PHYSICAL MEASUREMENTS OF GROUNDWATER CONTRIBUTIONS TO A LARGE LAKE

by

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Abstract

Population increases and climate change are expected to increase water stress in the semi-arid Okanagan Valley in the Interior of British Columbia. Groundwater discharge from the largest unconsolidated aquifer system in the Okanagan Valley to Okanagan Lake was directly measured between September 2011 and August 2013. Seepage meter measurements (331) and gradient calculations (73) were used to measure flow from the Kelowna aquifers in an effort to constrain groundwater values in a basin-scale water-balance model constructed to inform water use and planning decisions within the Okanagan Valley.

The complexity of the subsurface environment in the Kelowna area led to the construction of a 2-D MODFLOW transect to provide a sensitivity analysis of the percentage of total flow captured within the study area using a reasonable range of hydraulic conductivity values for the known confining and confined layers. Forty-two MODFLOW scenarios estimated 26% - 100% of the total flow from the Kelowna aquifers to Okanagan Lake was captured within the study area.

Long-term station seepage meter measurements showed a large range of annual variability with flux measurements which ranged from 10^{-11} to $10^{-9}/10^{-8}$ $m^3/m^2/s$. A substantial reduction in flows observed within the study area between study year one (4.1×10^5 m^3) and study year two (2.9×10^5 m^3) was potentially due to anthropogenic water extractions. The annual groundwater discharge estimate of 3.7×10^5 m^3 found flow from the Kelowna aquifers to be less than one percent of some previous estimates and likely less than seven percent of the volume being extracted from upgradient aquifers. Long-term provincial potentiometric monitoring indicated groundwater pumping rates have likely exceeded recharge in some Kelowna aquifers for the past 34 years. Other studies using modelling and geochemistry have suggested groundwater pumping is inducing recharge from adjacent fluvial water bodies in some areas.

The low discharge from the Kelowna aquifers to Okanagan Lake suggests cautious groundwater extraction rates need to be established in the Kelowna area to ensure the groundwater system can continue to support both human and environmental water needs.

Preface

Interim study results were published as:

Pyett, N. and Nichol, C. (2013). Physical measurements of groundwater contributions to a large lake. Conference proceedings from GeoMontreal: 66th Canadian Geotechnical Conference & 11th Joint CGS/IAH-CNC Groundwater Conference.

The paper is included in its entirety as Appendix G. The conference organisers, the Canadian Geotechnical Society (CGS), retain no copyright to the papers reproduced in the conference proceedings.

The text in the paper was wholly written by N. Pyett with editing contributions from C. Nichol. No sections of the paper have been fully reproduced within the thesis but portions of the background material (e.g. groundwater/surface water interactions) have been integrated into the thesis document. Figure 1 from Pyett & Nichol (2013) was created by C. Nichol but was not reused in the thesis. Figure 2 was a previously published figure (Roed and Greenough, 2004) which benefitted from overlays completed by C. Nichol. This figure was reused as thesis Figure 2.11 (with permission from C. Nichol and the copyright holder of the original figure). Results released in Pyett and Nichol (2013) were based only on data collected in the first year of a two year research project. The initial understanding of the results discussed within the paper were expanded on and clarified throughout Chapters 4 and 5 of the thesis document.

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To Erik, I hope all this work supports our hope of having more time together and inspires you to work hard towards any goal that makes you happy.

CHAPTER 1: INTRODUCTION

Projected population increases and potential climate change effects have led to concerns about future water availability in British Columbia's semi-arid Okanagan Valley. Relatively low precipitation rates and high domestic water use rates, coupled with the almost total allocation of local freshwater resources, prompted a local government watershed agency, the Okanagan Basin Water Board (OBWB), to initiate a basin-wide water supply and demand model (Okanagan Basin Water Board, 2011a). This model theoretically identifies all water within the Okanagan and describes its movements from precipitation to drainage out of the Okanagan basin. It is used to predict the specific impacts of climate change, and the implementation of water management strategies, on water availability within the basin. The OBWB uses this tool to assist regional and local governments conduct planning and to educate the public about water management issues.

