Gulf Islands, it may be prudent to include an allowance for potential water use by existing well owners exercising their full rights for domestic water use in the future.
9. In evaluating the results of any water budget analysis it would be prudent to also consider any indicators or evidence of any groundwater stresses that may be occurring in the area of investigation related to: water quantity conflicts such as well interference, reported wells going dry, well deepening, declining groundwater level trends, reduced spring flows, degradation of

physical or chemical water quality including salt water intrusion, groundwater-surface water conflicts, drought impacts, low flow concerns and potential impacts on aquatic habitat and fisheries.

5.2 Estimated (Q_{AVAIL}) and (Q_{ALLOC}) for the Four Test Areas

Table 17 summarizes the estimated values of (Q_{AVAIL}) and (Q_{ALLOC}) obtained using the GWAM for the four test aquifers and limitations of the water budgets examined.

6. PART 5 – RECOMMENDATIONS FOR FUTURE INVESTIGATION

In preparing this report a number of potential avenues for future investigation were identified as follows:

1. A survey of the specific methods used by other provinces and territories in Canada to determine groundwater availability and allocation quantities has not been carried out for this project. Provincial staff should contact the various agencies responsible for groundwater allocation across the country to survey and assess their approach and experience with this activity.
2. A regional mapping program aimed at delineating groundwater discharge areas for all mapped aquifers, sensitive streams and streams with *Water Allocation Restrictions* would be of benefit to water management planning in these areas. Methods that could be used for this program are provided in Appendix B, Table B1 and may include, for example, identifying areas of flowing artesian wells, zones of spring discharges, and assessing stream temperature data.
3. Consideration should be given to developing baseflow indices (BFI) for watersheds in British Columbia where hydrometric data is available. Methods developed by Barlow *et al*. (2015) for the United State Geological Survey (USGS), for example, may be appropriate for this work.
4. Water budget analyses would benefit by utilizing interdisciplinary teams of hydrologists, hydrogeologists and biologists to plan, investigate and integrate their approaches and findings for these activities.
5. In conducting future water budget analyses it may be beneficial to develop a standard set of symbols and terminology used to identify the specific budget components and subcomponents that are normally evaluated. The symbology utilized by Healy (2010), for example, would be worth considering.

Table 17: Summary of ($\mathbf{Q_{AVAIL}}$) and ($\mathbf{Q_{ALLOC}}$) quantities obtained using the GWAM analysis for the four test aquifers.

AQUIFER TYPE	DESCRIPTION	LOCATION	AQUIFER NO.	AREA km^2	Q_{AVAIL} m^3	Q_{AVAIL} Igpm	Q_{ALLOC} m^3	Q_{ALLOC} Igpm	COMMENTS	LIMITATIONS
5(a)	fractured sedimentary bedrock	Gabriola Island	706 and 709	52.2	1.54E+06	645	2.31E+05	97	Based on recharge rate of 10% of the driest year (1985) precipitation.	Analysis did not include any estimates of ET, $Q^{IRRreturn}_{in}$, ΔS^{Lakes}, Q^{SW}_{out}, Q^{SWpump}_{out}, ΔS^{GW} or Q^{GW}_{out}. EFN not considered.
1(b)	unconfined, unconsolidated along rivers of moderate stream order	Westwold Valley	98 and 289	37	6.87E+06	2875	1.49E+06	624	Based on the GWAM analysis for a relatively normal flow year (2011).	Data currently unavailable for a low flow year. Q_{AVAIL} and Q_{ALLOC} quantities are optimistic and do not include potential GW-SW interactions.
4(b)	confined, unconsolidated	West of Aldergrove	33	73	2.69E+07	11,258	5.60E+06	2244	Based on GWAM analysis for average annual (1945-2012) meteorological conditions.	Prolonged periods of drier than average conditions could result in reductions in inflows from aquitards in response to reduction in recharge to overlying units.
4(a)	unconfined, unconsolidated	Mill Bay	206	2.6	2.71E+05	113	5.19E+04	22	Based on GWAM analysis for driest period (1987-1989) meteorological conditions, and modifications of the water budget by Rathfelder (2018).	Additional groundwater development of the aquifer appears to be very limited.

7. CLOSURE

This report was prepared in accordance with generally accepted engineering, hydrogeological and consulting practices. It is intended for the prime use of the Government of British Columbia, in connection with its purpose as outlined under the scope of work for this project. This report is based on data and information available to the author from various sources at the time of its preparation and the findings of this report may therefore be subject to revision. Data and information supplied by others has not been independently confirmed or verified to be correct or accurate in all cases. Any errors, omissions or issues requiring clarification should be brought to the attention of the author. The author and Hy-Geo Consulting accept no responsibility for damages suffered by any third party as a result of any unauthorized use of this report.

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REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., and M. Smith. 1998. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements*. FAO Irrigation and drainage paper 56. United Nations, Rome. https://www.researchgate.net/publication/235704197_Crop_evapotranspiration-Guidelines_for_computing_crop_water_requirements-FAO_Irrigation_and_drainage_paper_56 (accessed April 2018).

Alley, W.M., Reilly, T.E., and O.L. Franke. 1999. *Sustainability of Ground-Water Resources,* U.S. Geological Survey Circular 1186, 79 p.

Alley, W. M., and S. A. Leake. 2004. The Journey from Safe Yield to Sustainability, *Ground Water*, Vol. 42, No.1, January-February, 12-16.

Anonymous. 2000. *Report: Shawnigan Creek Watershed: A Fisheries Perspective*. Urban Salmon Habitat Project. http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=36840 (accessed April 2018)

Australian Government. 2012. *Methods for Estimating Groundwater Discharge to Streams – Summary of Field Trials.* Summary report prepared by Sinclair Knight Merz (SKM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Banks, W.S.L, Paylor, R.L., and W.B. Hughes. 1996. Using Thermal-infrared Imagery to Delineate Ground-water Discharge*, Ground Water,* 34: 434–443.

Barlow, P.M., Cunningham, W.L., Zhai, T., and M.Gray. 2015. U.S. Geological Survey Groundwater Toolbox, A Graphical and Mapping Interface for Analysis of Hydrologic Data (Version 1.0)—User Guide for Estimation of Base Flow, Runoff, and Groundwater Recharge from Streamflow Data. U.S. Geological Survey Techniques and Methods, book 3, chap. B10, 27 p., http://dx.doi.org/10.3133/tm3B10 (accessed April 2018)

Barron, O., and T, Van Niel. 2009. Application of Thermal Remote Sensing to Delineate Groundwater Discharge Zones, *International Journal of Water,* 5: 109–124.

Batelaan, O., De Smedt, F., and L. Triest. 2003. Regional Groundwater Discharge: Phreatophyte Mapping, Groundwater Modelling and Impact Analysis of Land-use Change, *Journal of Hydrology* 275: 86–108.

Bay of Plenty Regional Council. 2016. Assessment of Water Availability and Estimates of Current Allocation Levels October 2016. Bay of Plenty Regional Council, Whakatane, New Zealand https://www.boprc.govt.nz/media/635488/assessment-of-water-availablity-report-rev-11.pdf (accessed April 2018).

Bear, J. 1979. *Hydraulics of Groundwater*. McGraw-Hill, New York. ISBN 0-486-45355-3 (pbk.)

Bennett, K., and A. Caverly. 2009. *Review of Ground Water/Surface Water Interactions within the City of Merritt, Kamloops*: B.C. Ministry of Environment, Kamloops, British Columbia. https://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=17457 (accessed April 2018)

Bennett, K. 2012. *A Water Budget for the Westwold Valley Aquifer, West of Salmon Arm, BC.* BC Ministry of Forests and Natural Resource Operations. http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=29189 (accessed April 2018).

Bernardinucci J. and K. Ronneseth. 2002. *Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater*. BC Ministry of Water, Land and Air Protection, Water Air and Climate Change Branch, Water Protection Section, Victoria, British Columbia.

Bredehoeft, J.D., Papadopulos, S.S., and H.H. Cooper, Jr. 1982. *Groundwater: The Water-Budget Myth, in* Scientific Basis of Water-Resource Management, Studies in Geophysics, Washington, DC: National Academy Press, p. 51–57.

Brandes, O.M., Ferguson, K., M'Gonigle, M., and C. Sandborn. 2005. *At a Watershed: Ecological Governance and Sustainable Water Management in Canada*. Produced by the Polis Project on Ecological Governance for the Walter and Duncan Gordon Foundation.

Brunke, M., and T. Gonser. 1997. The Ecological Significance of Exchange Processes between Rivers and Groundwater, *Freshwater Biology,* 37: 1–33.

Brydsten, L. 2006. *Modelling Groundwater Discharge Areas Using Only Digital Elevation Models as Input Data*. Technical Report TR-06-39. Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Burgess, R., and D.M. Allen. 2016. *Groundwater Recharge Model for Gabriola Island.* Final Report submitted to Regional District of Nanaimo. Department of Earth Sciences, Simon Fraser University. [online] http://www.rdn.bc.ca/dwwpreports (accessed April 2018).

Caissie, D., and N. El-Jabi. 2003. Instream Flow Assessment: From Holistic Approaches to Habitat Modelling. *Canadian Water Resources Journal*, 28:2, 173-183, DOI: 10.4296/cwrj2802173. http://dx.doi.org/10.4296/cwrj2802173 (accessed April 2018).

Cartwright K. 1974. Tracing Shallow Groundwater Systems by Soil Temperatures. *Water Resources Research* 10: 874–855.

Committee on Hydrologic Science. 2004. *Groundwater Fluxes across Interfaces*. The Board on Water Science and Technology, Division on Earth Life Studies. National Research Council of the National Academies. The National Academies Press, Washington, D.C.

Conant B. 2004. Delineating and Quantifying Ground Water Discharge Zones Using Streambed Temperatures. *Ground Water,* 42: 243–257.

Costelloe, J.F., Peterson, T.J., Halbert, K., Western, A.W., and J.J. McDonnell. 2015. Groundwater Surface Mapping Informs Sources of Catchment Baseflow. *Hydrol. Earth Syst. Sci*,, 19, 1599-1613.

Council of Canadian Academies. 2009. *The Sustainable Management of Groundwater in Canada.* Report of the Expert Panel on Groundwater. Ottawa, Ontario. ISBN 978-1-926558-11-0.

Culbertson, C.W., Huntington, T.G., Caldwell, J.M., and C. O'Donnell. 2014. *Evaluation of Aerial Thermal Infrared Remote Sensing to Identify Groundwater-discharge Zones in the Meduxnekeag River, Houlton, Maine*. U.S. Geological Survey Open-File Report 2013–1168, 21 p. http://dx.doi.org/10.3133/ofr20131168 (accessed April 2018).

Curry R.A., and D.L.G. Noakes. 1995. Groundwater and the Selection of Spawning Sites by Brook Trout (Salvelinus fontinalis)*, Canadian Journal of Fisheries and Aquatic Sciences*, 52: 1733–1740.

Dahl, M., Harrar, W.G., Henriksen, H.J., and C, Knudby. 1999. *Regional Variations in Groundwater Discharge to Streams.* Indlæg ved DVK temamøde om 'Minimumsafstrømning i vandløb' 9-10 juni 1999 i Silkeborg. http://www.geus.dk/dvk/abs-md.pdf (accessed April 2018).

Department of Water. 2013, *Gingin Groundwater Allocation Plan. For Public Comment,* Department of Water, Government of Western Australia, Perth, Australia.

Department of Water. 2015, *Gingin Groundwater Allocation Plan Methods Report*. Department of Water, Government of Western Australia, Perth, Australia.

DHI. 2007. *MIKE SHE User Manual, Volume 2: Reference Guide*. Danish Hydraulic Institute: Denmark.

Dingman S.L. 2001. *Physical Hydrology*. 2nd ed. New Jersey: Prentice Hall.

Doe, N. 2017. Locations and Names of Wetlands and Waterways on Gabriola. File: 661 Version 24.2. November 5. http://www.nickdoe.ca/pdfs/Webp661.pdf (accessed April 2018).

Doe, N. 2018. Fish Data. Gabriola Streamkeepers (GSK). File: 678, January 12. http://www.nickdoe.ca/pdfs/Webp678.pdf (accessed April 2018).

Douglas, T. 2006. *Review of Groundwater-Salmon Interactions in British Columbia.* Report prepared for Watershed Watch Salmon Society and Walter & Duncan Gordon Foundation.

Droogers P., and R.G. Allen. 2002. Estimating Reference Evapotranspiration under Inaccurate Data Conditions. *Irrigation and Drainage Systems*, Volume 16, Issue 1, February 2002, Pages 33-45 doi:10.1023/A:1015508322413.

Environment Canterbury. 2004. Groundwater Allocation Limits: Land-based Recharge Estimates. Technical Report, Investigations and Monitoring Group, Report No. U04/97. Canterbury Council. Christchurch, New Zealand. http://www.lawa.org.nz/explore-data/canterbury-region/water-quantity/ (accessed April 2018).

ESSA Technologies Ltd. and Solander Ecological Research. 2009. Instream Flow Needs Analysis for the Okanagan Water Supply & Demand Project. Report prepared for the Okanagan Basin Water Board (OBWB), Kelowna, BC. 152 p.

Farmwest. 2018. *Evaporation*. Internet website http://www.farmwest.com/climate/et (accessed April 2018).

Fetter, C.W. 1994. *Applied Hydrogeology*. Third Edition. Prentice Hall, New Jersey.

FLNR and ENV. 2016. Environmental Flow Needs Policy. Amendment No. 2. Ministry of Forests, Lands and Natural Resource Operations, Ministry of Environment, Victoria, BC.

Foster, S.B., and D.M Allen. 2015. Groundwater-Surface Water Interactions in a Mountain-to-Coast Watershed: Effects of Climate Change and Human Stressors, *Advances in Meteorology,* Volume 2015, Article ID 861805, 22 pages http://dx.doi.org/10.1155/2015/861805.

Gleeson, T., Wada, Y., Bierkens, M.F.P., and L.P.H. van Beek. 2012. Water Balance of Global Aquifers Revealed by Groundwater Footprint, *Research Letter in Nature*, Vol. 488, August. Macmillan Publishers Ltd.

Gleeson, T., and B. Richter. 2016. How Much Water Can we Pump and Protect Environmental Flows Through Time? Presumptive standards for Conjunctive Management of Aquifers and Rivers. Manuscript for peer review, in preparation for River Research and Applications "ARENA section".

Golder Associates Ltd. 2005. *Final Report: Comprehensive Groundwater Modelling Assignment*. Prepared for the Township of Langley, 94p.

Golder Associates Ltd. 2014. *Assessment of Long-Term Groundwater Availability for Domestic and Public Use and for Aquatic Habitats*. Prepared for the Township of Langley, 90 p.

Golder Associates Ltd. 2016. *Monthly Groundwater Budget for the Hopington Aquifer – Salmon River Area, BC.* Water Science Series, WSS2016-06, Province of British Columbia, Victoria, British Columbia. https://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=50857 (accessed April 2018).

Government of British Columbia. 2018a. *Water Allocation Restrictions*, http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-licensing-rights/water-allocation-restrictions((accessed April 2018).

Government of British Columbia. 2018b. *Biogeoclimatic Ecosystem Classification Program*. Research Branch, Ministry of Forests and Range. https://www.for.gov.bc.ca/HRE/becweb/resources/maps/index.html (accessed April 2018).

Government of British Columbia. 2018c. *Biogeoclimatic Ecosystem Classification Subzone/Variant Map for the South Island Resource District*, South Coastal Region, 1:250,000 scale. Ministry of Forests, Lands and Natural Resource Operations (MFLNR), Victoria, British Columbia. ftp://ftp.for.gov.bc.ca/HRE/external/!publish/becmaps/PaperMaps/wall/DSI_SouthIslandResourceDistrict_SouthCoastRegion__wall.pdf (accessed April 2018).

Government of British Columbia. 2018d. *Biogeoclimatic Ecosystem Classification Subzone/Variant Map for the Vernon Subunit*. 1:250,000 scale. Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), Victoria, British Columbia. ftp://ftp.for.gov.bc.ca/HRE/external/!publish/becmaps/PaperMaps/field/DVE_VernonSubunit_OkanaganShuswapResourceDistrict_ThompsonOkanaganRegion__field.pdf (accessed April 2018).

Government of British Columbia. 2018e. *Biogeoclimatic Ecosystem Classification Subzone/Variant Map for the Chilliwack Resource District*. 1:250,000 scale. Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), Victoria, British Columbia. ftp://ftp.for.gov.bc.ca/HRE/external/!publish/becmaps/PaperMaps/field/DCK_ChilliwackResourceDistrict_SouthCoastRegion__field.pdf (accessed April 2018).

Government of British Columbia. 2018f. *BC Water Resources Atlas.* Online at http://maps.gov.bc.ca/ess/hm/wrbc/ (accessed April 2018).

Government of British Columbia. 2018g. *Groundwater Level Data. Interactive Map.* https://governmentofbc.maps.arcgis.com/apps/webappviewer/index.html?id=b53cb0bf3f6848e79d66ffd09b74f00d (accessed April 2018).

Government of British Columbia. 2018h. *Water Allocation Restrictions*. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/water-rights/water_allocation_restrictions_may2016.pdf (accessed April 2018).

Government of Canada. 2018a. *Canadian Climate Normals*. Online at http://climate.weather.gc.ca/climate_normals/index_e.html (accessed April 2018).

Government of Canada. 2018b. *Historic Climate Data*. http://climate.weather.gc.ca/index_e.html (accessed April 2018).

Government of Canada. 2018c. *Historical Hydrometric Data Search*. Online at https://wateroffice.ec.gc.ca/search/historical_e.html (accessed April 2018).

GW Solutions, Inc. 2017. *State of Our Aquifers.* Report prepared for the Regional District of Nanaimo, Nanaimo, British Columbia. Project 17-15. http://www.rdn.bc.ca/dwwpreports (accessed April 2018).

GW Solutions, Inc. 2012. *Lower Englishman River Watershed Groundwater Surface Water Interaction.* Report prepared for the Mid Vancouver Island Habitat Enhancement Society, Parksville, British Columbia.

Halford, K.J., and G.C. Mayer. 2000. Problems Associated with Estimating Ground Water Discharge and Recharge from Stream-Discharge Records, *Ground Water*, Vol. 38, No.3, May, 331-342.

Harris, M. and S. Usher. 2017. *Preliminary Groundwater Budgets, Cobble Hill / Mill Bay Area, Vancouver Island.* B.C. Water Science Series, WSS2017-01. Prov. of B.C., Victoria, B.C.

Hodge W.S. 1978. *A Review of Groundwater Conditions on Gabriola Island*. BC Ministry of the Environment, Water Investigations Branch, Victoria BC.

Harvey, F.E., Lee, D.R., Rudolph, D.L., and S.K. Frape. 1997. Locating Groundwater Discharge in Large Lakes Using Bottom Sediment Electrical Conductivity Mapping, *Water Resources Research*, Vol.33, No.11, Pages 2609-2615, November 1997.

Hatfield Consultants. 2015. *Development of a Framework for Licensing Existing Groundwater Users in West Coast Region, BC - Analysis of Current Groundwater Use.* Hatfield Consultants. North Vancouver, BC.

Hatfield, T., and J. Bruce. 2000. Predicting Salmonid Habitat-flow Relationships for Streams from Western North America, *North American Journal of Fisheries Management*, 20:1005-1015.

Hatfield, T., Lewis, A., Ohlson, D., and M. Bradford. 2003. *Development of Instream Flow Thresholds as Guidelines for Reviewing Proposed Water Uses*., Consultants report for British Columbia Ministry of Sustainable Resource Management and British Columbia Ministry of Water, Land and Air Protection. Victoria, BC. 88p.

Hayashi, M., and D.O. Rosenberry. 2002. Effects of Ground Water Exchange on the Hydrology and Ecology of Surface Water, *Ground Water*, Vol. 40, No.3, May-June pp. 309-316.

Healy, R.W., Winter, T.C., LaBaugh, J.W., and O. L. Franke. 2007. *Water Budgets: Foundations for Effective Water-Resources and Environmental Management.* U.S. Geological Survey Circular 1308, 90 p.

Healy, R.W. 2010. *Estimating Groundwater Recharge*. Cambridge University Press. Cambridge, United Kingdom. ISBN 978-0-521-86396-4.

Hewlett, J.D., and A.R. Hibbert. 1963. Moisture and Energy Conditions within a Sloping Soil Mass During Drainage, *Journal of Geophysical Research*, 68: 1081-1087.

Hinton. M.J. 2014. *Groundwater-Surface Water Interactions in Canada.* Chapter 5 *in* Canada's Groundwater Resources, compiled and edited by A. Rivera, Fitzhenry & Whiteside, Markham, Ontario. ISBN 978-1-55455-292-4 (HC).

Hooper, R.P., and C.A. Shoemaker. 1986. A Comparison of Chemical and Isotopic Hydrograph Separation, *Water Resources Research*, Vol.22, No. 10 pp. 1444-1454.

Ji, T. 2016. *Identification of Groundwater Discharge along the Shoreline of Large Inland Lakes in Southern Ontario*. The University of Western Ontario Graduate Program in Civil and Environmental Engineering. Thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science.

Jowett, I. G. 1997. Instream Flow Methods: A Comparison of Approaches, *Regulated Rivers: Research and Management*, 13:115-127. John Wiley & Sons, Ltd.

Kalbus, E., Reinstorf, F., and M. Schirmer. 2006. Measuring Methods for Groundwater - Surface Water Interactions: a Review*, Hydrology and Earth System Sciences Discussions, European Geosciences Union*, 2006, 10 (6), pp.873-887.

Keser, N. 1976. *Interpretation of Landforms from Aerial Photographs.* Research Branch, Ministry of Forests. Province of British Columbia. Victoria. ISBN 0-7719-8135-X.

Kilpatrick, F.A., and Cobb, E.D., 1985. *Measurement of Discharge Using Tracers*. U.S. Geological Survey Techniques of Water Resources Investigations, Book 3, chap. A16, 26 p.

King J.M., Tharme, R.E., and C.A. Brown. 1999. *Definition and Implementation of Instream Flows.* Thematic Report for the World Commission on Dams. Southern Waters Ecological Research and Consulting: Cape Town, South Africa.

King, J. M., Tharme, R.E., and M.S. de Villiers. 2008. *Manual* For *the Building Block Methodology (updated version).* Water Research Commission Report No. TT 354/08. Cape Town, South Africa.

Kohut, A. 1988. *Assessment of Groundwater at Hanceville.* Memorandum to D. Peterson, Ministry of Environment and Parks, Water Management Branch. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=6149 (accessed April 2018).

Kohut, A.P., and D. A. Johanson. 1998. *Assessment of Groundwater Availability and Quality, Galiano Island, British Columbia.* Ministry of Environment, Lands and Parks, Victoria, British Columbia. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=6457 (accessed April 2018).

Kreye, R., Wei, M., and D. Reksten. 1996. *Defining the Source Area of Water Supply Springs*. Hydrology Branch, Ministry of Environment, Lands and Parks. Victoria, British Columbia. ISBN 0-7726-2903-X. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=17862 (accessed April 2018).

Le Breton, G. 1976b. *Groundwater Return Flow from Irrigation at a Test Study Site in the Salmon River Valley, Shuswap Lake Basin*. Groundwater Section, Water Investigations Branch, Water Resources Service. Province of British Columbia.

Le Breton, G. 1976a. *Groundwater Storage and Baseflow in the Westwold - Falkland Area, Salmon River Valley, Shuswap Lake Basin*. Water Resources Service, Water Investigations Branch File: 0239014-A. Department of Environment. Victoria, British Columbia. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=6182 (accessed April 2018).

Lee, D. R. 1977. A Device for Measuring Seepage Flux in Lakes and Estuaries*, Limnology and Oceanography* 22(1): 140-147.

Lee, D. R. and J. A. Cherry. 1978. A Field Exercise on Groundwater Flow Using Seepage Meters and Mini-piezometers*, Journal of Geological Education,* 27: 6-10.

Lee, D.R., Geist, D.R., Saldi, K., Hartwig, D., and T. Cooper. 1997. *Locating Ground-water Discharge in the Hanford Reach of the Columbia River.* Report RC-M-22, PNNL-11516, Atomic Energy of Canada Ltd., Pacific Northwest National Laboratory, AECL, Chalk River, Ontario, Canada, 37 p.

Levick, L.R., Goodrich, D.C., Hernandez, M., Fonseca, J., Semmens, D.J., Stromberg, J., Tluczek, M., Leidy, R.A., Scianni, M.., Guertin, D.P., and W.G. Kepner. 2008. *The Ecological and Hydrological Significance of Ephemeral and Intermittent Streams in the Arid and Semi-arid American Southwest*. U.S. Environmental Protection Agency and USDA/ARS Southwest Watershed Research Center, Washington DC, EPA/600/R-08/134, ARS/233046.

Lewis, A., Hatfield, T., Chilibeck, B., and C. Roberts. 2004. *Assessment Methods for Aquatic Habitat and Instream Flow Characteristics in Support of Applications to Dam, Divert, or Extract Water from Streams in British Columbia.* Report prepared for Ministry of Water, Land & Air Protection and Ministry of Sustainable Resource Management.

Liebscher, H., Hii, B., and D. McNaughton. 1992. *Nitrates and Pesticides in the Abbotsford Aquifer, Southwestern British Columbia.* Environment Canada Report, Vancouver, B.C.

Lin, Yu-Feng, Wang, J., and A.J. Valocchi. 2016. *Making Groundwater Recharge and Discharge Estimate Maps in One Day*. ArcUser Online. ESRI. Online at http://www.esri.com/news/arcuser/0408/groundwater.html (accessed April 2018).

Linnansaari, T., Monk, W.A., Baird, D.J., and R.A. Curry. 2013. *Review of Approaches and Methods to Assess Environmental Flows Across Canada and Internationally*. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/039. vii + 75 p. Internet website http://www.dfo-mpo.gc.ca/library/348885.pdf (accessed April 2018).

Lowen, D. A., and D. B. Letvak. 1981. *Report on Groundwater – Surface Water Interrelationship, Lower Mission Creek, B.C.* Ministry of Environment, Province of British Columbia. Victoria. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=4415 (accessed April 2018).

McCallum. M., Andersen, M.S., Rau, G.C., Larsen, J.R., and R.I Acworth. 2014. River-aquifer Interactions in a Semiarid Environment Investigated Using Point and Reach Measurements, *Water Resour. Res*., 50, 2815–2829, doi:10.1002/2012WR012922.

Meisner, J.D., Rosenfeld, J.S., and H.A. Regier. 1985. The Role of Groundwater in the Impact of Climate Warming on Stream Salmonines, *Fisheries*, Vol. 13. No3.

Ministry of Environment. 2009. *Provincial Observation Well Network Review British Columbia.* Report prepared by Hy-Geo Consulting, Hodge Hydrogeology Consulting, Azar & Associates. Victoria, British Columbia. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=20489 (accessed April 2018).

Ministry of Environment. 2014. *Preliminary Conceptual Models and Water Budget Methodologies for Aquifers in British Columbia.* Report prepared by Hy-Geo Consulting, Victoria, British Columbia. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=42805 (accessed April 2018).

Ministry of Environment. 2015. *Development of Preliminary Water Budgets for Two Aquifer Areas in British Columbia.* Report including errata sheet prepared by Hy-Geo Consulting, Victoria, British Columbia. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=48989 (accessed April 2018).

Ministry of Environment. 2018a. *Aquifer Classification Database*. Online at https://a100.gov.bc.ca/pub/wells/public/common/aquifer_report.jsp (accessed April 2018).

Ministry of Environment. 2018b. *Provincial Groundwater Observation Well Network*. Online at http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/groundwater-wells/aquifers/groundwater-observation-well-network (accessed April 2018).

MOEE. 1995. *Hydrogeological Technical Information Requirements for Land Development Applications*. Victoria, BC: Ministry of Environment and Energy.

National Research Council. 1997. *Valuing Ground Water: Economic Concepts and Approaches*. Chapter 2: Ground Water Resources: Hydrology, Ecology, and Economics. Washington, DC: The National Academies Press, 1997. doi:10.17226/5498.

Neilson-Welch, L., and D. Allen, D. 2007. *Groundwater and Hydrogeological Conditions in the Okanagan Basin, British Columbia: A State-of-the-Basin.* Prepared for Okanagan Basin Water Board for Objective 1 of the Phase 2 Groundwater Supply and Demand Project, December 2007.

Obedkoff, W. 1976. *Salmon River Study, Low Flow Water Resource Use.* Water investigations Branch, Ministry of Environment, Victoria, British Columbia. http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=13058 (accessed April 2018).

Okanagan Basin Water Board. 2014. *Final Report, Okanagan Water Allocation Tool Plan.* Report prepared by Western Water Associates Ltd., Polar Geoscience Ltd., and Essa Technologies Ltd., Project 13-049-01

Pacific Climate Impacts Consortium. 2013. *Climate Summary for: South Coast Region.* Part of a series on the resource regions of British Columbia. University of Victoria. Victoria, British Columbia. https://www.pacificclimate.org/sites/default/files/publications/Climate_Summary-South_Coast.pdf (accessed April 2018).

Parsons, R., and J. Wentzel. 2007. *Groundwater Resource Directed Measures Manual.* Water Research Commission, South Africa. WRC Report No TT 299/07.

PEI Department of Environment, Labour & Justice. 2013. *Water Extraction Permitting Policy.* Government of Prince Edward Island.

Petts, G.E., Bickerton, M.A., Crawford, C., Lerner, D.N., and D. Evans. 1999. Flow Management to Sustain Groundwater-Dominated Stream Ecosystems, *Hydrol. Process*, 13, 497-53. John Wiley & Sons Ltd.

Poff, N.L., Allan, D.J., and M.B. Bain. 1997. *The Natural Flow Regime: A Paradigm for River Conservation and Restoration.* BioScience, 47, 769-84. http://wec.ufl.edu/floridarivers/RiverClass/Papers/Poff%20et%20al.%2097%20natflow_paradigm.pdf (accessed April 2018).

Poole, G.C., and C.H. Berman. 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation, *Environmental Management*, 27: 787-802.

Ponce, V. M., Pandey, R.P., and S. Ercan. 2000. Characterization of Drought Across Climatic Spectrum, *Journal of Hydrologic Engineering, ASCE*, Vol. 5, No. 2, April, 222-224.

Rathfelder, K.M. 2016. *Modelling Tools for Estimating Effects of Groundwater Pumping on Surface Waters.* Province of British Columbia, Ministry of Environment, Water Science Series WSS2016-09.

Rathfelder, K.M. 2018. Mill Bay Sensitivity and Water Budget. Excel® File.

Reilly, T.E., Dennehy, K.F., Alley, W.M., and W.L. Cunningham. 2008. *Ground-Water Availability in the United States.* U.S. Geological Survey Circular 1323, 70 p., http://pubs.usgs.gov/circ/1323/ (accessed April 2018).

Richards, R. P. 1987. *Cowichan River Surface/Groundwater Study.* Hydrology Section Report. Ministry of Environment, Province of British Columbia. Victoria. http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=5064 (accessed April 2018).

Rosenberry, D.O., Striegl, R.G., and D.C. Hudson. 2000. Plants as Indicators of Focused Ground Water Discharge to a Northern Minnesota Lake, *Ground Water*, 38(2): 296-303.

Rosenberry, D.O., and J.W. LaBaugh. 2008. *Field Techniques for Estimating Water Fluxes between Surface Water and Ground Water.* U.S. Geological Survey Techniques and Methods 4–D2, Reston, Virginia.

Sass, G.Z., Creed, I.F., Riddell, J., and S.E. Bayley. 2013. Regional-scale Mapping of Groundwater Discharge Zones Using Thermal Satellite Imagery, *Hydrol, Process*, John Wiley & Sons, Ltd.

Schuetz, T., and M. Weiler. 2011. Quantification of Localized Groundwater Inflow into Streams Using Ground-based Infrared Thermography, *Geophysical Research Letters*, 38: L03401. doi: 10.1029/2010GL046198.

Scibek, J. 2005. *Modelling the Impacts of Climate Change on Groundwater: A Comparative Study of Two Unconfined Aquifers in Southern British Columbia and Northern Washington State*. Master of Science thesis, Department of Earth Sciences, Simon Fraser University.

Scibek, J., Allen, D.M., Cannon, A.J., and P.H. Whitfield. 2007. Groundwater-Surface Water Interaction Under Scenarios of Climate Change Using a High-Resolution Transient Groundwater Model, *Journal of Hydrology*, 333(2-4): 165-181.

Selker, J., Selker, F., Huff, J., Short, R., Edwards, D., Nicholson, P., and A. Chin. 2014. Practical Strategies for Identifying Groundwater Discharges into Sediment and Surface Water with Fiber Optic Temperature Measurement, *Environ. Sci.: Processes Impacts*, 16, 1772.

Soulsby, C., Malcolm, I.A,, Tetzlaff, D,, and A.F. Youngson. 2009. Seasonal and Inter-annual Variability in Hyporheic Water Quality Revealed by Continuous Monitoring in a Salmon Spawning Stream, *River Research and Applications,* 25: 1304–1319.

Springer, A.E., and L.E. Stevens. 2009. Spheres of Discharge of Springs, *Hydrogeology Journal*, 17(1): 83-93. doi:10.1007/s10040-008-0341-y

SRK Consulting Inc. 2003. *Modeling Report on Potential Impacts to the Chemainus River, Vancouver Island, BC due to Pumping Wells*. Report prepared for Thurber Engineering Ltd. Project Number 1CT010.00. Vancouver, British Columbia.

SRK Consulting. 2013. Water Budget Project: RDN Phase One (Gabriola, DeCourcey & Mudge Islands-Electoral Area B). Report prepared for Regional District of Nanaimo, Nanaimo, British Columbia. http://www.rdn.bc.ca/dms/documents/dwwp-reports/gabriola-water-region/phase_1_water_budget_study_gabriola_-_2013.pdf (accessed April 2018).

Stewart, M.K. 2015. Promising New Baseflow Separation and Recession Analysis Methods Applied to Streamflow at Geldhu Catchment, New Zealand, Copernicus Publications, *Hydrol. Earth Syst. Sci*., 19, 2587–2603, 2015 www.hydrol-earth-syst-sci.net/19/2587/2015/

Stoertz, M. W., and K. R. Bradbury. 1989. Mapping Recharge Areas Using a Ground-Water Flow Model – A Case Study, *Ground Water*, Vol. 27, No.2, March-April, p. 220-228.

Tharme, R.E. 2003. A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Developments and Applications of Environmental Flow Methodologies for Rivers, *Riv. Res. Appl.*, 19: 397-441.

Thornthwaite, C. W., and J. R. Mather. 1957. *Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance*. Laboratory of Climatology, Publications in Climatology, 10(3), 185-311.

Thurber, 2016. *Mill Bay Waterworks District Operational Data for Wells 21614, 15603,1387, 786.* Thurber Engineering Ltd. File 14-73-7. Correspondence dated January 12, 2016.

Tóth, J. 1971. Groundwater discharge: A Common Generator of Diverse Geologic and Morphologic Phenomena, *International Association of Scientific Hydrology Bulletin*, 16:1, 7-24, DOI: 10.1080/02626667109493029

Vaccaro, J.J., and K.J. Maloy. 2006. *A Thermal Profile Method to Identify Potential Ground-water Discharge Areas and Preferred Salmonid Habitats for Long River Reaches*. U.S. Geological Survey Scientific Investigations Report 2006-5136, 16 p.

van der Gulik, T., Neilsen, D., Fretwell, R, and S. Tam. 2003. *Agriculture Water Demand Model.* Report for Cowichan Valley Regional District, June 2013.

van der Gun, J., and A. Lipponen. 2010. Reconciling Groundwater Storage Depletion due to Pumping with Sustainability, *Sustainability,* 2, 11: 3418-3435.

Waikato Regional Council. 2016. *Groundwater Availability, Technical Information*. Waikato Regional Council, Hamilton, New Zealand. http://www.waikatoregion.govt.nz/Environment/Natural-resources/Water/ (accessed April 2018).

Wei, M. 1988. *Trout Creek Landslide.* Memorandum to A. Kohut, Groundwater Section, Water Management Branch, Ministry of Environment and Parks. Victoria, British Columbia. File 82E/12. Available at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=4369 (accessed April 2018).

Wei, M., Allen, D.M., Kohut, A.P, Grasby, S.E., Ronneseth, K., and B. Turner. 2009. Understanding the Types of Aquifers in the Canadian Cordillera Hydrogeologic Region to Better Manage and Protect Groundwater. Streamline, Watershed Management Bulletin, Vol.13/No.1. Forrex Forum for Research and Extension in Natural Resources, British Columbia.

Wei, M., K. Ronneseth, K., Allen, D.M., Kohut, A.P., Grasby, S.E., and B. Turner. 2014. *Cordilleran Hydrogeological Region.* Chapter 9 in Canada's Groundwater Resources, compiled and edited by A. Rivera, Fitzhenry & Whiteside, Markham, Ontario. ISBN 978-1-55455-292-4 (HC).

Western Water Associates. 2014. *Final Report Okanagan Water Allocation Tool Plan.* Report prepared for Okanagan Basin Water Board by Western Water Associates Ltd., Polar Geoscience Ltd., and ESSA Technologies Ltd., Project 13-049-01.

Wilson J., and C. Rocha. 2012. Regional Scale Assessment of Submarine Groundwater Discharge in Ireland Combining Medium Resolution Satellite Imagery and Geochemical Tracing Techniques, *Remote Sensing of Environment*, 119: 21–34.

Winter, T. C., 2001. The Concept of Hydrologic Landscapes, *J. of the American Water Resources Assoc*, 37(2), pp. 335-349.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. *Ground Water and Surface Water—A Single Resource.* U.S. Geological Survey Circular 1139, 79p.

APPENDIX A. REPRESENTATIVE WATER BUDGET EQUATIONS

Table A1. Summary of representative water budget equations for various aquifer types.

TYPE	DESCRIPTION	REPRESENTATIVE WATER BUDGET EQUATIONS	COMMENTS
A.	***UNCONSOLIDATED AQUIFERS***		
1.	predominantly unconfined aquifers of fluvial or glaciofluvial origin,along river or stream valleys		
1a.	aquifers along major rivers of higher stream order	$P + Q^{SW}_{in} + Q^{GW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*P, ET and* Q^{SW} will likely be significant
1b.	aquifers along rivers of moderate stream order	$P + Q^{SW}_{in} + Q^{GW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*P, ET and* Q^{SW} will likely be significant
1c.	aquifers along lower order (< 3-4) streams	$P + Q^{SW}_{in} + Q^{GW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*P, ET and* Q^{SW} will likely be significant
2.	predominantly unconfined deltaic sand and gravel aquifers	$P + Q^{SWCreeks}_{in} + Q^{GW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	hydraulic connection with surface waters significant
3.	predominantly unconfined alluvial fan, colluvial sand and gravel aquifers.	$P + Q^{SW}_{in} + Q^{GW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	hydraulic connection with surface waters significant
4.	sand and gravel aquifers of glacial or pre-glacial origin		
4a.	predominantly unconfined sand and gravel aquifers of glaciofluvial origin	$P + Q^{SW}_{in} + Q^{GW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + \Delta S^{Lakes} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*P and ET* will likely be significant
4b.	predominantly confined sand and gravel aquifers of glacial or pre-glacial origin	$Q^{SW}_{in} + Q^{GW}_{in} + Q^{GWLeak}_{in} = R - \Delta S^{GW} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*(a) P and ET may not be significant, (b) Mountain Block Recharge* (MBR) and leakage under pumping conditions from overlying layers may be significant
4c.	predominantly confined sand and gravel aquifers associated with glaciomarine environments	$Q^{SW}_{in} + Q^{GW}_{in} + Q^{GWLeak}_{in} = R - \Delta S^{GW} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*(a) P and ET may not be significant, (b) Mountain Block Recharge* (MBR) and leakage under pumping conditions from overlying layers may be significant

Table A1 (Cont.). Summary of representative water budget equations for various aquifer types.

TYPE	DESCRIPTION	REPRESENTATIVE WATER BUDGET EQUATIONS	COMMENTS
B.	***BEDROCK AQUIFERS***		
5.	sedimentary rock aquifers		
5a.	fractured sedimentary bedrock aquifers	$P + Q^{SW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + \Delta S^{SWlakes} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*(a) P and ET* will likely be less significant and limited by aquifer storativity, (b) groundwater flow and available storage calculations should be considered
5b.	karstic limestone aquifers	$P + Q^{SW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + \Delta S^{SWlakes} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*(a) ET* may be be less significant, (b) aquifer storativity may be highly variable and high in some areas, (c) groundwater flow and available storage calculations should be considered,(d) interaction with surface water regimes likely
6.	crystalline bedrock aquifers		
6a.	flat-lying or gently-dipping volcanic flow rock aquifers	$P + Q^{SW}_{in} + Q^{GW}_{in} + Q^{IRRreturn}_{in} = R + ET - \Delta S^{GW} + \Delta S^{SWlakes} + Q^{SW}_{out} - Q^{GWpump}_{out} + Q^{SWpump}_{out} - Q^{GW}_{out}$	*(a) ET* may be less significant, (b) aquifer storativity may be highly variable and high in some areas, (c) groundwater flow and available storage calculations should be considered,(d) interaction with surface water regimes likely

APPENDIX B. ESTIMATING GROUNDWATER DISCHRAGE SUPPORTING AQUATIC HABITAT

B.1 Groundwater Flow Systems

In any region or aquifer, groundwater is always in a dynamic state moving from areas of higher energy (recharge areas) towards areas of lower potential energy (discharge areas). The resultant groundwater flow systems that develop may be relatively shallow or very deep reflecting recharge that may have occurred recently or many tens or thousands of years ago. These concepts are illustrated in Figure B1.