Extensive research on surface water, groundwater, evaporation, human water use and water management issues, and environmental instream flow needs was completed prior to the creation of the Okanagan Supply and Demand Project (Phase II) MIKE-SHE model to ensure it accurately represented water movement and storage in the natural environment (Figure 1.1). Groundwater/surface water interactions were identified as one of the largest potential sources of error within the model due to a general lack of available hydrogeological information (Summit Environmental Consultants Ltd., 2010). A detailed study accurately quantifying groundwater/surface water flows within a strategically selected discrete area could be used to improve the calibration of the overall regional model. The Kelowna shoreline on Okanagan Lake was identified as an area of research interest because the Kelowna aquifers contain the largest volume of unconsolidated aquifer storage within the valley and were estimated to provide the sixth largest groundwater flow into Okanagan Lake (Golder Associates and Summit Environmental Consultants Ltd., 2009), (Figure 1.2). The Kelowna area also hosts the largest population within the valley. Human activities in the area, such as pumping, irrigation, and urban leakage, escalate the complexity of modelling groundwater/surface water interactions and increase the value of directly measuring groundwater discharge at this site.

Groundwater discharge into lacustrine environments can be difficult to quantify accurately due to its temporal and spatial variability. Recharge to groundwater systems can vary annually and inter-annually with precipitation volume and distribution changes. Fluctuations in the relative and absolute height of the receiving water body over time impact the hydraulic gradient driving groundwater flow. The spatial distribution of groundwater flows is largely controlled by the distribution of hydraulic conductivity (K) in the unconsolidated sediments, which is determined by historical sediment deposition regimes and current conditions at the sediment/water interface. Physical measurement studies must ensure an adequate spatial coverage and temporal extent to accurately describe groundwater discharge to a lake.

1.1 Objectives

This project aims to measure groundwater discharge from the Kelowna aquifers to Okanagan Lake and improve the understanding of groundwater/surface water interactions in the Kelowna area.

To support these goals, the study was developed to meet the following objectives:

1) Directly measure groundwater discharge from the Kelowna aquifers to Okanagan Lake.
    a. Investigate the spatial and temporal distribution of groundwater discharge within the study area;
    b. Ensure adequate spatial coverage of high flow areas to quantify groundwater flux rates within the study area;
    c. Compare the results of multiple flux measurement methods to constrain results; and
    d. Examine the potential routes of groundwater discharge from any confined aquifers to the lake.
2) Investigate the potential implications of the observed groundwater discharge volume and patterns.
    a. Compare groundwater flux rates observed at the Kelowna study site with other studies;

b. Relate the long-term groundwater flux record with other parameters (water levels in the adjacent aquifers, surface water discharge volumes, precipitation, and lake levels) for potential transferability of estimates to other study locations; and
c. Place the resulting groundwater flow estimation in a regional water budget context.

1.2 Research Value

The results of this research will provide a direct measured estimate of the total groundwater discharge from the Kelowna aquifers which can be used for water resource planning. It will allow the OBWB Supply and Demand model to become a better tool for anticipating the impacts of water management decisions and climate change on the Okanagan Valley water supply. Additionally, results of this research can be used to validate previous water-balance modelling attempts undertaken in the Kelowna area or to quantify groundwater flow to assist future groundwater contaminants research.

1.3 Thesis Format

This thesis is organized into six chapters and seven appendices. Chapter 1 describes project initiation and outlines the main study objectives. Background materials can be found in Chapter 2 including: site specific geology, hydrology, climate, hydrogeology and groundwater/surface water interactions information; a groundwater discharge and measurement methods literature review; and an explanation of the approach developed for this study. The methods descriptions in Chapter 3 outline specific steps taken to quantify groundwater discharge into Okanagan Lake. Field data and the results of modelling are then processed and reported as results in Chapter 4. Chapter 5 discusses factors affecting the pattern of groundwater discharge on site, the impacts of error and variability on the overall flow calculation, and places the calculated annual groundwater discharge volumes in a regional context. The relative usefulness of the different field methods and the range of MODFLOW scenario results are also discussed. Conclusions are listed in Chapter 6 along with suggestions for future related research.