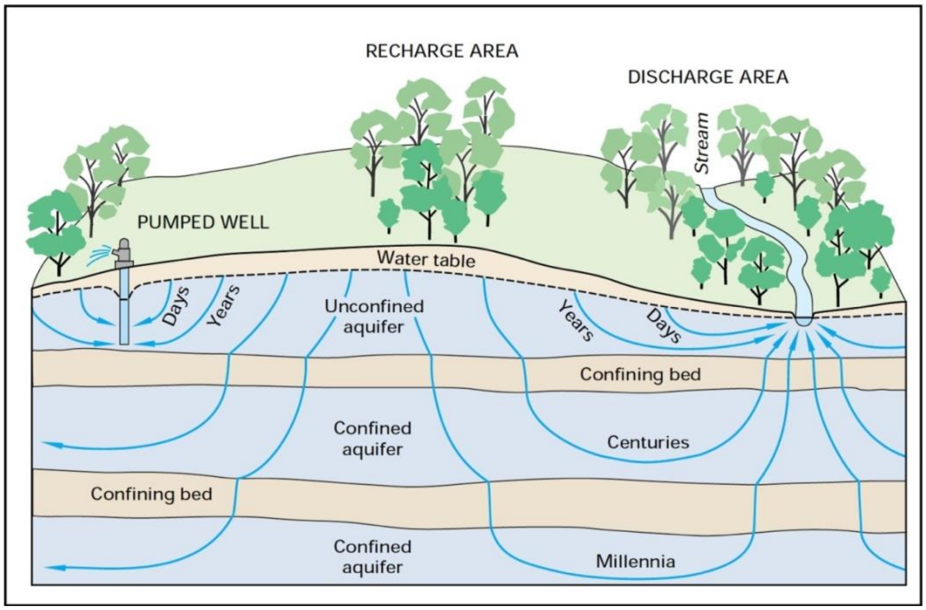


Figure B1: Schematic cross-section illustrating groundwater flow systems, recharge and discharge areas. Adapted from Winter et al., (1998).

Groundwater flow systems range from being local (10^0 to 10^2 m) to intermediate (10^2 to 10^3 m) and regional (10^3 to 10^5 m) in scale (Hayashi and Rosenberry, 2002). Local flow systems are the most dynamic being the shallowest flow systems and having the greatest potential for interchange with surface waters. In groundwater recharge areas, groundwater is moving downwards and laterally. In groundwater discharge areas, groundwater is moving upwards where it may discharge at the land surface as springs or continue to move laterally downgradient where confined by overlying units of lower permeability. Groundwater discharge areas tend to occur at lower elevations, at the bottoms of linear and circular depressions in the topography, on lower reaches of slopes and depressions, as well as near major breaks in slopes (Tóth, 1971). Evidence of discharge at the ground surface is not a prerequisite for delineating a groundwater discharge area, zone or region.

B.2 Identifying Groundwater Discharge Areas

Groundwater discharge areas may be identified, mapped, and measured using a number of different methods as outlined in Table B1. Some methods used to identify and measure groundwater discharge areas can also be used to quantify the discharge. A comprehensive discussion of each of these methods is beyond the scope of this report. Some specific methods for quantifying groundwater discharge are discussed in the following sections. Figure B2 illustrates some examples of groundwater discharges occurring in a mountainous watershed environment, including springs, lines of springs, discharge areas along a change in slope and groundwater discharge from unconfined and partially confined unconsolidated alluvial aquifers contributing to the baseflow of a high order stream.

Table B1: Methods available for identifying and measuring groundwater discharge.

General Method	Specific Methods	Principles	Example References
Mapping	spring and seepage zone locations from existing databases, aerial photography interpretation and field mapping	indicates upward moving groundwater	Tóth (1971), Kreye *et al*., (1996), Kohut and Johanson (1998), Springer and Stevens (2009), Hinton (2014)
	distribution of flowing artesian wells from existing databases and field surveys	hydraulic heads above ground level indicating upward moving groundwater	Tóth (1971), Kohut and Johanson (1998)
	distribution of wetlands from topographic maps, aerial photography interpretation and field mapping	may indicate upward moving groundwater	Tóth (1971), Keser (1976)
	distribution of saline soils from existing databases and aerial photography	evapotranspiration of discharging groundwater with elevated concentrations of dissolved minerals may indicate upward moving groundwater	Tóth (1971)
	distribution of muck and peat deposits from soil and surficial geology mapping	may indicate upward moving groundwater	Tóth (1971), Keser (1976)
	distribution of phreatophytes from existing vegetation maps, databases and field mapping	indicate zones of upward moving groundwater	Tóth (1971), Batelaan *et al*., (2003), Rosenberry et al., (2000)
	distribution of spawning beds from existing databases and field mapping	indicates zones of upward moving groundwater which moderates stream temperatures, cooler in summer and warmer in winter	Curry and Noakes (1995), Soulsby *et al*., (2009), Meisner *et al*., (1988), Douglas (2006)
	thermal satellite imagery	in shallow groundwater systems, upward fluxes of groundwater discharge reduces seasonal temperature variation in layers close to and at the surface, enables delineation of discharge zones indicating cooler temperatures in summer and warmer temperatures in winter	Sass *et al*., (2013), Barron and Van Niel (2009).
	infrared satellite thermography	enables delineation of zones indicating cooler temperatures in summer and warmer temperatures in winter	Banks *et al*., (1996), Schuetz and Weiler (2011), Culbertson *et al*., (2014).
	interferometric synthetic aperture radar (InSAR)	generates maps of surface deformation or digital elevation	Committee on Hydrologic Science, (2004)
	geological and geomorphologic contact zones from published maps, aerial photography interpretation and field surveys	groundwater discharging along contact zones reflecting changes in rock type and permeability	Kreye *et al*., (1996), Kohut (1988)

Table B1 (cont.). Methods available for identifying and measuring groundwater discharge.

General Method	Specific Methods	Principles	Example References
Mapping (cont.)	geomorphological features from published maps, aerial photography interpretation and field surveys	e.g. lower slopes of alluvial fans, distributary channel features, deltas, and estuaries indicating zones of discharging groundwater	Springer and Stevens (2009)
	distribution of karst deposits from published geological maps	karst features, sinkholes, springs	Springer and Stevens (2009), Hinton (2014)
	water table mapping, from water levels in wells	converging water table contours	Tóth (1971), Liebscher *et al*., (1992).
	numeric groundwater flow models	enables identification of recharge and discharge zones, based on water level contours and hydraulic conductivity values	Stoertz and Bradbury (1989)
	GIS applications	mapping of recharge and discharge areas	Lin *et al*., (2016)
Measurement and surveys	surface water temperature measurements, thermal profile measurements from field surveys	enables delineation of zones indicating cooler temperatures in summer and warmer temperatures in winter	Vaccaro and Maloy (2006)
	soil temperatures from field surveys	cooler temperatures in summer and warmer temperatures in winters	Cartwright (1974)
	distribution of streambed temperatures from field surveys	cooler temperatures in summer and warmer temperatures in winters	Conant (2004), McCallum *et al*., (2014)
	groundwater chemistry indicators from existing databases and field surveys	elevated levels of conductivity, total dissolved solids, chloride, iron and other major ions in water samples,	Tóth (1971), Batelaan *et al*., (2003), Soulsby *et al*., (2009).
	geochemical tracing techniques, including introducing tracers into streams	monitoring of variations in natural isotopes and other chemical , e.g. radon-222 (^{222}Rn), monitoring dilution of tracers with time	geochemical tracing techniques, including introducing tracers into streams Kilpatrick and Cobb (1985).
	low flow monitoring and hydrograph analysis based on existing databases and field surveys	indications of baseflow components of streamflow, hydrograph baseflow separation, recession analysis	Winter *et al*., (1998), Costelloe *et al*., (2015).
	stream discharge measurements	enables identification of gaining and losing reaches of streams indicative of groundwater discharge and recharge zones	Vaccaro and Maloy (2006), Lowen and Letvak (1981), Richards (1987), Poole (2001)
	stream gradients from topographic mapping	changes in slope from steep to shallow	Tóth (1971)

Table B1 (cont.). Methods available for identifying and measuring groundwater discharge.

General Method	Specific Methods	Principles	Example References
Measurement and surveys (cont.)	topography, digital elevation models (DEM) and slope analysis	groundwater discharging at toe of slopes, delineation of discharge zones based on DEM, shape of water table is a subdued replica of the land surface	Tóth (1971), Brydsten (2006)
	electrical resistivity tomography (ERT) surveys	land and water based electrical surveys to indicates groundwater- surface water interfaces and discharge zones	Ji (2016)
	lake sediment temperatures from field surveys	enables delineation of zones indicating cooler temperatures in summer and warmer temperatures in winter compared to air and surface water temperatures	Harvey *et al*., (1997)
	seepage meter monitoring and piezometer water level readings, flow net analyses	instruments used to measure shallow groundwater point discharge into surface waters, flow directions and estimate flow	Lee (1977), Lee and Cherry (1978), Fetter (1994)
	electrical conductivity profiling of streams	enables identification of groundwater discharge zones with higher electrical conductivity	Vaccaro and Maloy (2006), Lee, *et al*., (1997)
	Distributed Temperature Sensing to Identify Groundwater Discharge (DTSIS)	fiber optic temperature measurements to detect seepage at sediment interface with surface water	Selker *et al*., (2014)

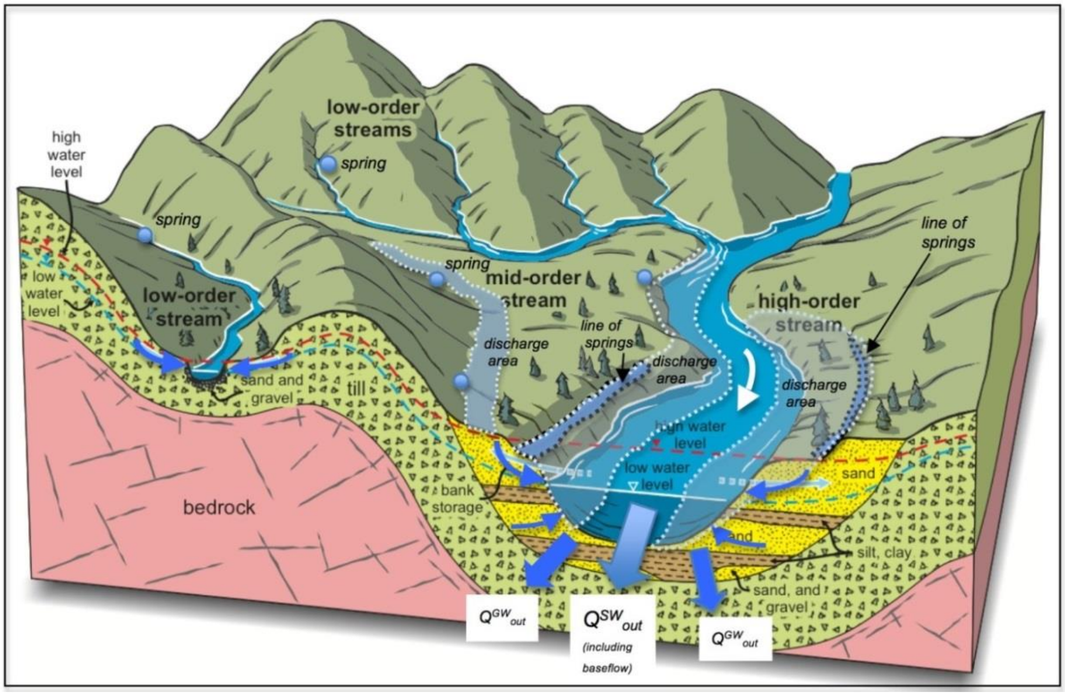


Figure B2: Schematic diagram illustrating examples of groundwater discharge occurring in a mountainous watershed environment. Figure modified after Hinton (2014).

Baseflow as described by Dingman (2001) is regarded as water that enters a stream from persistent, slowly varying sources and maintains streamflow between water-input events. It may be derived in part from groundwater discharge as well as discharge from lakes, reservoirs, wetlands, snowpack, glaciers and as suggested by Hewlett and Hibbert (1963), partially saturated soils on upland hillslopes. Gleeson and Richter (2016) in considering streamflow depletion, focus on *groundwater-derived baseflow* which they consider the most common and volumetrically significant portion of the delayed water sources in many, but not all rivers.

The baseflow index (BFI) of a river is a ratio of the mean annual baseflow in a river divided by total annual flow (mean annual runoff, or MAR). It may be used as an indicator of groundwater fed or groundwater dominated river regimes. Parsons and Wentzel (2007) suggest that low baseflow indices, for example, characteristic of ephemeral or highly seasonal streams are unlikely to be groundwater fed while perennial rivers with a moderate to high baseflow index e.g. > 0.2 may indicate a significant groundwater component. Levick *et al*., (2008) report that groundwater-surface water (GW-SW) interactions in intermittent and ephemeral drainages in arid and semi-arid regions can be very dynamic. Such drainages can support a diversity of habitat and ecological functions, even in the absence of surface flows. Pumping near these drainages can stress or kill riparian vegetation by reducing the frequency of surface flows or by lowering the water table below the root zone. This can promote invasion of non-native and more drought-tolerate species, which in turn affects wildlife habitat. While an ephemeral stream may not significantly support baseflow, it doesn't necessarily mean it is immune from pumping impacts or that it should necessarily have a lower baseflow index.

B.3 Spatial and Temporal Variations

All groundwater discharge zones are subject to spatial and temporal variations dependent upon a number of factors including: hydrologic setting, landscape heterogeneity, climatic variations, changes in hydraulic head distribution, effects of groundwater and surface water diversions, variations in surface water flows, water level fluctuations, erosion and changes in land use. Figure B3, for example, illustrates seasonal variations in flow observed for a spring discharge. Both spatial and temporal variations may be anticipated to be more pronounced and variable for local groundwater discharge conditions compared to regional discharge settings. Although differences in hydrological and geomorphic processes adjacent to low and high order streams have been recognized, little research has been done to synthesize the resulting variable nature of GW-SW interactions across scales (Hinton, 2014). In a series of papers and reports Winter *et al.,* (1998), and Winter (2001) have developed the concept of hydrologic landscapes based on the land-form, geology, and climate, which indirectly accounts for regional scale. Winter *et al.*, (1998) have characterized the general GW-SW interactions for these varying landscapes.

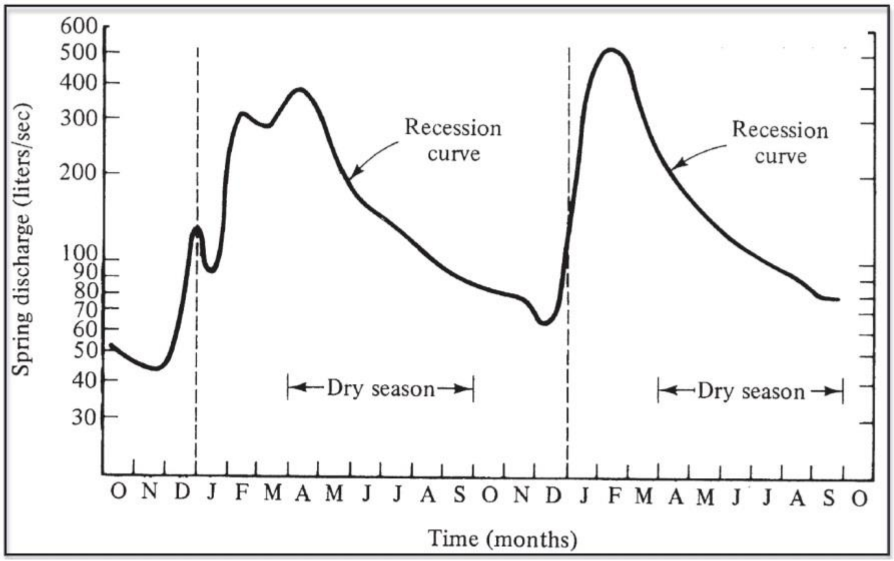


Figure B3: Seasonal variations in spring flow. Adapted from Bear (1979).

Identifying and mapping the spatial distribution of groundwater discharge areas are critical aspects for quantifying groundwater discharge of an aquifer and assessing inputs to surface waters. Measurements made at large regional scales e.g. remote sensing, often need supporting information generated at smaller scales and vice versa (Committee on Hydrologic Science, 2004).

Identifying and mapping the spatial distribution of groundwater discharge areas are critical aspects for quantifying groundwater discharge of an aquifer and assessing inputs to surface waters.

B.4 Groundwater Discharge Areas and Aquatic Habitat

Under natural conditions, groundwater may ultimately discharge into springs, wetlands, lakes, streams, major rivers and ocean waters. Figures B4 and B5 illustrate the concept of groundwater discharging to a stream where the water table is higher than the stream level. Under these conditions the stream is regarded as a gaining stream as it receives water from the groundwater regime or *phreatic zone*.

The zone where groundwater and surface water interact and mix is termed the *hyporheic zone* which is often an active region supporting aquatic life and the aquatic habitat or ecosystem (Figure B5). It should be noted that the hyporheic zone can exist not only across a stream as shown in Figure B5B but longitudinally along a reach of the stream (Figure B5A).

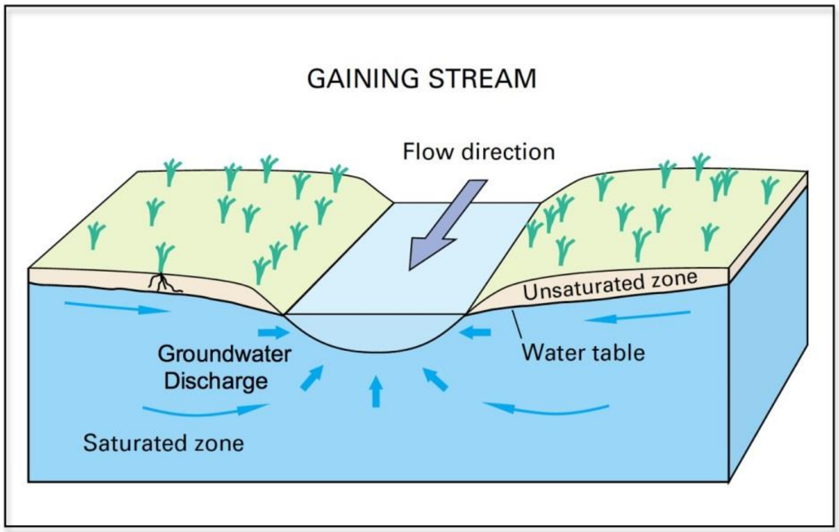


Figure B4: Concept of a gaining stream where the stream receives water from the groundwater regime through groundwater discharge. Adapted from Alley et al., (1999).

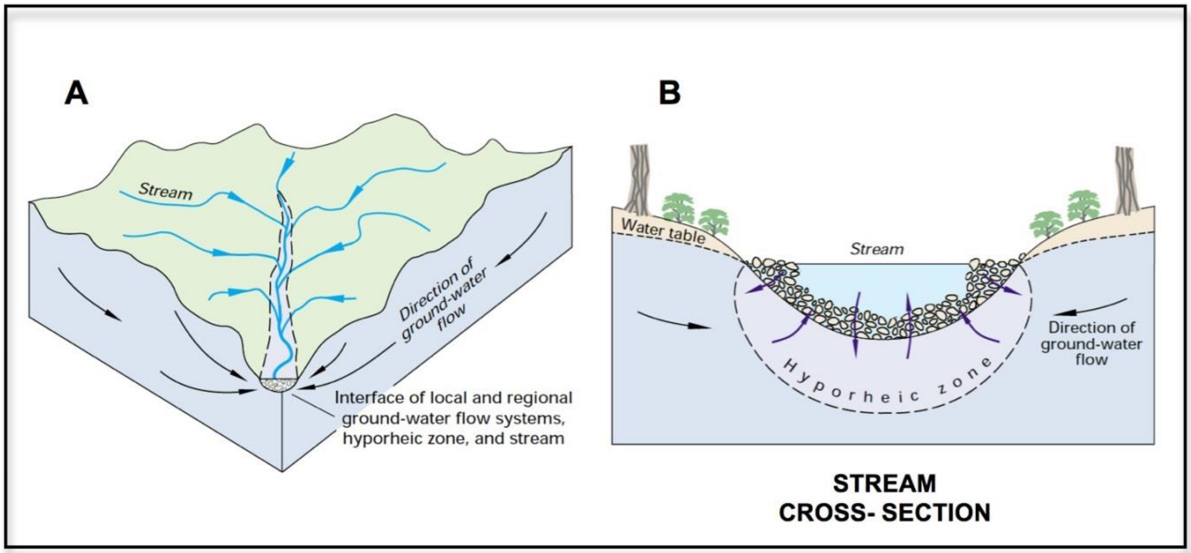


Figure B5: Concept of the hyporheic zone where groundwater and streamflow interact and mix to support aquatic habitat. From Winter et al., (1998).

Hyporheic zones contain variable proportions of groundwater and surface water where microbial activity and chemical transformation are enhanced (Alley *et al*., (1999). They are often important spawning habitats for fish where the streams bring oxygen into contact with eggs that were deposited in sediments and where stream temperatures are modulated by groundwater inflows. Figure B6 illustrates groundwater flow conditions within the hyporheic zones in two stream type examples. Brunke and Gonser (1997) provide more details on the hydrological, chemical, zoological and metabolic interactions that may occur in the hyporheic zone and indicate that they tend to vary widely in space and time as well as from system to system.

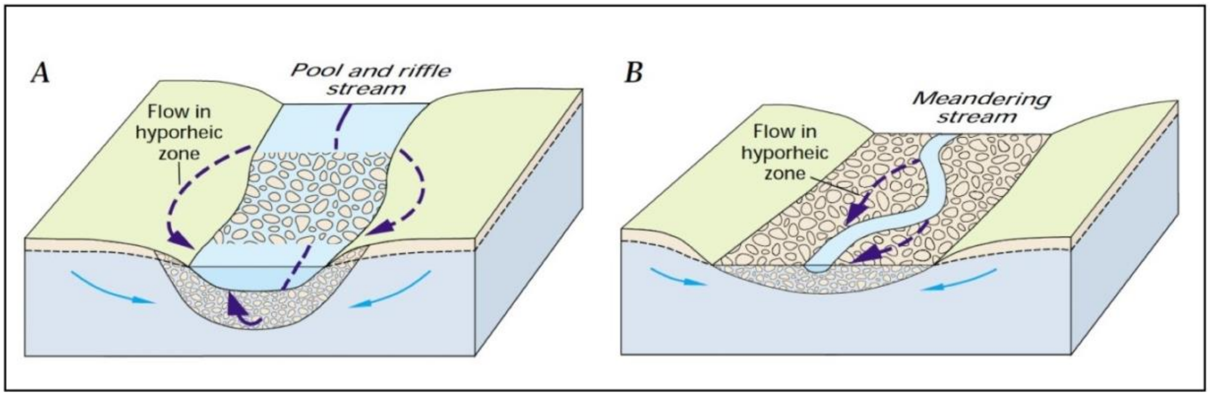


Figure B6: Examples of groundwater flow within the hyporheic zones associated with (A) abrupt changes in streambed slope, and (B) stream meanders. From Winter et al., (1998).

B.5 Aquatic Habitats

Under the *Water Sustainability Act*, *aquatic ecosystem* is defined as:

> "in relation to a stream, means the natural environment of the stream, including
> (a) the stream channel, the vegetation in the stream and the water in the stream, and
> (b) fish, wildlife and other living organisms insofar as their life processes
> i. are carried out in the stream, and
> ii. depend on the natural environment of the stream".

The *Water Sustainability Regulation* further, defines "fish habitat" as

> "means the areas of an aquatic ecosystem on which fish depend, directly or indirectly, in order to carry out their life processes, including areas for spawning grounds, nurseries, rearing, food supply and migration".

Stream under the *Water Sustainability Act*, means:

> (a) "a natural watercourse, including a natural glacier course, or a natural body of water, whether or not the stream channel of the stream has been modified, or
> (b) a natural source of water supply, including, without limitation, a lake, pond, river, creek, spring, ravine, gulch, wetland or glacier, whether or not usually containing water, including ice, but does not included an aquifer;".

It follows, therefore, that every lake, pond, river, creek, spring, wetland and glacier in British Columbia meets the definition of being an aquatic ecosystem. Apart from springs, however, not every such water body is necessarily influenced by a source of groundwater discharge throughout its length or area. Groundwater discharge areas or zones tend to be discreet, localized or focused as springs, as linear zones along valleys and stream channels, lake shores, ocean shorelines and at changes in topographic slope. Discharge zones may range in size from a few mm (the thickness of an open fracture zone or bedding plane contact) to several km in length. Areas of discharge may range from less than a square meter to several square kilometres.

For water allocation considerations in British Columbia the prime areas of groundwater discharge that would be of interest are those associated with:

(a) springs,
(b) wetlands,

(c) ponds and lakes, and
(d) creeks and rivers.

A brief discussion of the possible interactions between groundwater and these surface water sources is provided below. Groundwater discharge to marine and submarine aquatic habitats (e.g. intertidal zones, salt marshes) have not been considered in this analysis.

B.4.1 Springs

While springs originate as points of groundwater discharge they are regarded under the *Water Sustainability Act* as a surface water source where they emerge and flow at the land surface. Hence, in British Columbia they are subject to licensing and use approvals as water in a stream. Springs may occur as isolated features, as a linear feature (spring line), as part of a wetland, at the head of a creek, or within a riparian zone, floodplain or river channel. For water use purposes, smaller springs may be cased to contain or minimize their flow. Water flowing from a spring may also be termed a brook. The publication *Defining the Source Area of Water Supply Springs* presents an approach for defining the source areas of water supply springs in British Columbia (Kreye *et al.,* 1996). In a few situations in the province, water flowing from artesian wells and mine shafts has been licensed.

B.4.2 Wetlands

Wetlands include bogs, fens, marshes,swamps and shallow water distinguished by their generic origin, and properties such as vegetation, morphology, soils, water levels, hydrology, and hydrochemistry (Hinton, 2014). Wetlands are found in a wide range of hydrologic settings including groundwater discharge areas that rely upon inflow from local and regional groundwater flow systems to sustain wetland water levels (Hinton, 2014). They may receive groundwater inflow throughout their entire bed, have outflow throughout their entire bed, or have both inflow and outflow at different localities (Winter *et al.,* 1998). Wetlands may form an integral part of a creek or river regime. Wetlands, marshes, and wooded areas along streams (riparian zones) help maintain wildlife habitat and the quality of nearby surface water (Winter *et al*.,1998).

B.4.3 Ponds and Lakes

Groundwater inputs (discharge) to ponds or lake can occur directly along the shorelines or through lake sediments and indirectly as groundwater discharge to creeks or rivers flowing into lakes (Hinton, 2014). Direct groundwater discharge occurs where the adjacent water table is higher than lake level. Intensity of groundwater discharge varies in response to fluctuating groundwater, lake levels and the distribution and magnitude of hydraulic conductivity.

B.4.3 Creeks and Rivers

Groundwater interactions with creeks and rivers are most widespread and significant and usually have the largest GW-SW fluxes among all surface water bodies (Hinton, 2014). Groundwater discharge to creeks and rivers is particularly important to sustaining surface water flows during periods of dry weather and maintaining aquatic habitats. Currently 15 streams (4 rivers and 10 creeks) in the province have been designated as sensitive streams under Schedule B of the *Water Sustainability Regulation* of WSA. A sensitive stream designation protects fish populations that are at risk from damage to the stream's aquatic ecosystem. In addition many streams in the province have in place *Water Allocation Restrictions* that may range from including minimum fish flow clauses in a water licence, to suspending the issuance of any further licences on a water body (Government of British Columbia, 2018a).

Poff et al., (1997) indicate that the ecological structures and function of creeks and rivers are controlled by five critical components of the flow regime including:

- *magnitude* - the amount of water moving past a fixed location at any given time;
- *frequency* - how often a flow of a given magnitude is observed over a given time interval;
- *duration* - the period of time associated with specific flow conditions;
- *timing* - the regularity with which a given flow condition occurs (e.g. annual peak flows); and,
- *rate of change* - how quickly a flow changes from one condition to the next.

Together, these components describe the variable flow conditions for aquatic ecosystems and each of these flow conditions has a unique influence on the integrity of creek and river ecosystems and related lake, wetland and groundwater systems (Brandes et al., 2005). These same aspects can be applied to the groundwater component of baseflow.

To date, there have been relatively few detailed studies completed of GW-SW interactions in the province. In 1976, Le Breton examined groundwater storage and baseflow in the Westwold-Falkland area of the Salmon River Valley employing analytical estimates of groundwater flow using Darcy's Law. More recent studies have used water budget methods and numerical modeling techniques to address specific issues such as groundwater pumping effects and climate change.

In 2003, SRK Consulting Inc., constructed a preliminary numerical model to assess the potential impacts of proposed pumping wells on the Chemainus River in the District of North Cowichan, Vancouver Island. They found that due to the interconnectivity of the alluvial aquifer with the river that high pumping under any scenario will cause water to flow from the river to the aquifer in proportion to the pumping rate and that the potential to impact rivers flows would be greatest during the summer months.

Scibek *et al.,* (2007) used a three-dimensional transient groundwater flow model to simulate three climate time periods (1960–1999, 2010–2039, 2040–2069) for estimating future impacts of climate change on groundwater–surface water interactions and groundwater levels within the unconfined Grand Forks aquifer in south-central British Columbia. Their results indicated that future climate scenarios show a shift in river peak flow to an earlier date in a year and aquifer water levels shift by the same interval. Maximum groundwater levels associated with the peak hydrograph are very similar to present climate because the peak discharge is not predicted to change, only the timing of the peak.

In 2009, Bennett and Caverly (2009) used river temperature data to assess GW-SW interactions in the Coldwater River within the City of Merritt during summer low flow conditions. One of their conclusions was that surface water losses due to groundwater pumping of the Merritt aquifer are resulting in summer low flows that are well below short term survival levels for fish and "only maintains degraded habitat quality and quantity for salmon, trout and aquatic insects that make up their food supply".

In 2012, GW Solutions, Inc., examined GW-SW interactions in the Englishman River watershed on Vancouver Island. They concluded that interaction between the overburden aquifer and the Englishman River starts with the first occurrence of permeable granular deposits and increases along the main stem of the river as the aquifers get more numerous and thicker. In the lower section of the watershed and down to its estuary, the overburden aquifers contribute approximately 30% of the summer low flow. They also concluded that the bedrock also plays an important role in providing 30% to 40% of the summer low flow, although "it is still poorly understood and the groundwater flow in the bedrock aquifers needs to be further characterized".

In 2012, Bennett developed an empirical water budget for the Westwold aquifer to assess the feasibly of using a simplified spreadsheet water budget to quantitatively determine the primary components of groundwater recharge and discharge to an aquifer. He found that natural groundwater outflow into the Salmon River as baseflow was the largest outflow from the aquifer representing approximately 50% to 60% of the total groundwater outflow.

Foster and Allen (2015), used a coupled numerical computer model (MIKE SHE), to explore the seasonally and spatially dynamic nature of GW-SW interactions in the Cowichan Watershed on Vancouver Island, British Columbia, Canada. They found that the calibrated model simulates a transition of the Cowichan River from mostly gaining within the upper valley, to a losing stream near the coast where groundwater diversions are focused.

B.6 Quantifying Groundwater Discharge

As indicated in Table B1 there are a number of methods that, in addition to identifying zones of groundwater discharge, some can also be used to measure and quantify discharge. Rosenberry and LaBaugh (2008) provide details on field techniques for estimating water fluxes between surface water and ground water. A summary of various methods reported for estimating and quantifying discharge is provided in Table B2. Methods include: direct physical measurements of flow, chemical measurements, temperature measurements, surface water hydrograph analysis, mass balance, analytical analysis and numerical models. A discussion of each of the methods available, however, is beyond the scope of this report.

Figure B7 summarizes methods available for various aquatic habitats. Methods range from physical measurements such as flow metering, temperature and chemical monitoring chemical, river hydrograph analysis to numerical modeling. Two of the methods that have been commonly used by investigators are groundwater estimates based on Darcy’s Law and the hydrograph analysis (hydrograph separation) method. These are discussed briefly in Appendix E.

Springs, as point locations of groundwater discharge, may be ideal for direct flow measurements but may represent only a portion of the overall discharge occurring in an area. Wetlands can be complex, dynamic and difficult to measure but may represent a significant portion of the water balance in a basin (Committee on Hydrologic Science, 2004). Baseflow conditions in streams and rivers can provide a measure of basin-wide groundwater discharge, yet there is often great uncertainty in such measurements (Committee on Hydrologic Science, 2004).

Findings of the Committee on Hydrologic Science (2004) indicate that “There are no uniformly applicable methods for measuring and quantifying recharge/discharge fluxes in space and time, so our understanding of distribution and process is limited.” The literature research conducted for this project confirms these same findings. This is not surprising given the inherent hydrologic variability and uncertainties often characteristic of natural hydrologic systems. Halford and Mayer (2000) in their investigation of estimating groundwater discharge and recharge from stream-discharge records, conclude that “multiple, alternative methods of estimating ground water discharge and recharge should be used because of the uncertainty associated with any one technique.” Kalbus *et al.*, (2006) after reviewing various measuring methods for GW-SW interactions, conclude that “a multi-scale approach combining multiple techniques can considerably reduce uncertainties and constrain estimates of fluxes between groundwater and surface water.” Table B3, provides some general indicators for assessing the potential degree of GW-SW interactions for observed stream characteristics and aquifer types.

Table B2: Various methods used to quantify groundwater discharge to aquatic habitats.

General Methods	Specific Methods	Description	Instruments	Comments	Examples References
Physical Measure-ments	hydraulic gradient method	calculates groundwater inflow, based on the local aquifer properties, and the observed hydraulic gradient between a river gauging station and a nearby observation bore. useful in determining local groundwater flux conditions close to gauging stations,	flumes, gauges and flow or current meters	not necessarily representative of inflow rates over longer reaches	Australian Government (2012)
	flow difference monitoring, differential gauging or incremental streamflow monitoring	sequential river flow measurements along a river reach, spatial variations in groundwater inflow or outflow estimated from the differences between adjacent flow gaugings	flumes, gauges and flow or current meters	best applied under low flow conditions and in catchments where the difference between the downstream flow and the sum of the upstream flow and tributary flow is large relative to the downstream flow, applied at a reach scale	Australian Government (2012), McCallum et al., (2014), Kalbus et al., (2006)
	direct measurement with various instruments	flow monitoring of springs, measurement of seepage areas along shorelines of wetlands, ponds and lakes	Seepage meters, piezometers, flumes, gauges and flow or current meters	seepage meters are suited for shallow fine-grained sediments and low energy environments, results vary with fluctuating water levels, wave action, heterogeneity of sediments, usually applied at a local scale	Kalbus et al., (2006), Lee (1977), Lee and Cherry (1978).
Chemical Measure-ments	longitudinal chemistry method	measurements of river chemistry along a stream reach at a point in time.		successful in catchments using tracers with a clear distinction between groundwater and surface water concentrations, and where the groundwater end- member tracer concentrations could be accurately estimated, applied at a local scale	Australian Government (2012)
	Chemical hydrograph separation	involves monitoring changes in tracer concentrations in river flow over time to determine changes in the relative proportions of surface runoff and groundwater inflow		combination of various tracers and hydrologic data can yield the reliable results, applied at a local scale	Australian Government (2012), Kalbus et al., (2006), Hooper and Shoemaker, 1986.

Table B2 (Cont.): Various methods used to quantify groundwater discharge to aquatic habitats.

General Methods	Specific Methods	Description	Instruments	Comments	Examples References
Hydrograph Analysis	baseflow separation	method distinguishes streamflow derived from surface runoff and that derived from groundwater, based on the time-series record of streamflow		limited number of gauging stations and sufficient periods of record may be a constraint, enables calculation of discharge rates averaged over the upstream length.	Australian Government (2012), Kalbus *et al.,* (2006)
	recession analysis	recession analysis aims to model the decrease of streamflow during rainless periods to extract parameters descriptive of water storage in the catchment			Stewart, 2015.
Mass Balance	water budget analysis	can be used to quantify various parts or aspects of the hydrologic cycle including groundwater discharge		requires a good understanding of all the hydrologic components active in a particular area	
Temperature Measure-ments	monitoring river bed temperatures and stream temperatures	natural heat used a tracer, thermal front related to Darcy flux	temperature sensors installed to varying depths, or set in different arrays	robust and relatively inexpensive	McCallum et al., (2014), Kalbus et al., (2006), Conant (2004)
Numerical Models	three-dimensional transient groundwater flow models, e.g. MODFLOW, MIKE SHE and others	models simulate groundwater flow and response to changes in hydrologic inputs		models need to be calibrated to groundwater heads, transient streamflow and distributed baseflow, challenges involve delineating zones controlling interactions and the hydraulic conductivity and thickness of these zones	Dahl et al., (1999).
Analytical Analysis	Darcy's Law	used to estimate quantity of lateral groundwater discharge through an aquifer		requires information on the hydraulic gradient, hydraulic conductivity, and area through which flow takes place, usually applied at a local scale	Kalbus et al., (2006)
	flow net analysis	used to indicate groundwater flow regime of an aquifer, contours can indicate river- aquifer relationships and combined with Darcy's Law can indicate the rate of groundwater discharge		requires water level information from wells and hydraulic conductivity	Bear (2007), Liebscher et al., (1992).

Table B3: General relationships between stream characteristics and potential degree of groundwater interaction.

Stream characteristics	BFI	Stream Gradient	Adjacent	Stream Hydrograph	Width of Riparian Zones	Channel Width	Proximity of Wetlands and Springs	Thickness of Stream Bed	Nature of Stream Bed	Aquifer Types
High degree of groundwater interaction, groundwater - dominated	high, > 05. Close to 1.0 for springs	low	low	Relatively stable	wide, >10 m	wide, >10 m	significant	Significant > 10 m	sand and gravel	Unconsolidated, Types 1 and 2, and karst bedrock 5b
Moderate degree of groundwater interaction	moderate, 2 to 0.5	low to moderate	low to moderate	variable	moderate, 2 to 10 m	moderate, 2 to 10 m	occasional	Moderate 1 to 10 m	sand and gravel	Unconsolidated, Types 3 and 4a, karst bedrock 5b and 6a volcanic
Low degree of groundwater interaction	Low < 0.2	steep	high	Large fluctuations, highly variable seasonal and annual flows	narrow, <1 to 2 m	narrow, <1 to 2 m	none	thin, < 1m	sand clay and rocks	Unconsolidated, Types 4b, 4c and bedrock 5a and 6

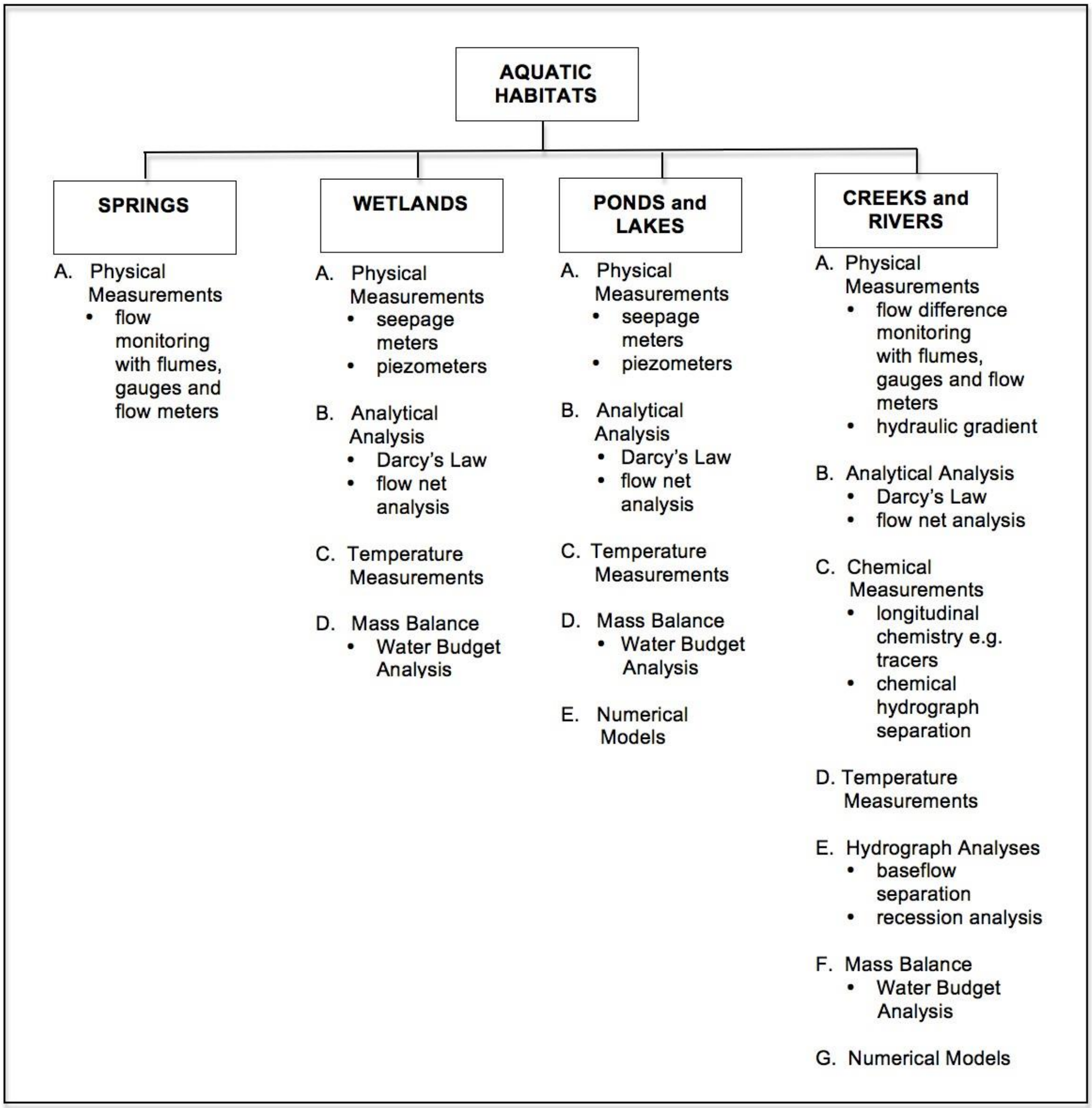


Figure B7: Summary of various methods for quantifying groundwater discharge to aquatic habitats.