Appendices A to G include all associated large data sets, such as precipitation data, raw seepage meter measurements, and supplementary materials such as seepage meter designs and a conference paper reporting interim results.

CHAPTER 1: FIGURES

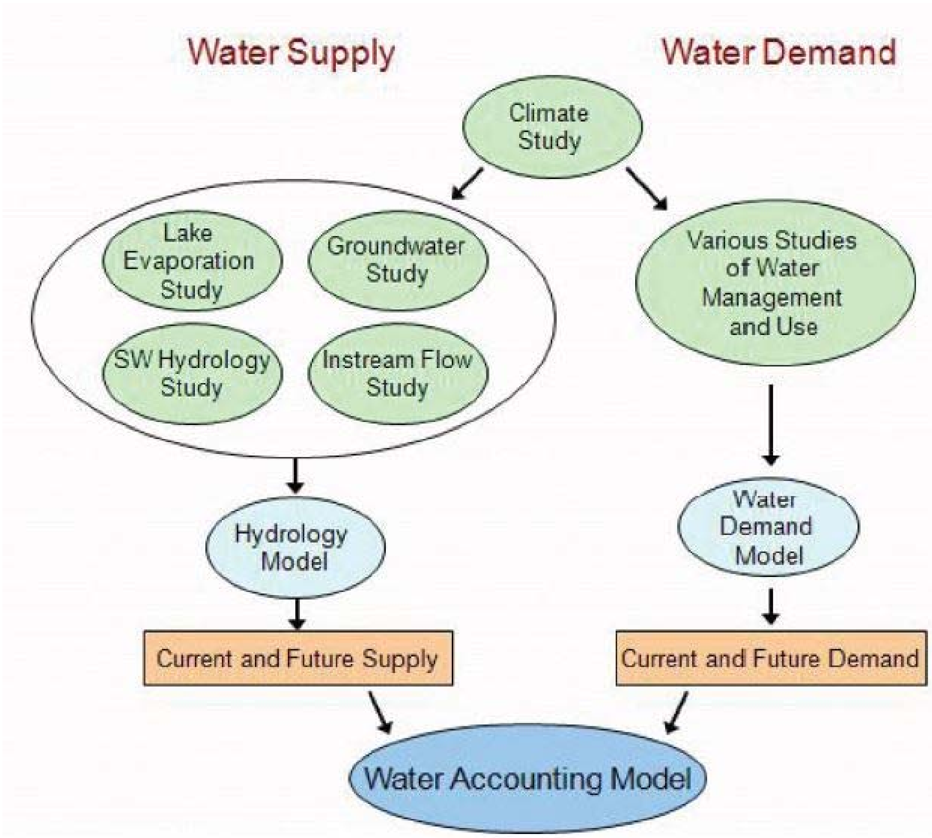


Figure 1.1 Okanagan Supply and Demand Project – Water Accounting Model background studies and models (Source: Summit Environmental Consultants Ltd., 2010).