In terms of proposing a specific method to estimate groundwater discharge supporting aquatic habitat, an integrated approach following the procedures outlined below is suggested.

1. identify and delineate the scale and specific aquatic habitat e.g. river reach, wetland wherein groundwater discharge needs to be evaluated and purpose of the evaluation;
2. using as many of the methods, available and feasible, identify, delineate and determine the probable origin of the discharge, map the location(s) and extent of any obvious and potential discharge zones;
3. compile and assess any available supporting topographic, hydrologic, geologic, hydrometric, fisheries data, well record and observation well data, etc., that would augment the above;
4. determine what methods and time scale may be appropriate for measuring groundwater discharge for the aquatic habitat of interest and select at least two or three methods for field measurement surveys and/or desk top analysis; and
5. analyze and evaluate the results of above investigations.

The first three steps are essentially the basis of a groundwater-surface water assessment. Western Water Associates (2014), for example, have recommended a hydrogeological assessment to map groundwater-surface water linkage zones for individual groundwater aquifers in the Okanagan, focusing on priority aquifers. In this manner, proposed and existing groundwater extraction locations could then be reviewed in the context of the mapped GW-SW linkage zones to connect the extraction to a specified water body (Okanagan Basin Water Board (2014).

At a regional scale, remote sensing techniques such as thermal satellite imagery can provide extensive and spatially complete data sets that could be integrated with data generated at smaller scales of investigation including historically available data including: geology maps, aquifer maps, well records, observation well data and hydrometric data. A regional mapping program aimed at delineating groundwater discharge areas for all mapped aquifers, sensitive streams and streams with *Water Allocation Restrictions* would be of benefit to water management planning in these areas.

A regional mapping program aimed at delineating groundwater discharge areas for all mapped aquifers, sensitive streams and streams with *Water Allocation Restrictions* would be of benefit to water management planning in these areas.

B.7 Assessing Environmental Flow Needs

As discussed in Section 2.3 of the main report, *environmental flow needs* (EFN) are defined in Section 1 of *Water Sustainability Act as,* "in relation to a stream, means the volume and timing of water flow required for the proper functioning of the aquatic ecosystem of the stream." The act also defines *critical environmental flow threshold*, as: "in relation to the flow of water in a stream, means the volume of water flow below which significant or irreversible harm to the aquatic ecosystem of the stream is likely to occur".

Numerous methods have been developed internationally for estimating environmental flow needs (EFN) of streams for various purposes. Environmental flow needs are often referred to by various researchers and jurisdictions as instream flow needs (IFN), instream flow requirements (IFR) or environmental flow requirements (EFR). The complexity of instream flow studies is dependent on the objectives and the resources requiring protection, as well as the magnitude of the project (Caissie and El-Jabi, 2013). King *et al*., (1999) indicate that "the selection of an appropriate environmental flow methodology for application in any country is likely to be context-specific and primarily constrained by the availability of appropriate data on the river system of concern, as well as local limitations in terms of time, finances, expertise and logistical support". A brief discussion of some of these methods can be found in Jowett (1997), ESSA Technologies Ltd., and Solander Ecological Research (2009) and Linnansaari *et al.,* (2013). Tharme (2003) reviewed over 200 individual environmental flow assessment methodologies and classified them into four general categories which he termed: 1) Hydrological, 2) Hydraulic rating, 3) Habitat simulation, and 4) Holistic methodologies. Based on Tharme (2003), these are summarized as follows:

B.7.1 Hydrological Methods

Hydrological methods rely primarily on the use of hydrological data, usually in the form of naturalized, historical monthly or daily flow records, for making environmental flow recommendations. They are often referred to as fixed-percentage or look-up table methodologies, where a set proportion of flow, often termed the *minimum flow* represents the EFN intended to maintain the freshwater fishery, other highlighted ecological features, or river health at some acceptable level, usually on an annual, seasonal or monthly basis (Tharme, 2003). They are generally regarded as low resolution environmental flow estimates and are considered to be most appropriate at the planning level of water resource development, or in low controversy situations where they may be used as preliminary flow targets (Tharme, 2003).

B.7.2 Hydraulic Rating Methods

Hydraulic rating (also known as habitat retention) methods use changes in simple hydraulic variables, such as wetted perimeter or maximum depth, usually measured across single, limiting river cross-sections (e.g. riffles), as a surrogate for habitat factors known or assumed to be limiting to target biota. It assumes that ensuring some threshold value of the selected hydraulic parameter at altered flows will maintain the biota and/or ecosystem integrity. Environmental flows are calculated by plotting the variable of concern against discharge wherein a breakpoint, interpreted as a threshold below which habitat quality becomes significantly degraded, is identified on the response curve. Alternatively the minimum EFN is set as the discharge producing a fixed percentage reduction in habitat (Tharme, 2003).

B.7.3 Habitat Simulation Methods

Habitat simulation methods, also referred to as microhabitat or habitat modelling methodologies, attempt to assess EFN on the basis of a detailed analyses of the quantity and suitability of instream physical habitat available to target species or assemblages under different discharges (or flow regimes), on the basis of integrated hydrological, hydraulic and biological response data (Tharme, 2003). Flow-related changes in physical microhabitat are modeled in various hydraulic programs, using data on one or more hydraulic variables, most commonly depth, velocity, substratum composition, cover and complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within the river study reach (Tharme, 2003). The simulated available habitat conditions are linked with information on the range of preferred to unsuitable microhabitat conditions for target species, lifestages, assemblages and/or activities, and are often depicted using seasonally defined habitat suitability index curves (Tharme, 2003). The resultant outputs, usually in the form of habitat–discharge curves for the biota, or extended as habitat time and exceedance series, are used to predict optimum flows as EFN (Tharme, 2003).

B.7.4 Holistic Methods

Holistic methodologies are focused on addressing the EFN of an entire riverine ecosystem where important and/or critical flow events are identified in terms of select criteria defining flow variability, for some or all major components or attributes of the riverine ecosystem (Tharme, 2003). This can be done either through a bottom-up, or a top-down or combination process that requires considerable multidisciplinary expertise and input. The basis of most approaches is the systematic construction of a modified flow regime from scratch (i.e. bottom-up), on a month-by-month (or more frequent) and element-by-element basis, where each element represents a well-defined feature of the flow regime intended to achieve particular ecological, geomorphological, water quality, social or other objectives in the modified system. In contrast, in top-down, generally scenario-based approaches, environmental flows are defined in terms of acceptable degrees of departure from the natural (or other reference) flow regime, rendering them less susceptible to any omission of critical flow characteristics or processes than their bottom-up counterparts. The most advanced holistic methodologies routinely utilize several of the tools for hydrological, hydraulic and physical habitat analysis featured in the three types of EFN previously discussed, within a modular framework, for establishing the EFN of the riverine ecosystem (Tharme, 2003).

It is apparent that the majority of methods that have been developed to assess environmental flows to date are primarily focused on analysis of hydrometric, geomorphic and biological parameters. Very few methods apart from those considering baseflow or low flow analyses appear to include any suggestions of assessing the significance of groundwater discharge components.

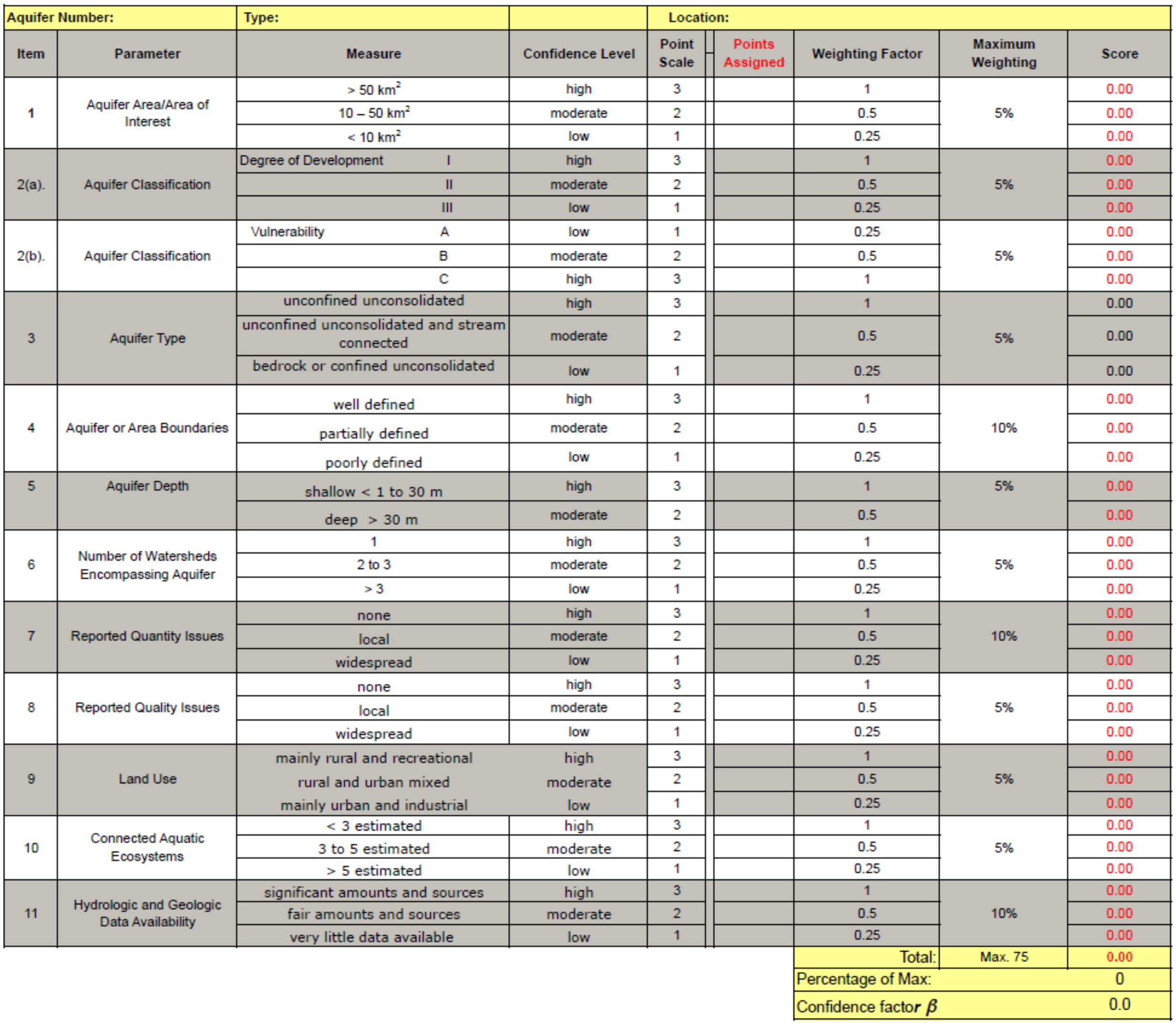
Holistic approaches involving multi-disciplinary teams in various fields including hydrology, hydrogeology, geomorphology, water quality and various disciplines of ecology (e.g. fisheries, botany) and stakeholder interests could be very beneficial for determining environmental flow needs. Linnansaari *et al.,* (2013) for example, describe the Building Block Methodology (BBM) and variations of the method which has been used in South Africa, Norway, and the eastern Canadian Arctic. The BBM includes three main parts namely: 1. A comprehensive information gathering / preparatory phase, 2. BBM Workshop, and 3. Follow-up activities linking the workshop with the engineering and planning concerns. Appendix F outlines the main features of the BBM., approach. The *Environmental Flow Assessments for Rivers Manual for the Building Block Methodology* (King *et al*., 2008) provides a comprehensive discussion on the importance of groundwater in river regimes, suggested data needs and studies necessary to address environmental flow needs.

Petts *et al.,* (1999) describe a method for determining the minimum acceptable flow (MAF) for groundwater-dominated streams in England. Their approach, termed the *Ecologically Acceptable Flow Regime* (EAFR) involves four stages namely:

1. An ecological assessment of the river and specification of an ecological objective comprising specific targets (e.g. spawning habitat for trout in the autumn or wetland habitats in spring for riparian species),
2. Determining benchmark flows to meet these targets,
3. Using benchmark flows to construct “Ecologically Acceptable Hydrographs” which may include provision for wet-year and drought conditions, and
4. Giving the hydrographs acceptable frequencies and combining them to define a flow duration curve, the *Ecologically Acceptable Flow Regime* (EAFR) where the area below the EAFR flow duration curve defines the MAF volume.

APPENDIX C. AQUIFER AND GROUNDWATER AREA RATING WORKSHEET

Table C1. Interim aquifer and groundwater area confidence rating worksheet.

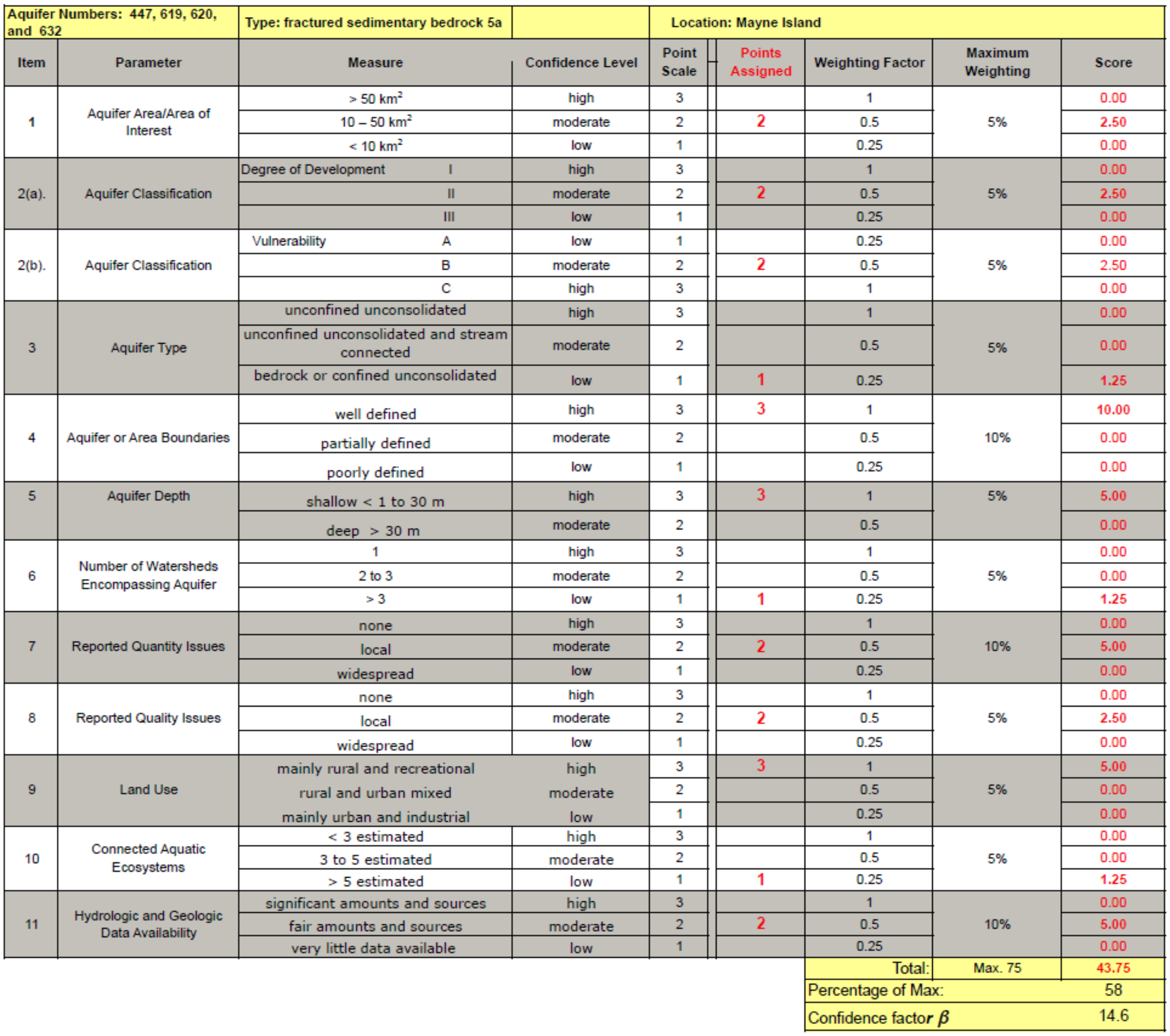


Aquifer Number:		**Type:**		**Location:**				
Item	**Parameter**	**Measure**	**Confidence Level**	**Point Scale**	**Points Assigned**	**Weighting Factor**	**Maximum Weighting**	**Score**
1	Aquifer Area/Area of Interest	> 50 km^2	high	3		1	5%	0.00
		10 – 50 km^2	moderate	2		0.5		0.00
		< 10 km^2	low	1		0.25		0.00
2(a).	Aquifer Classification	Degree of Development I	high	3		1	5%	0.00
		II	moderate	2		0.5		0.00
		III	low	1		0.25		0.00
2(b).	Aquifer Classification	Vulnerability A	low	1		0.25	5%	0.00
		B	moderate	2		0.5		0.00
		C	high	3		1		0.00
3	Aquifer Type	unconfined unconsolidated	high	3		1	5%	0.00
		unconfined unconsolidated and stream connected	moderate	2		0.5		0.00
		bedrock or confined unconsolidated	low	1		0.25		0.00
4	Aquifer or Area Boundaries	well defined	high	3		1	10%	0.00
		partially defined	moderate	2		0.5		0.00
		poorly defined	low	1		0.25		0.00
5	Aquifer Depth	shallow < 1 to 30 m	high	3		1	5%	0.00
		deep > 30 m	moderate	2		0.5		0.00
6	Number of Watersheds Encompassing Aquifer	1	high	3		1	5%	0.00
		2 to 3	moderate	2		0.5		0.00
		> 3	low	1		0.25		0.00
7	Reported Quantity Issues	none	high	3		1	10%	0.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
8	Reported Quality Issues	none	high	3		1	5%	0.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
9	Land Use	mainly rural and recreational	high	3		1	5%	0.00
		rural and urban mixed	moderate	2		0.5		0.00
		mainly urban and industrial	low	1		0.25		0.00
10	Connected Aquatic Ecosystems	< 3 estimated	high	3		1	5%	0.00
		3 to 5 estimated	moderate	2		0.5		0.00
		> 5 estimated	low	1		0.25		0.00
11	Hydrologic and Geologic Data Availability	significant amounts and sources	high	3		1	10%	0.00
		fair amounts and sources	moderate	2		0.5		0.00
		very little data available	low	1		0.25		0.00
						Total:	Max. 75	0.00
						Percentage of Max:		0
						Confidence factor β		0.0

Table C2. Example aquifer and groundwater area confidence rating for the Abbotsford Aquifer.

Aquifer Number: 0015		Type: Unconsolidated 4a.		Location: Abbostsford				
Item	**Parameter**	**Measure**	**Confidence Level**	**Point Scale**	**Points Assigned**	**Weighting Factor**	**Maximum Weighting**	**Score**
1	Aquifer Area/Area of Interest	> 50 km^2	high	3	3	1	5%	5.00
		10 – 50 km^2	moderate	2		0.5		0.00
		< 10 km^2	low	1		0.25		0.00
2(a).	Aquifer Classification	Degree of Development I	high	3	3	1	5%	5.00
		II	moderate	2		0.5		0.00
		III	low	1		0.25		0.00
2(b).	Aquifer Classification	Vulnerability A	low	1	1	0.25	5%	1.25
		B	moderate	2		0.5		0.00
		C	high	3		1		0.00
3	Aquifer Type	unconfined unconsolidated	high	3	3	1	5%	5.00
		unconfined unconsolidated and stream connected	moderate	2		0.5		0.00
		bedrock or confined unconsolidated	low	1		0.25		0.00
4	Aquifer or Area Boundaries	well defined	high	3	3	1	10%	10.00
		partially defined	moderate	2		0.5		0.00
		poorly defined	low	1		0.25		0.00
5	Aquifer Depth	shallow < 1 to 30 m	high	3		1	5%	0.00
		deep > 30 m	moderate	2	2	0.5		2.50
6	Number of Watersheds Encompassing Aquifer	1	high	3		1	5%	0.00
		2 to 3	moderate	2	2	0.5		2.50
		> 3	low	1		0.25		0.00
7	Reported Quantity Issues	none	high	3		1	10%	0.00
		local	moderate	2	2	0.5		5.00
		widespread	low	1		0.25		0.00
8	Reported Quality Issues	none	high	3		1	5%	0.00
		local	moderate	2		0.5		0.00
		widespread	low	1	1	0.25		1.25
9	Land Use	mainly rural and recreational	high	3		1	5%	0.00
		rural and urban mixed	moderate	2	2	0.5		2.50
		mainly urban and industrial	low	1		0.25		0.00
10	Connected Aquatic Ecosystems	< 3 estimated	high	3		1	5%	0.00
		3 to 5 estimated	moderate	2	2	0.5		2.50
		> 5 estimated	low	1		0.25		0.00
11	Hydrologic and Geologic Data Availability	significant amounts and sources	high	3	3	1	10%	10.00
		fair amounts and sources	moderate	2		0.5		0.00
		very little data available	low	1		0.25		0.00
						Total:	Max. 75	52.50
						Percentage of Max:		70
						Confidence factor β		17.5

Table C3. Example aquifer and groundwater area confidence rating for Mayne Island bedrock aquifers.



Aquifer Numbers: 447, 619, 620, and 632		**Type: fractured sedimentary bedrock 5a**		**Location: Mayne Island**				
Item	**Parameter**	**Measure**	**Confidence Level**	**Point Scale**	**Points Assigned**	**Weighting Factor**	**Maximum Weighting**	**Score**
1	Aquifer Area/Area of Interest	> 50 km^2	high	3		1	5%	0.00
		10 – 50 km^2	moderate	2	2	0.5		2.50
		< 10 km^2	low	1		0.25		0.00
2(a).	Aquifer Classification	Degree of Development I	high	3		1	5%	0.00
		II	moderate	2	2	0.5		2.50
		III	low	1		0.25		0.00
2(b).	Aquifer Classification	Vulnerability A	low	1		0.25	5%	0.00
		B	moderate	2	2	0.5		2.50
		C	high	3		1		0.00
3	Aquifer Type	unconfined unconsolidated	high	3		1	5%	0.00
		unconfined unconsolidated and stream connected	moderate	2		0.5		0.00
		bedrock or confined unconsolidated	low	1	1	0.25		1.25
4	Aquifer or Area Boundaries	well defined	high	3	3	1	10%	10.00
		partially defined	moderate	2		0.5		0.00
		poorly defined	low	1		0.25		0.00
5	Aquifer Depth	shallow < 1 to 30 m	high	3	3	1	5%	5.00
		deep > 30 m	moderate	2		0.5		0.00
6	Number of Watersheds Encompassing Aquifer	1	high	3		1	5%	0.00
		2 to 3	moderate	2		0.5		0.00
		> 3	low	1	1	0.25		1.25
7	Reported Quantity Issues	none	high	3		1	10%	0.00
		local	moderate	2	2	0.5		5.00
		widespread	low	1		0.25		0.00
8	Reported Quality Issues	none	high	3		1	5%	0.00
		local	moderate	2	2	0.5		2.50
		widespread	low	1		0.25		0.00
9	Land Use	mainly rural and recreational	high	3	3	1	5%	5.00
		rural and urban mixed	moderate	2		0.5		0.00
		mainly urban and industrial	low	1		0.25		0.00
10	Connected Aquatic Ecosystems	< 3 estimated	high	3		1	5%	0.00
		3 to 5 estimated	moderate	2		0.5		0.00
		> 5 estimated	low	1	1	0.25		1.25
11	Hydrologic and Geologic Data Availability	significant amounts and sources	high	3		1	10%	0.00
		fair amounts and sources	moderate	2	2	0.5		5.00
		very little data available	low	1		0.25		0.00
						Total:	Max. 75	43.75
						Percentage of Max:		58
						Confidence factor β		14.6

APPENDIX D. AQUIFER/AREA RATING GUIDE CRITERIA

The aquifer/area rating guide is based on previous guides such as that used to rate and prioritize aquifers for the establishment of future observation wells (Ministry of Environment, 2009). This rating guide provides a semi-quantitative and qualitative measure and is subject to information being readily available for the aquifer or area under consideration. In this guide the maximum score achievable is 75% and the criteria are weighted accordingly not to exceed this value. The percentage is then applied against the maximum confidence value of 25 to determine the confidence factor. A high score indicates a high confidence rating while a low score indicates a low confidence rating. A brief discussion of the criteria used in the rating guide is provided below. As the rating guide is subjective in part, the knowledge, experience and judgment of the person conducting the rating will also enter into the evaluation.

Criterion 1: Aquifer Area/Area of Interest

Aquifer areas can be found at the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/. In terms of rating water availability, the confidence level increases with aquifer size. The aquifer size range reflects values considered by Berardinucci and Ronneseth (2002). Larger aquifer size indicates larger volumes of groundwater being available in comparison to existing and potential groundwater demands.

Criterion 2(a): Aquifer Classification, Degree of Development

Information on Aquifer Classification, Degree of Development can be found at the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/ . In terms of rating water availability, the confidence level increases with the degree of development. The level of development as described by Berardinucci and Ronneseth (2002), is a relative and subjective term, comparing the amount of groundwater withdrawn from an aquifer (demand) to the aquifer's inferred ability to supply groundwater for use (productivity).

Criterion 2(b): Aquifer Classification, Vulnerability

Information on Aquifer Classification, Vulnerability can be found at the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/ . In terms of rating water availability, the confidence level decreases with the degree of vulnerability as higher vulnerability increases the possibility of quality degradation. The level of vulnerability of an aquifer as described by Berardinucci and Ronneseth (2002), is a measure of its vulnerability to a contaminant that is introduced at the land surface.

Criterion 3: Aquifer Type

Aquifer type is an indication of aquifer complexity and can be determined by examining the aquifer descriptions at the *Aquifer Classification Database* (Ministry of Environment, 2018a), internet website https://a100.gov.bc.ca/pub/wells/public/common/aquifer_report.jsp . In terms of rating water availability, the confidence level is highest for unconfined unconsolidated aquifers and less for stream connected unconfined unconsolidated aquifers and least for bedrock and confined unconsolidated aquifers.

Criterion 4: Aquifer or Area Boundaries

Aquifer boundaries can be viewed at the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/ and at the *Aquifer Classification Database* (Ministry of

Environment, 2018a). In terms of rating water availability, the confidence level increases with the boundary definition. Berardinucci and Ronneseth (2002) discuss how aquifer boundaries are delineated.

Criterion 5: Aquifer Depth

Information on aquifer depth can be found at the *Aquifer Classification Database* (Ministry of Environment, 2018a) and can also be inferred on the basis of aquifer type in many cases and examination of well depth information. Bedrock aquifers for example are usually deep (> 30 m).

Criterion 6: Number of Watersheds Encompassing Aquifer

The number of watersheds encompassing an aquifer can be determined by examining topography, drainage features and aquifer boundaries at the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/ . In terms of rating water availability, the confidence level is highest if only one watershed is involved and decreases with additional watersheds. More streams introduces more complexity with groundwater-surface water interactions and less confidence.

Criterion 7: Reported Quantity Issues

Information on reported quantity issues can be found at the *Aquifer Classification Database* (Ministry of Environment, 2018a) and available reports. Issues may include, for example, well interference, declining water levels and poor well yields, and conflicts with surface water use. In terms of rating water availability, confidence levels decrease as quantity issues increase. Information on trends in groundwater levels can be found at the *Provincial Groundwater Observation Well Network* (Ministry of Environment, 2018b).

Criterion 8: Reported Quality Issues

Information on reported quality issues can be found at the *Aquifer Classification Database* (Ministry of Environment, 2018a) and available reports. Issues may include groundwater quality degradation from various sources such as salt water intrusion, septic wastes, and fertilizer use. In terms of rating water availability, confidence levels decrease as quality issues increase.

Criterion 9: Land Use

Information on general land use can be viewed at the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/ . In terms of rating water availability, confidence levels decrease as land use becomes more intensified.

Criterion 10: Connected Aquatic Ecosystems

Information on connected ecosystems can be obtained by viewing aquifer boundaries in relationship to surface water drainage systems, parks and protected areas shown at the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/ . Reports on sensitive ecosystems are also available at EcoCat http://a100.gov.bc.ca/pub/acat/public/welcome.do . In terms of rating water availability, confidence levels decrease as more ecosystems are identified. A schedule of designated streams, originally established under the Sensitive Streams Designation and Licensing Regulation of the *Fish Protection Act* is now maintained under Schedule B of the Water Sustainability Regulation of WSA. A sensitive stream designation protects fish populations that are at risk from damage to the stream's aquatic ecosystem. In addition many streams in the province have in place *Water Allocation Restrictions* that may range from including minimum fish flow clauses in a water licence, to suspending the issuance of any further licences on a water body (Government of British Columbia, 2018h).

Criterion 11: Hydrologic and Geologic Data Availability

Hydrologic (including climate and hydrometric) and geologic data are available from various sources including the *B.C. Water Resources Atlas*, internet website http://maps.gov.bc.ca/ess/hm/wrbc/, Government of Canada (2018b and 2018c), Provincial Observation Well Network (Government of British Columbia, 2018g) and British Columbia Geological Survey, internet site http://www.empr.gov.bc.ca/MINING/GEOSCIENCE/Pages/default.aspx . In terms of rating water availability, confidence levels are higher when significant amounts and sources of meteorological, hydrometric and geologic information are available.

APPENDIX E. GROUNDWATER DISCHARGE METHODS

Two Methods for Estimating Groundwater Discharge Supporting Aquatic Habit

E.1 Darcy's Law

Where groundwater discharges to a surface water body such as a river or lake have been identified, the quantity of groundwater discharge (flux) can be determined for a known cross section of aquifer using Darcy's Law in the form

$$Q^{GW}_{out} = K\,I\,A \qquad \text{Equation 1}$$

where

Q^{GW}_{out} = quantity of lateral groundwater outflow or discharge

K = hydraulic conductivity of the aquifer

I = hydraulic gradient, and

A = area of aquifer through which the flow takes place

These relationships are illustrated in Figure E1.

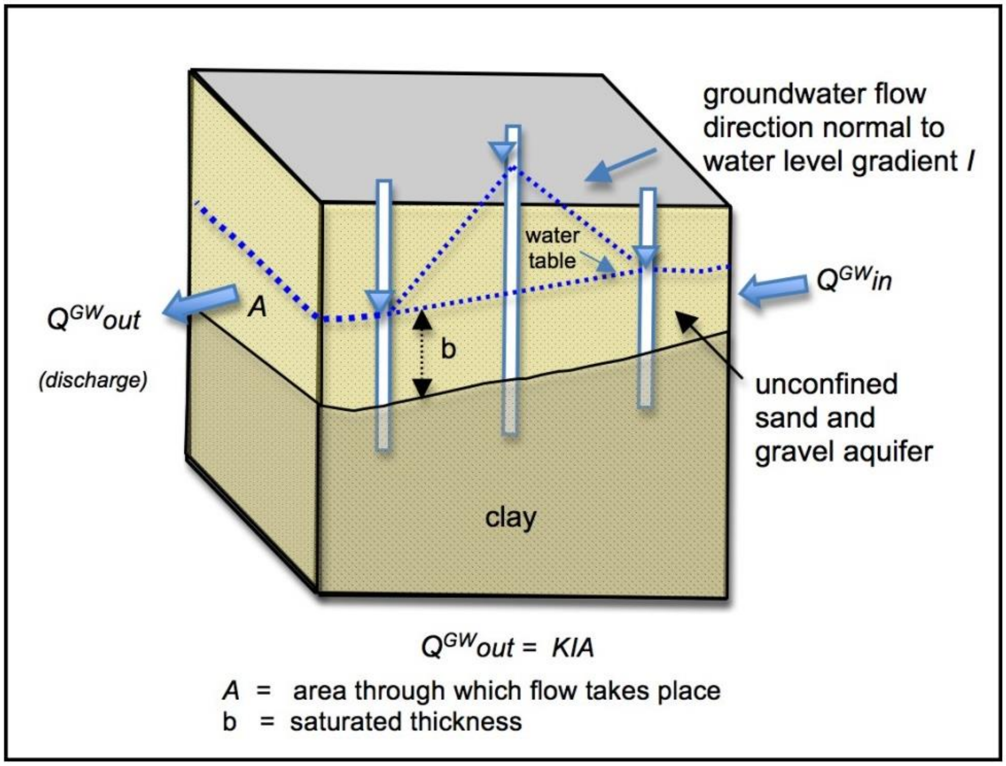


Figure E1: Schematic illustrating use of Darcy's Law to quantify groundwater discharge.

Employing Darcy's Law requires knowledge of an aquifer's relationship to the receiving environment e.g. a creek, extent and thickness of the aquifer, information on aquifer parameters, and hydraulic gradients.

E.2 Hydrograph – Baseflow Separation

Methods for estimating cumulative groundwater inflow to a river include analyzing streamflow hydrographs to determine the groundwater component of base flow. Various methods are available for analyzing stream hydrographs to determine the baseflow component (Winter *et al*., 1998). Figure E2 illustrates the results of using one particular method used to analyze a streamflow hydrograph for the Homochitto River in Mississippi (Winter *et al.,* 1998).

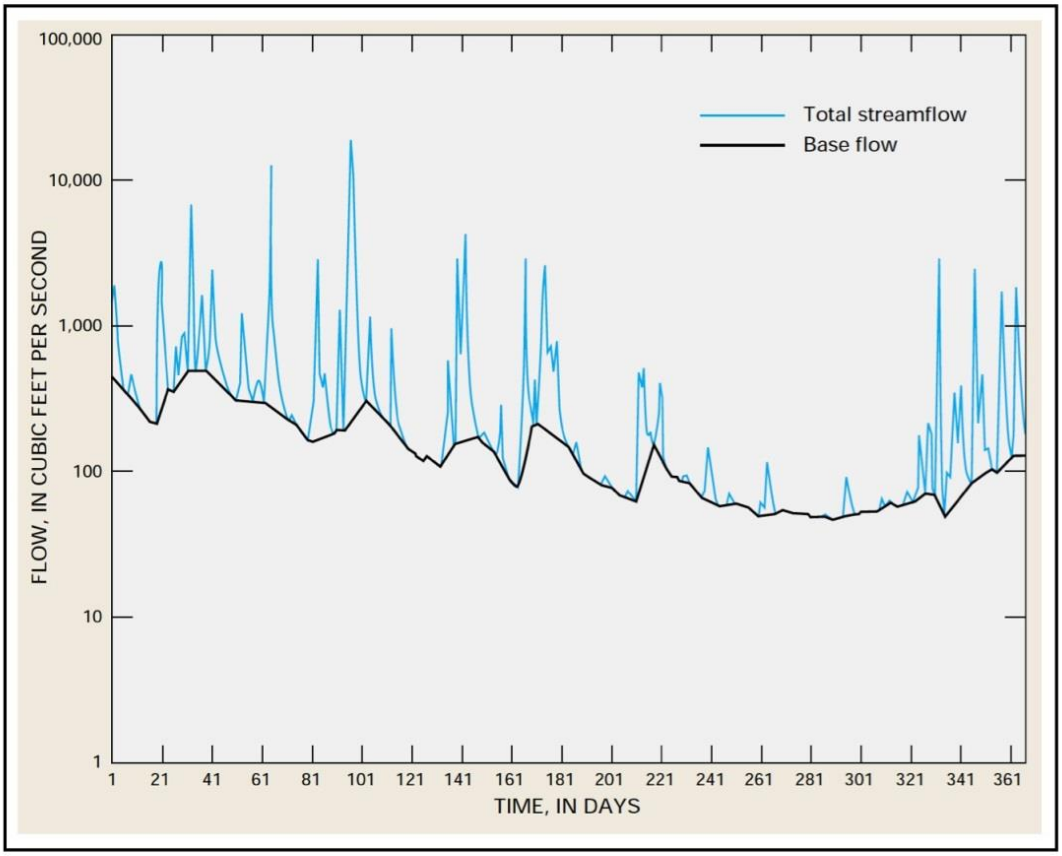


Figure E2: Estimation of groundwater component of streamflow from hydrograph for the Homochitto River in Mississippi, from Winter et al., (1998).

The United States Geological Survey (USGS) has developed a user guide estimating baseflow, runoff and groundwater recharge from streamflow data (Barlow *et al*., 2015). The guide includes six hydrograph separation methods and provides guidance on their application. Use of more than one method to analyze a streamflow record and comparing the results with multiple methods is suggested (Barlow *et al*., 2015).

APPENDIX F. BBM METHODOLOGY

Main Parts of the BBM Methodology for Determining Environmental Flow Needs (modified after Linnansaari *et al*., (2012)

1. A comprehensive information gathering / preparatory phase

A structured set of activities is followed to collect and display the best available information on the river for consideration by the workshop participants. The collected information includes social use of riverine resources, flow regime evaluations (historic and present), hydraulic analysis, geomorphology, water chemistry, groundwater and biological surveys for vegetation, aquatic invertebrates and fish. The Building Block Methodology (BBM) manual includes detailed instructions on how the data is collected for each criteria. The information is collected in a "Starter Document" that is provided to the participants of BBM workshop. The conceptual model of the BBM approach is illustrated in Figure 1.

2. BBM Workshop

The BBM workshop typically involves ~20 people comprising of water managers, engineers and river scientists. The workshop consists of four main sessions and typically takes 2 - 4 days to complete. The first session is a visit to the field sites that are being considered followed by another session where all the gathered information is presented. In the third session, the actual modified environmental flow regime is designed based on monthly flows and special purpose flows and reported as %MAF (Mean Annual Flow). Finally, further research needs are identified to address major uncertainty and to improve the environmental flow regime (EFR). A technical report is produced after the workshop that outlines the environmental flow regime and describes the reasoning for the different flow components.

3. Follow-up activities linking the workshop with the engineering and planning concerns

Following the workshop, the flow regime described in the workshop is incorporated in a hydrological yield analysis. This reveals whether or not the EFR can be met without conflict with potential consumptive users. If conflicts are identified, adjustments are made until a compromise is achieved.