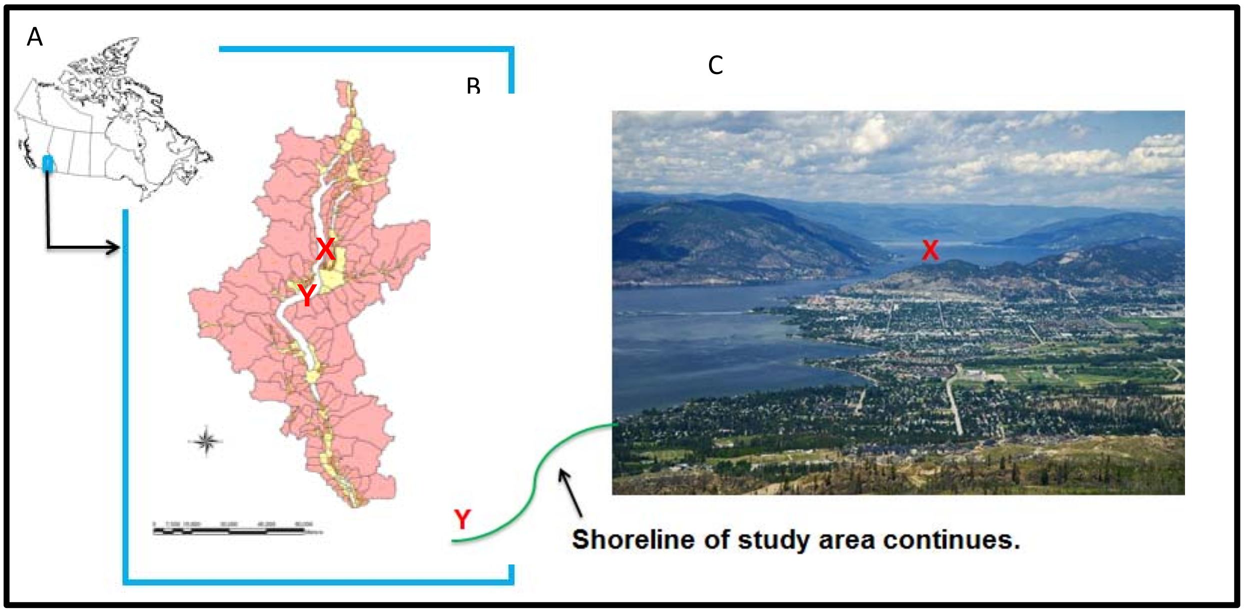


Figure 1.2 Study location including: (A) location of Okanagan Basin within Canada (B) location (X to Y) of main study area within the Okanagan Basin (modified from Golder Associates and Summit Environmental Consultants Ltd., 2009), and (C) oblique view of study area.

CHAPTER 2: BACKGROUND

2.1 Literature Review

2.1.1 Patterns of Groundwater Discharge in Large Water Bodies

Groundwater is observed to flow from recharge areas to discharge areas (such as lakes) through sediments along a hydraulic gradient (Winter, 1999). In a homogeneous and isotropic unconfined aquifer discharging to a straight shoreline in steady state conditions, discharge to a lake decreases exponentially with increasing distance from shore (Figure 2. 1), (McBride and Pfannkuch, 1975). The distance from shore at which the specific discharge falls below the minimum detectable level of the measurement method (L_{ND}, metres) is dependent on the magnitude of the hydraulic gradient (Munter and Anderson, 1981), the slope angle of the lakebed (Yong et al., 2007), the hydraulic conductivity of lakebed sediments (Munter and Anderson, 1981), and the sensitivity of the flux measurement equipment (LaBaugh and Rosenberry, 2008). Natural aquifer/lacustrine systems are typically comprised of heterogeneous sediments and receive transient recharge creating temporally and spatially variable groundwater discharge patterns. Groundwater discharge to a lake is influenced by sediment heterogeneities, shoreline profile shape, and regional hydraulic gradient changes.

2.1.1.1 Sediment heterogeneity

Hydraulic conductivity along a flow path is determined by the historical depositional environment and the modern sediment depositional and transport processes occurring at the sediment/water interface. Historical fluvial, lacustrine, glacial and deltaic depositional settings create geologic patterns in the subsurface that facilitate or restrict groundwater flow. Fluvial systems can create conduits of high K materials while low K glaciolacustrine sediments can confine flow.

Many processes create spatial heterogeneity at the sediment/water interface in lacustrine environments including fluvial activity at points of inflow to a lake and edge effects such as shoreline currents and wave action (LaBaugh and Rosenberry, 2008). The type of sediment arriving at the lacustrine sediment/water interface from fluvial activity is dictated by the energy of the surface water flows and the material available from the contributing basin. Seasonal high surface water runoff volumes can scour sediments from river beds or deltaic fans and transport them to places of secondary deposition within the lake. Shoreline currents and waves are capable of repositioning sediments; increasing or decreasing the hydraulic conductivity at the sediment/water interface. Scouring removes fine material and leaves coarser sediments in place while deposition of fines can decrease hydraulic conductivity and therefore decrease groundwater flow rates. The ability of wave movements to control sediment distributions decreases with water depth as the circular motion of waves is attenuated with distance from the surface (Wetzel, 2001). Areas of the lakebed affected by wave action can be referred to as "within wave base" while the sediment/water interface in deeper portions of the lake is "out of wave base".

Researchers studying groundwater discharge into lakes and oceans have uncovered flow heterogeneities: across study areas (Cable et al., 1997a), with distance out from shore (Woessner and Sullivan, 1984; Shaw and Prepas, 1990b; Cable et al., 1997b; Schneider et al., 2005), and within individual sampling locations (Shaw and Prepas, 1990a). Differences between flux rates across study areas were investigated by the installation of flux measurement equipment in transects parallel to the shoreline (Cable et al., 1997a) or by comparing point measurements collected in different areas (Attanayake and Waller, 1988; Boyle, 1994; Sebestyn and Schneider, 2001; Schneider et al., 2005; Kidmose et al., 2011). Sampling location scale (small scale) heterogeneities were investigated by measuring flux at multiple points in a two metre by two metre area to characterize flux variability (Shaw and Prepas, 1990a; Boyle, 1994).

2.1.1.2 Shoreline profile shape

High energy fluvial systems release sediment when they reach a less energetic lacustrine system forming a delta with topset, foreset and bottomset beds (Figure 2.2). Build-up of sediments within the river channel can cause the river to breach its banks and find a new route to the lake, creating a new delta or lobe. Fine materials can be removed from inactive deltas by currents and waves and the angle of foreset beds increases with coarser sediment types (Ritter et al., 2006). Prior discharge studies have shown that steeper shoreline profiles release less total flow than gradual shoreline profiles but distribute the discharge more evenly across the seepage face (Yong et al., 2007). Bottomset beds are primarily comprised of low hydraulic conductivity clays (Ritter et al., 2006); limiting flow in those areas.

2.1.1.3 Changes in regional hydraulic gradient

Groundwater discharge rates to non-perched lakes fluctuate in time due to changes in hydraulic gradient. These changes are driven by a combination of upgradient and downgradient controls. Upgradient water table height is influenced by temporally variable precipitation, seasonal recharge, and other natural and human groundwater recharges and withdrawals. The elevation of the surface of the downgradient receiving water body can be controlled by natural drainage patterns, human controls in dammed systems, and wind driven water movements within the lake (currents and seiche). Dammed lakes held at high water levels may decrease groundwater discharge through the creation of an artificially decreased regional gradient. Surface seiche, observed as oscillations (or rocking) of lake water in a basin, is caused by water mounding after strong one-directional wind activity. Changes to the surface height of a lake observed during a seiche event have been shown to affect instantaneous groundwater discharge rates (Taniguchi and Fukuo, 1996). The impact of seiche events on groundwater discharge measurements collected over longer periods of time is dependent on the oscillation period and magnitude (Wetzel, 2001). Small magnitudes would be resolved within measurement error and sampling intervals substantially longer than the oscillation period should integrate impacts to groundwater discharge.

The period of an oscillation has been observed to range from minutes to fourteen (14) hours and can be estimated in a simple rectangular lake using (Wetzel, 2001):

$$t = \frac{2l}{\sqrt{g\bar{z}}} \qquad [1]$$

Where the period (t, seconds) equals twice the length of the basin at the surface (l, metres) divided by the square root of the acceleration of gravity (g, 9.81 m/s^2) multiplied by the mean depth of the basin ($\bar{z}$, metres).

Observed oscillations have had magnitudes between one (1) mm and two (2) metres (Taniguchi and Fukuo, 1996; Wetzel, 2001). The magnitude of an oscillation is related to the force applied by the wind so larger magnitudes are generally observed in larger lakes. Actual magnitude and period of a seiche event can be complicated by basin morphology and wind direction changes.

The temporal distribution of discharge to large water bodies has been investigated using measurement of groundwater discharge at one location (Boyle 1994; Cable et al. 1997b; Sebestyen and Schneider, 2001; Taniguichi et al., 2003; Schneider et al., 2005). Intervals between sampling have ranged from 30 minutes (Cable et al., 1997b) to years (Boyle, 1994; Schneider et al., 2005), depending on flow rates and project logistical constraints. Many study locations have found evidence of intra-annual variation (Woessner and Sullivan, 1984; Krillin et al., 2010). Variations in inter-annual groundwater discharge have been observed by Boyle (1994), Cable et al. (1997b), Sebestyen and Schneider (2001), Schneider et al. (2005) and Krillin et al. (2010). The largest inter-annual variability was found by Cable et al. (1997b) with discharge varying by up to 50% between subsequent years.