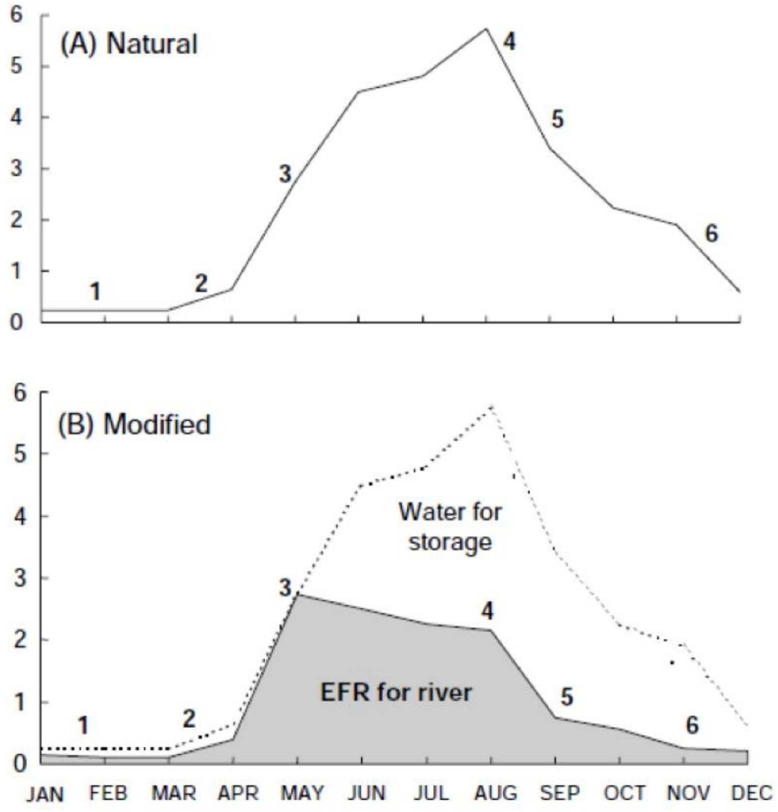


Figure 1. *Conceptual model of the Building Block Methodology approach. Using a natural hydrograph, key components of the river flow are identified (A), and some proportion of these building blocks are retained to provide an environmental flow regime. For example, blocks 1 and 6 are used to retain perennial low flows of the hydrograph, blocks 2, 4 and 5 are used to separate wet and dry seasons, and block 3 is used to introduce a first larger flood of the wet season. Source: King et al. (2008),*

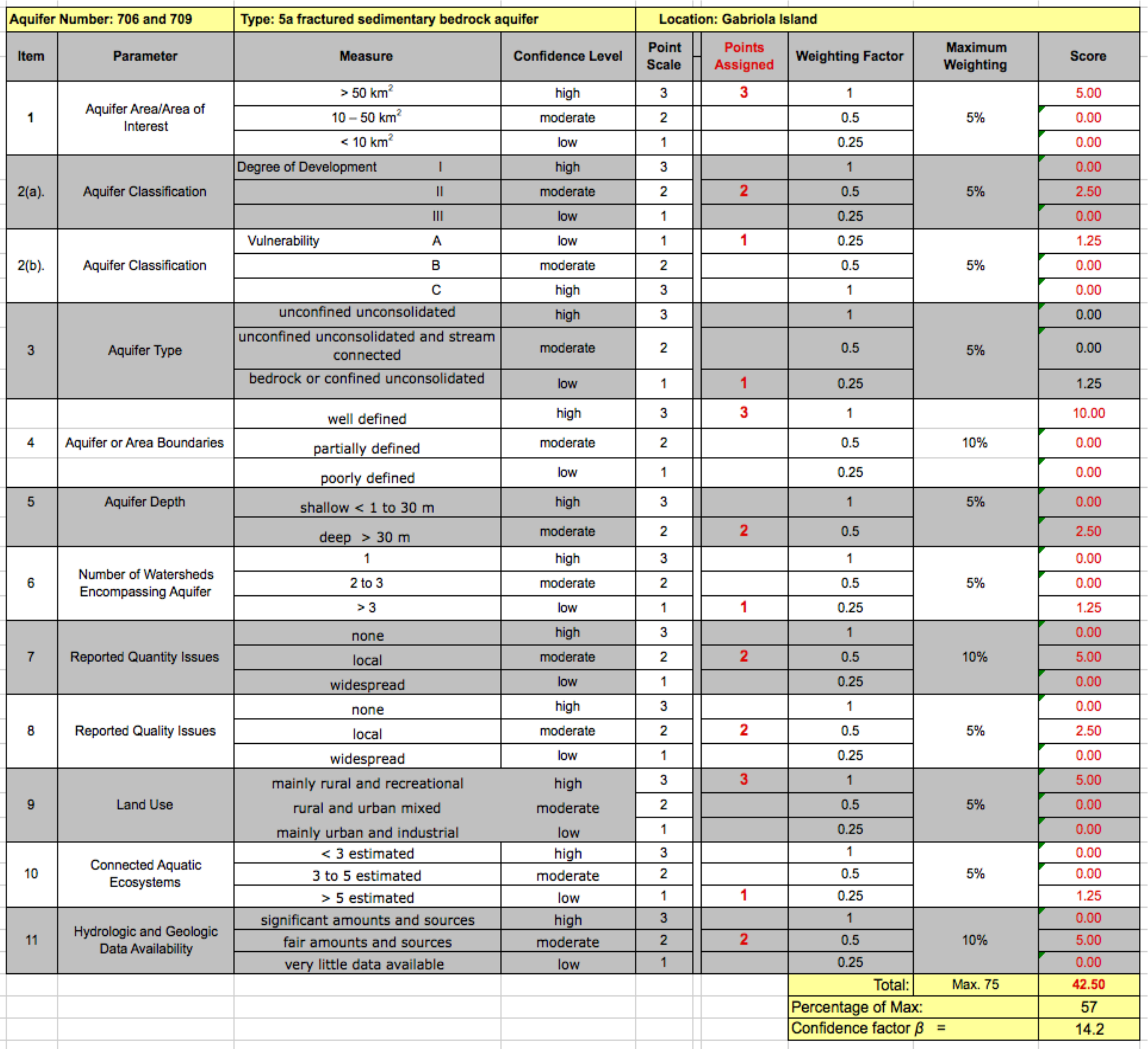
Figure adapted from Linnansaari et al., (2012) based on King et al., (2008).

APPENDIX G. SPREADSHEET TEMPLATE FOR GWAM WATER BUDGET ANALYSES

This appendix is provided as a separate Excel file attachment.

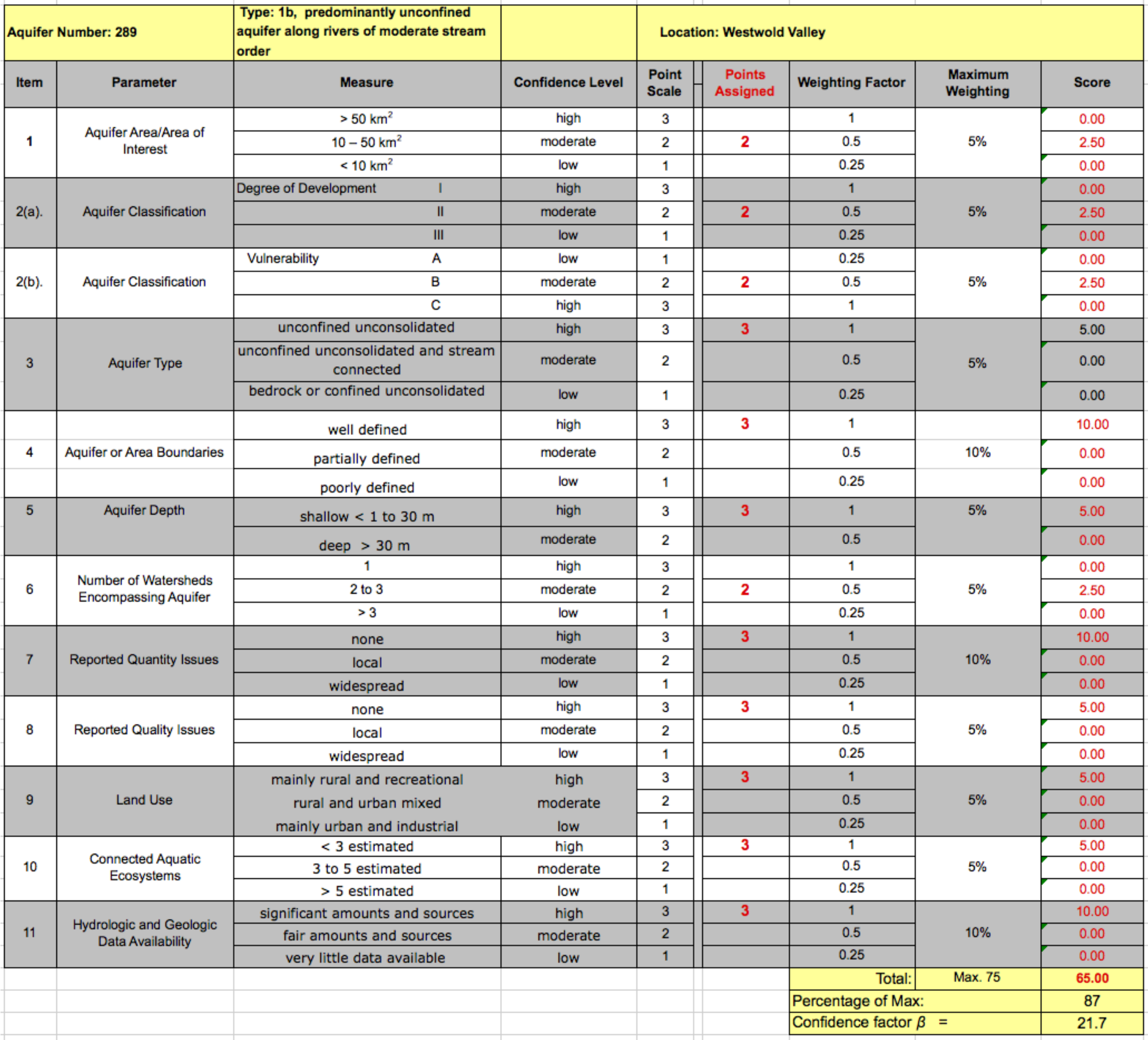
APPENDIX H. CONFIDENCE RATINGS OF FOUR TEST AQUIFERS

Table H1: Confidence rating for the Gabriola Island aquifers.



Aquifer Number: 706 and 709		Type: 5a fractured sedimentary bedrock aquifer		Location: Gabriola Island				
Item	Parameter	Measure	Confidence Level	Point Scale	Points Assigned	Weighting Factor	Maximum Weighting	Score
1	Aquifer Area/Area of Interest	> 50 km^2	high	3	3	1	5%	5.00
		10 – 50 km^2	moderate	2		0.5		0.00
		< 10 km^2	low	1		0.25		0.00
2(a).	Aquifer Classification	Degree of Development I	high	3		1	5%	0.00
		II	moderate	2	2	0.5		2.50
		III	low	1		0.25		0.00
2(b).	Aquifer Classification	Vulnerability A	low	1	1	0.25	5%	1.25
		B	moderate	2		0.5		0.00
		C	high	3		1		0.00
3	Aquifer Type	unconfined unconsolidated	high	3		1	5%	0.00
		unconfined unconsolidated and stream connected	moderate	2		0.5		0.00
		bedrock or confined unconsolidated	low	1	1	0.25		1.25
4	Aquifer or Area Boundaries	well defined	high	3	3	1	10%	10.00
		partially defined	moderate	2		0.5		0.00
		poorly defined	low	1		0.25		0.00
5	Aquifer Depth	shallow < 1 to 30 m	high	3		1	5%	0.00
		deep > 30 m	moderate	2	2	0.5		2.50
6	Number of Watersheds Encompassing Aquifer	1	high	3		1	5%	0.00
		2 to 3	moderate	2		0.5		0.00
		> 3	low	1	1	0.25		1.25
7	Reported Quantity Issues	none	high	3		1	10%	0.00
		local	moderate	2	2	0.5		5.00
		widespread	low	1		0.25		0.00
8	Reported Quality Issues	none	high	3		1	5%	0.00
		local	moderate	2	2	0.5		2.50
		widespread	low	1		0.25		0.00
9	Land Use	mainly rural and recreational	high	3	3	1	5%	5.00
		rural and urban mixed	moderate	2		0.5		0.00
		mainly urban and industrial	low	1		0.25		0.00
10	Connected Aquatic Ecosystems	< 3 estimated	high	3		1	5%	0.00
		3 to 5 estimated	moderate	2		0.5		0.00
		> 5 estimated	low	1	1	0.25		1.25
11	Hydrologic and Geologic Data Availability	significant amounts and sources	high	3		1	10%	0.00
		fair amounts and sources	moderate	2	2	0.5		5.00
		very little data available	low	1		0.25		0.00
						Total:	Max. 75	42.50
						Percentage of Max:		57
						Confidence factor β =		14.2

Table H2: Confidence rating for the Westwold Valley Aquifer.



Aquifer Number: 289		Type: 1b, predominantly unconfined aquifer along rivers of moderate stream order			Location: Westwold Valley			
Item	**Parameter**	**Measure**	**Confidence Level**	**Point Scale**	**Points Assigned**	**Weighting Factor**	**Maximum Weighting**	**Score**
1	Aquifer Area/Area of Interest	> 50 km^2	high	3		1	5%	0.00
		10 – 50 km^2	moderate	2	**2**	0.5		2.50
		< 10 km^2	low	1		0.25		0.00
2(a).	Aquifer Classification	Degree of Development I	high	3		1	5%	0.00
		II	moderate	2	**2**	0.5		2.50
		III	low	1		0.25		0.00
2(b).	Aquifer Classification	Vulnerability A	low	1		0.25	5%	0.00
		B	moderate	2	**2**	0.5		2.50
		C	high	3		1		0.00
3	Aquifer Type	unconfined unconsolidated	high	3	**3**	1	5%	5.00
		unconfined unconsolidated and stream connected	moderate	2		0.5		0.00
		bedrock or confined unconsolidated	low	1		0.25		0.00
4	Aquifer or Area Boundaries	well defined	high	3	**3**	1	10%	10.00
		partially defined	moderate	2		0.5		0.00
		poorly defined	low	1		0.25		0.00
5	Aquifer Depth	shallow < 1 to 30 m	high	3	**3**	1	5%	5.00
		deep > 30 m	moderate	2		0.5		0.00
6	Number of Watersheds Encompassing Aquifer	1	high	3		1	5%	0.00
		2 to 3	moderate	2	**2**	0.5		2.50
		> 3	low	1		0.25		0.00
7	Reported Quantity Issues	none	high	3	**3**	1	10%	10.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
8	Reported Quality Issues	none	high	3	**3**	1	5%	5.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
9	Land Use	mainly rural and recreational	high	3	**3**	1	5%	5.00
		rural and urban mixed	moderate	2		0.5		0.00
		mainly urban and industrial	low	1		0.25		0.00
10	Connected Aquatic Ecosystems	< 3 estimated	high	3	**3**	1	5%	5.00
		3 to 5 estimated	moderate	2		0.5		0.00
		> 5 estimated	low	1		0.25		0.00
11	Hydrologic and Geologic Data Availability	significant amounts and sources	high	3	**3**	1	10%	10.00
		fair amounts and sources	moderate	2		0.5		0.00
		very little data available	low	1		0.25		0.00
						Total:	Max. 75	**65.00**
						Percentage of Max:		87
						Confidence factor β =		21.7

Table H3: Confidence rating for the West of Aldergrove Aquifer.

Aquifer Number: 33		**Type: 4b, predominantly confined sand and gravel aquifer of glacial or pre-glacial origin**		**Location: West of Aldergrove**				
Item	**Parameter**	**Measure**	**Confidence Level**	**Point Scale**	**Points Assigned**	**Weighting Factor**	**Maximum Weighting**	**Score**
1	Aquifer Area/Area of Interest	> 50 km^2	high	3	**3**	1	5%	5.00
		10 – 50 km^2	moderate	2		0.5		0.00
		< 10 km^2	low	1		0.25		0.00
2(a).	Aquifer Classification	Degree of Development I	high	3		1	5%	0.00
		II	moderate	2	**2**	0.5		2.50
		III	low	1		0.25		0.00
2(b).	Aquifer Classification	Vulnerability A	low	1		0.25	5%	0.00
		B	moderate	2		0.5		0.00
		C	high	3	**3**	1		5.00
3	Aquifer Type	unconfined unconsolidated	high	3		1	5%	0.00
		unconfined unconsolidated and stream connected	moderate	2		0.5		0.00
		bedrock or confined unconsolidated	low	1	**1**	0.25		1.25
4	Aquifer or Area Boundaries	well defined	high	3	**3**	1	10%	10.00
		partially defined	moderate	2		0.5		0.00
		poorly defined	low	1		0.25		0.00
5	Aquifer Depth	shallow < 1 to 30 m	high	3	**3**	1	5%	5.00
		deep > 30 m	moderate	2		0.5		0.00
6	Number of Watersheds Encompassing Aquifer	1	high	3		1	5%	0.00
		2 to 3	moderate	2		0.5		0.00
		> 3	low	1	**1**	0.25		1.25
7	Reported Quantity Issues	none	high	3	**3**	1	10%	10.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
8	Reported Quality Issues	none	high	3	**3**	1	5%	5.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
9	Land Use	mainly rural and recreational	high	3		1	5%	0.00
		rural and urban mixed	moderate	2	**2**	0.5		2.50
		mainly urban and industrial	low	1		0.25		0.00
10	Connected Aquatic Ecosystems	< 3 estimated	high	3	**3**	1	5%	5.00
		3 to 5 estimated	moderate	2		0.5		0.00
		> 5 estimated	low	1		0.25		0.00
11	Hydrologic and Geologic Data Availability	significant amounts and sources	high	3	**3**	1	10%	10.00
		fair amounts and sources	moderate	2		0.5		0.00
		very little data available	low	1		0.25		0.00
						Total:	Max. 75	**62.50**
						Percentage of Max:		83
						Confidence factor β =		20.8

Table H4: Confidence rating for the Mill Bay Aquifer.

Aquifer Number: 206		**Type: 4a, predominantly unconfined aquifers of fluvial or glaciofluvial origin,along river or stream valleys**		**Location: Mill Bay**				
Item	**Parameter**	**Measure**	**Confidence Level**	**Point Scale**	**Points Assigned**	**Weighting Factor**	**Maximum Weighting**	**Score**
1	Aquifer Area/Area of Interest	> 50 km^2	high	3		1	5%	0.00
		10 – 50 km^2	moderate	2		0.5		0.00
		< 10 km^2	low	1	1	0.25		1.25
2(a).	Aquifer Classification	Degree of Development I	high	3		1	5%	0.00
		II	moderate	2	2	0.5		2.50
		III	low	1		0.25		0.00
2(b).	Aquifer Classification	Vulnerability A	low	1	1	0.25	5%	1.25
		B	moderate	2		0.5		0.00
		C	high	3		1		0.00
3	Aquifer Type	unconfined unconsolidated	high	3	3	1	5%	5.00
		unconfined unconsolidated and stream connected	moderate	2		0.5		0.00
		bedrock or confined unconsolidated	low	1		0.25		0.00
		well defined	high	3	3	1		10.00
4	Aquifer or Area Boundaries	partially defined	moderate	2		0.5	10%	0.00
		poorly defined	low	1		0.25		0.00
5	Aquifer Depth	shallow < 1 to 30 m	high	3	3	1	5%	5.00
		deep > 30 m	moderate	2		0.5		0.00
6	Number of Watersheds Encompassing Aquifer	1	high	3		1	5%	0.00
		2 to 3	moderate	2	2	0.5		2.50
		> 3	low	1		0.25		0.00
7	Reported Quantity Issues	none	high	3	3	1	10%	10.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
8	Reported Quality Issues	none	high	3	3	1	5%	5.00
		local	moderate	2		0.5		0.00
		widespread	low	1		0.25		0.00
9	Land Use	mainly rural and recreational	high	3		1	5%	0.00
		rural and urban mixed	moderate	2	2	0.5		2.50
		mainly urban and industrial	low	1		0.25		0.00
10	Connected Aquatic Ecosystems	< 3 estimated	high	3		1	5%	0.00
		3 to 5 estimated	moderate	2	2	0.5		2.50
		> 5 estimated	low	1		0.25		0.00
11	Hydrologic and Geologic Data Availability	significant amounts and sources	high	3	3	1	10%	10.00
		fair amounts and sources	moderate	2		0.5		0.00
		very little data available	low	1		0.25		0.00
						Total:	Max. 75	**57.50**
						Percentage of Max:		77
						Confidence factor β =		19.2

APPENDIX I. SPREADSHEET EXAMPLE RESULTS OF APPLYING GWAM TO THE FOUR TEST AREAS

Table I1: Results of utilizing 5% of normal precipitation for calculating recharge on Gabriola Island.

AQUIFER TYPES 5a, 5b, 6a, 6b

Based on:	Normal Year Precipitation			Water Budget Analysis					Aquifer/Area:		Gabriola Island			
			1971-2000						Aquifer Type:		5a	BDRK		
														m^3
INPUTS	*Units*		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	*Annual Totals*

INPUTS	*Units*		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	*Annual Totals*
P	mm		130	106	87	57	45	41	26	28	39	81	147	138	4.83E+07
Q^{SW}_{in}	m^3														0.00E+00
Q^{GW}_{in}	m^3														0.00E+00
R_{month}	m^3		3.39E+05	2.77E+05	2.27E+05	1.49E+05	1.17E+05	1.07E+05	6.79E+04	7.31E+04	1.02E+05	2.11E+05	3.84E+05	3.60E+05	2.41E+06
R	m^3		3.39E+05	2.77E+05	2.27E+05	1.49E+05	1.17E+05	1.07E+05	6.79E+04	7.31E+04	1.02E+05	2.11E+05	3.84E+05	3.60E+05	2.41E+06
Q^{GWLeak}_{in}	m^3														0.00E+00
$Q^{IRReturn}_{in}$	m^3														0.00E+00
OUTPUTS	*Units*														
ET	mm														0.00E+00
Q^{GWpump}_{out}	m^3		3.26E+04	3.26E+04	3.26E+04	8.94E+04	9.24E+04	1.34E+05	1.32E+05	1.32E+05	9.64E+04	3.36E+04	3.36E+04	3.26E+04	8.73E+05
Q^{SWpump}_{out}	m^3														0.00E+00
Q^{SW}_{out}	m^3														0.00E+00
Q^{GW}_{out}	m^3														0.00E+00
STORAGE	*Units*														
ΔS^{SW}	m^3														0.00E+00
ΔS^{GW}	m^3														0.00E+00
$\Delta S^{SWLakes}$	m^3														0.00E+00

Fundamental Equations: $R = P + Q^{SW}_{in} + Q^{IRRreturn}_{in} - ET - \Delta S^{SWLakes} - Q^{SW}_{out} - Q^{SWpump}_{out}$

$Q_{AVAIL} = R - Q^{GWpump}_{out} - \alpha Q^{GW}_{out}$

$R/P =$ 5.0 %

Confidence Factor: $\beta =$ 0.15

EFN Factor: $\alpha =$ 0

Ratio: $Q^{GWpump}_{out}/Q_{AVAIL} =$ 56.6 %

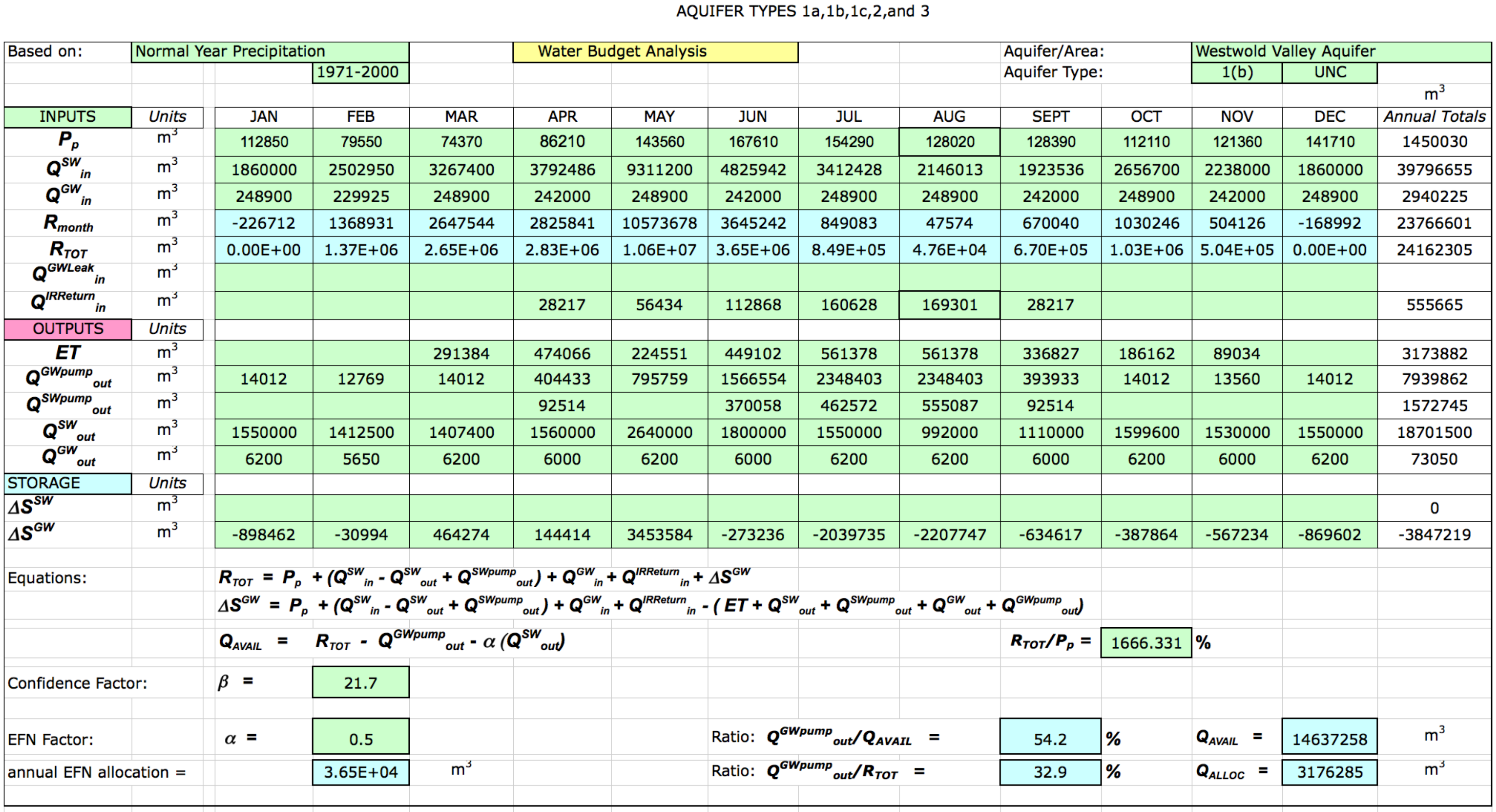
$Q_{AVAIL} =$ 1.54E+06 m^3

annual EFN allocation = 0.00E+00 m^3

Ratio: $Q^{GWpump}_{out}/R =$ 36.2 %

$Q_{ALLOC} =$ 2.31E+05 m^3

Table I2: Results of water budget analysis for 2011 for the Westwold Valley Aquifer.



AQUIFER TYPES 1a,1b,1c,2,and 3

Based on:	Normal Year Precipitation				Water Budget Analysis					Aquifer/Area:		Westwold Valley Aquifer		
			1971-2000							Aquifer Type:		1(b)	UNC	
														m^3
INPUTS	Units	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	Annual Totals
P_p	m^3	112850	79550	74370	86210	143560	167610	154290	128020	128390	112110	121360	141710	1450030
Q^{SW}_{in}	m^3	1860000	2502950	3267400	3792486	9311200	4825942	3412428	2146013	1923536	2656700	2238000	1860000	39796655
Q^{GW}_{in}	m^3	248900	229925	248900	242000	248900	242000	248900	248900	242000	248900	242000	248900	2940225
R_{month}	m^3	-226712	1368931	2647544	2825841	10573678	3645242	849083	47574	670040	1030246	504126	-168992	23766601
R_{TOT}	m^3	0.00E+00	1.37E+06	2.65E+06	2.83E+06	1.06E+07	3.65E+06	8.49E+05	4.76E+04	6.70E+05	1.03E+06	5.04E+05	0.00E+00	24162305
Q^{GWLeak}_{in}	m^3													
$Q^{IRReturn}_{in}$	m^3				28217	56434	112868	160628	169301	28217				555665
OUTPUTS	Units													
ET	m^3			291384	474066	224551	449102	561378	561378	336827	186162	89034		3173882
Q^{GWpump}_{out}	m^3	14012	12769	14012	404433	795759	1566554	2348403	2348403	393933	14012	13560	14012	7939862
Q^{SWpump}_{out}	m^3				92514		370058	462572	555087	92514				1572745
Q^{SW}_{out}	m^3	1550000	1412500	1407400	1560000	2640000	1800000	1550000	992000	1110000	1599600	1530000	1550000	18701500
Q^{GW}_{out}	m^3	6200	5650	6200	6000	6200	6000	6200	6200	6000	6200	6000	6200	73050
STORAGE	Units													
ΔS^{SW}	m^3													0
ΔS^{GW}	m^3	-898462	-30994	464274	144414	3453584	-273236	-2039735	-2207747	-634617	-387864	-567234	-869602	-3847219

Equations:

$$R_{TOT} = P_p + (Q^{SW}_{in} - Q^{SW}_{out} + Q^{SWpump}_{out}) + Q^{GW}_{in} + Q^{IRReturn}_{in} + \Delta S^{GW}$$

$$\Delta S^{GW} = P_p + (Q^{SW}_{in} - Q^{SW}_{out} + Q^{SWpump}_{out}) + Q^{GW}_{in} + Q^{IRReturn}_{in} - (ET + Q^{SW}_{out} + Q^{SWpump}_{out} + Q^{GW}_{out} + Q^{GWpump}_{out})$$

$$Q_{AVAIL} = R_{TOT} - Q^{GWpump}_{out} - \alpha (Q^{SW}_{out})$$

R_{TOT}/P_p = 1666.331 %

Confidence Factor: β = 21.7

EFN Factor: α = 0.5

annual EFN allocation = 3.65E+04 m^3

Ratio: $Q^{GWpump}_{out}/Q_{AVAIL}$ = 54.2 %

Ratio: Q^{GWpump}_{out}/R_{TOT} = 32.9 %

Q_{AVAIL} = 14637258 m^3

Q_{ALLOC} = 3176285 m^3

Table I3: Results of water budget analysis for the West of Aldergrove Aquifer.

AQUIFER TYPE 4b and 4c

Based on: Normal Year Precipitation 1945-2012

Water Budget Analysis

Aquifer/Area: West Aldergrove Aquifer

Aquifer Type: 4(b) UNC

INPUTS	*Units*	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	m^3 *Annual Totals*
P	mm													0
Q^{SW}_{in}	m^3													0
Q^{GW}_{in}	m^3	291524	263312	291524	282120	291524	282120	291524	291524	282120	291524	282120	291524	3432460
R_{month}	m^3	2411707	2178316	2411707	2333910	2411707	2333910	2411707	2411707	2333910	2411707	2333910	2411707	28395905
R	m^3	2.41E+06	2.18E+06	2.41E+06	2.33E+06	2.41E+06	2.33E+06	2.41E+06	2.41E+06	2.33E+06	2.41E+06	2.33E+06	2.41E+06	28395905
Q^{GWLeak}_{in}	m^3	2411707	2178316	2411707	2333910	2411707	2333910	2411707	2411707	2333910	2411707	2333910	2411707	28395905
$Q^{IRReturn}_{in}$	m^3													0
OUTPUTS	*Units*													
ET	mm													0
Q^{GWpump}_{out}	m^3	96822	99572	106780	117346	126450	147440	173765	159342	137646	112254	101143	98235	1476795
Q^{SWpump}_{out}	m^3													0
Q^{SW}_{out}	m^3													0
Q^{GW}_{out}	m^3	2577836	2328368	2577836	2494680	2577836	2494680	2577836	2577836	2494680	2577836	2494680	2577836	30351940
STORAGE	*Units*													
ΔS^{SW}	m^3													0
ΔS^{GW}	m^3	28573	13688	18615	4004	-1055	-26090	-48370	-33947	-16296	13141	20207	27160	-370
ΔS^{Lakes}	m^3													0

Revised Equations:

$$\Delta S^{GW} = (Q^{GW}_{in} + Q^{GWLeak}_{in}) - (Q^{GWPump}_{out} + Q^{GW}_{out})$$

$$R = Q^{GWLeak}_{in} = (Q^{GW}_{out} + Q^{GW}_{pumpout}) - (Q^{GW}_{in}) + \Delta S^{GW}$$

$$Q_{AVAIL} = R - Q^{GWpump}_{out} - \alpha Q^{GW}_{out}$$

Confidence Factor: β = 20.8

EFN Factor: α = 0

annual EFN allocation = 0.00E+00 m^3

Ratio: $Q^{GWpump}_{out}/Q_{AVAIL}$ = 5.5 %

Ratio: Q^{GWpump}_{out}/R = 5.2 %

Q_{AVAIL} = 2.69E+07 m^3

Q_{ALLOC} = 5.60E+06 m^3

Table I4: Results of water budget analysis for average year precipitation for the Mill Bay Aquifer.

AQUIFER TYPE 4a

Based on: Normal Year Precipitation 1977-2006

Water Budget Analysis

Aquifer/Area: Mill Bay Aquifer

Aquifer Type: 4(a) UNC

INPUTS	*Units*	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	m^3 *Annual Totals*
P	mm	201.4	138.7	117.9	68.5	48.9	39.5	23.3	28.3	37.4	109.7	220.9	206.2	3188154
Q^{SW}_{in}	m^3	50108	43900	31777	15364	5448	2210	1312	426	358	3289	23246	49531	226969
Q^{GW}_{in}	m^3													0
R_{month}	m^3	229577	149538	107917	25916	-31195	-49193	-47993	-21597	-7199	78928	242168	236079	912946
R_P	m^3	229577	149538	107917	25916	0	0	0	0	0	78928	242168	236079	1070123
Q^{GWLeak}_{in}	m^3													0
$Q^{IRReturn}_{in}$	m^3													0
OUTPUTS	*Units*													
ET	mm													
Q^{GWpump}_{out}	m^3	34535	37413	43169	46047	51803	57559	63315	66193	57559	46047	40291	31657	575588
Q^{SWpump}_{out}	m^3													0
Q^{SW}_{out}	m^3	45932	40324	29129	14084	4994	2025	1203	391	329	3015	21309	45403	208138
Q^{GW}_{out}	m^3	92806	89369	99681	98535	103118	98535	99681	97390	92806	93952	89369	90514	1145756
STORAGE	*Units*													
ΔS^{GW}	m^3	106412	26332	-32285	-117386	-154467	-155909	-162887	-163548	-150336	-60797	114445	118036	-632390
ΔS^{SW}	m^3													0
$\Delta S^{SWLakes}$	m^3													0

Equations:

$$R_P + Q^{SW}_{in} = Q^{SW}_{out} + Q^{GW}_{out} + Q^{GWpump}_{out} + \Delta S^{GW}$$

$$Q_{AVAIL} = R_{TOT} - Q^{GWpump}_{out} - \alpha Q^{GW}_{out}$$

$$R_{TOT} = R_P + Q^{SW}_{in}$$

Confidence Factor: β = 19.2

R_P/P = 33.6 %

EFN Factor: α = 0.5

Ratio: $Q^{GWpump}_{out}/Q_{AVAIL}$ = 387.3 %

Q_{AVAIL} = 148626 m^3

annual EFN allocation = 5.73E+05 m^3

Ratio: Q^{GWpump}_{out}/R_{TOT} = 44.4 %

Q_{ALLOC} = 28536 m^3

Table I5: Results of water budget analysis for driest period (1987-1989) precipitation for the Mill Bay Aquifer.

AQUIFER TYPE 4a

Based on:	Driest Year Precipitation			Water Budget Analysis				Aquifer/Area:		Mill Bay Aquifer			
			1989					Aquifer Type:		4(a)	UNC		
													m^3
INPUTS	*Units*	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	*Annual Totals*
P	mm	214.2	70.4	120.2	65	56	6.8	14.2	18.4	5.6	13.8	156.8	211.2	2448182
Q^{SW}_{in}	m^3	50108	43900	31777	15364	5448	2210	1312	426	358	3289	23246	49531	226969
Q^{GW}_{in}	m^3													0
R_{month}	m^3	188310	107984	167904	10078	-39594	-50392	-43193	-17997	-11998	30595	120102	152377	614176
R_P	m^3	188310	107984	167904	10078	0	0	0	0	0	30595	120102	152377	777350
Q^{GWLeak}_{in}	m^3													0
$Q^{IRReturn}_{in}$	m^3													0
OUTPUTS	*Units*													
ET	mm													
Q^{GWpump}_{out}	m^3	34535	37413	43169	46047	51803	57559	63315	66193	57559	46047	40291	31657	575588
Q^{SWpump}_{out}	m^3													0
Q^{SW}_{out}	m^3	45932	40324	29129	14084	4994	2025	1203	391	329	3015	21309	45403	208138
Q^{GW}_{out}	m^3	94252	87077	96243	95097	99681	96243	99681	98535	93952	97390	92806	95097	1146054
STORAGE	*Units*													
ΔS^{GW}	m^3	63699	-12930	31140	-129786	-151030	-153617	-162887	-164693	-151482	-112568	-11058	29751	-925461
ΔS^{SW}	m^3													0
$\Delta S^{SWLakes}$	m^3													0

Equations:

$$R_P + Q^{SW}_{in} = Q^{SW}_{out} + Q^{GW}_{out} + Q^{GWpump}_{out} + \Delta S^{GW}$$

$$Q_{AVAIL} = R_{TOT} - Q^{GWpump}_{out} - \alpha\, Q^{GW}_{out}$$

$$R_{TOT} = R_P + Q^{SW}_{in}$$

$R_P/P =$ 31.8 %

Confidence Factor: $\beta =$ 19.2

EFN Factor: $\alpha =$ 0.5

annual EFN allocation = 5.73E+05 m^3

Ratio: $Q^{GWpump}_{out}/Q_{AVAIL} =$ -398.9 %

Ratio: $Q^{GWpump}_{out}/R_{TOT} =$ 57.3 %

$Q_{AVAIL} =$ -144296 m^3

$Q_{ALLOC} =$ -27705 m^3

Table I6: Results of water budget analysis for average year precipitation for the Mill Bay Aquifer based on data from Rathfelder (2018)..

AQUIFER TYPE 4a

Based on: Normal Year Precipitation 1977-2006

Water Budget Analysis

Aquifer/Area: Mill Bay Aquifer

Aquifer Type: 4(a) UNC

INPUTS	Units	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	m^3 *Annual Totals*
P	mm	201.4	138.7	117.9	68.5	48.9	39.5	23.3	28.3	37.4	109.7	220.9	206.2	3188154
Q^{SW}_{in}	m^3	50108	43990	31777	15364	5448	2210	1312	426	358	3289	23246	49531	227059
Q^{GW}_{in}	m^3	10423	10037	11195	11066	11581	11066	11195	10937	10423	10551	10037	10165	128676
R_{month}	m^3	229430	149442	107848	25900	-31175	-49161	-47962	-21583	-7194	78877	242013	235928	912363
R_P	m^3	229430	149442	107848	25900	0	0	0	0	0	78877	242013	235928	1069438
Q^{GWLeak}_{in}	m^3													0
$Q^{IRReturn}_{in}$	m^3													0
OUTPUTS	*Units*													
ET	mm													
Q^{GWpump}_{out}	m^3	20051	21722	25064	26735	34467	44394	49931	51602	35614	26735	23393	18380	378088
Q^{SWpump}_{out}	m^3													0
Q^{SW}_{out}	m^3													0
Q^{GW}_{out}	m^3	108939	99101	94452	77997	71475	65938	66526	64942	62312	66408	82134	107638	967862
STORAGE	*Units*													
ΔS^{GW}	m^3	160971	82646	31304	-52402	-88913	-97056	-103950	-105181	-87145	-426	169769	169606	79223
ΔS^{SW}	m^3													0
$\Delta S^{SWLakes}$	m^3													0

Equations:

$$R_P + Q^{SW}_{in} + Q^{GW}_{in} = Q^{SW}_{out} + Q^{GW}_{out} + Q^{GWpump}_{out} + \Delta S^{GW}$$

$$Q_{AVAIL} = R_{TOT} - Q^{GWpump}_{out} - \alpha\, Q^{GW}_{out}$$

$$R_{TOT} = R_P + Q^{SW}_{in} + Q^{GW}_{in}$$

$R_P/P =$ 33.5 %

Confidence Factor: $\beta =$ 19.2

EFN Factor: $\alpha =$ 0.5

annual EFN allocation = 4.84E+05 m^3

Ratio: $Q^{GWpump}_{out}/Q_{AVAIL} =$ 67.1 %

Ratio: $Q^{GWpump}_{out}/R_{TOT} =$ 26.5 %

$Q_{AVAIL} =$ 563154 m^3

$Q_{ALLOC} =$ 108126 m^3

Table I7: Results of water budget analysis for driest period (1987-1989) precipitation for the Mill Bay Aquifer based on data from Rathfelder (2018).

AQUIFER TYPE 4a

Based on:	Driest Year Precipitation													
			1987-1989		Water Budget Analysis					Aquifer/Area:		Mill Bay Aquifer		
										Aquifer Type:		4(a)	UNC	
														m^3
INPUTS	*Units*	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	*Annual Totals*
P	mm	214.2	70.4	120.2	65	56	6.8	14.2	18.4	5.6	13.8	156.8	211.2	2448182
Q^{SW}_{in}	m^3	50108	43990	31777	15364	5448	2210	1312	426	358	3289	23246	49531	227059
Q^{GW}_{in}	m^3	10551	9779	10809	10680	11195	10809	11195	11066	10551	10937	10423	10680	128675
R_{month}	m^3	188190	107915	167797	10072	-39569	-50360	-43166	-17986	-11991	30576	120025	152279	613782
R_P	m^3	188190	107915	167797	10072	0	0	0	0	0	30576	120025	152279	776854
Q^{GWLeak}_{in}	m^3													0
$Q^{IRReturn}_{in}$	m^3													0
OUTPUTS	*Units*													
ET	mm													
Q^{GWpump}_{out}	m^3	20051	21722	25064	26735	34467	44394	49931	51602	35614	26735	23393	18380	378088
Q^{SWpump}_{out}	m^3													0
Q^{SW}_{out}	m^3													0
Q^{GW}_{out}	m^3	109325	98329	93294	76839	70317	65166	66526	65328	62698	67566	83292	109182	967862
STORAGE	*Units*													
ΔS^{GW}	m^3	119473	41633	92025	-67458	-88141	-96541	-103950	-105438	-87403	-49499	47009	84928	-213362
ΔS^{SW}	m^3													0
$\Delta S^{SWLakes}$	m^3													0

Equations:

$$R_P + Q^{SW}_{in} + Q^{GW}_{in} = Q^{SW}_{out} + Q^{GW}_{out} + Q^{GWpump}_{out} + \Delta S^{GW}$$

$$Q_{AVAIL} = R_{TOT} - Q^{GWpump}_{out} - \alpha\, Q^{GW}_{out}$$

$$R_{TOT} = R_P + Q^{SW}_{in} + Q^{GW}_{in}$$

$R_P/P =$ 31.7 %

Confidence Factor: $\beta =$ 19.2

EFN Factor: $\alpha =$ 0.5

Ratio: $Q^{GWpump}_{out}/Q_{AVAIL} =$ 139.7 %

$Q_{AVAIL} =$ 270569 m^3

annual EFN allocation = 4.84E+05 m^3

Ratio: $Q^{GWpump}_{out}/R_{TOT} =$ 33.4 %

$Q_{ALLOC} =$ 51949 m^3