2.1.2 Methods in Groundwater/Surface Water Interactions

Locating sites of groundwater discharge and quantifying groundwater flux rates can be accomplished using physical, temperature, chemical, biological, regional groundwater modelling, or water-balance techniques. A series of submarine groundwater discharge (SGD) experiments and method comparison trials were summarized in review papers by Taniguchi et al. (2002) and Burnett et al. (2006). These papers were selected as an introduction to common methods used in groundwater/surface water interactions research. The United States Geological Survey's (USGS) comprehensive "*Field techniques for estimating water fluxes between surface water and ground water*" (Rosenberry and LaBaugh, 2008) further directed method literature review efforts (Table 2.1).

2.1.2.1 Physical Methods

Physical methods quantify groundwater movement by measuring groundwater fluxes, or hydraulic heads and the hydraulic conductivity of sediments, using direct measurement equipment such as seepage meters (Figure 2.3a) or piezometers (Figure 2.3b).

Lee-type seepage meters (Lee, 1977), built from sections of a 208 L steel drum, capture groundwater fluxes across the sediment/water interface in a water collection bag (Figure 2.3a). They can be used in lacustrine, marine and fluvial environments. Vertical flux rates (q, $m^3/m^2/s$, calculated from: volume of water collected / area of sediment-water interface / known amount of time), can then be converted to groundwater flows (Q, m^3/s) by applying the flux measurement to an applicable area. The Lee (1977) seepage meter design has undergone modern adjustments such as pre-filling and shielding groundwater discharge collection bags with covers to prevent anomalous influxes of water (LaBaugh and Rosenberry, 2008; Brodie et al., 2009). Collection bag covers can be directly attached to the seepage meter (Zamora, 2008) or be placed next to the seepage meter at the sediment water interface (Brodie et al., 2009) (Figure 2.4).

Control measurements are used to quantify the impacts of wave action, long-shore currents, and other factors on a seepage meter measurement by excluding groundwater discharge from the collection bag during a trial. This can be accomplished by installing a standard seepage meter over an impermeable barrier such as a “kiddie pool” placed at the sediment/water interface and filled with sediment (Cable et al., 1997b). Control measurement error estimates are then applied to all seepage meter measurements. Cable et al. (1997b) used control measurements to show the presence of wave action increases the variability of groundwater flux measurements (ie. increased standard deviation) and that therefore measurements taken below wave base are expected to more precisely measure actual groundwater flux rates than measurements taken within wave base.

Seepage meter measurements often support other primary investigation methods such as water-balance or temperature modelling (Kidmose et al., 2011; Smerdon et al., 2005; Jensen and Engesgaard, 2010). Seepage meters generally underestimate actual flux so a correction factor is applied to measurements to adjust for frictional flow loss within the meter, restrictions to flow through connectors, and resistance to bag expansion and contraction. Correction rates chosen have ranged between 1.05 and 1.84, depending on the bag type and diameter of the tubing selected (LaBaugh and Roseberry, 2008).

Discharge can be measured by combining measurements of hydraulic gradient and hydraulic conductivity. Gradient methods use Darcy's Law to calculate groundwater flux rates:

$$q = K \frac{(h_1 - h_2)}{\Delta l} \qquad [2]$$

Where the flux rate (q, $m^3/m^2/s$) equals the sediment hydraulic conductivity (K, m/s) multiplied by the hydraulic gradient (change in hydraulic head over distance, m/m). This method can be applied over kilometres to investigate study site scale gradients or over metres to examine vertical flux gradients along the shoreline. It can include lateral and/or vertical components of flow. Large scale investigations may use hydraulic heads measured in water wells and surface water bodies to calculate gradient while the hydraulic conductivity may represent the average K water will encounter along the flow path (LaBaugh and Rosenberry, 2008). The use of piezometers installed directly into the lake bed at multiple depths can estimate the vertical hydraulic gradient in sediments along the shoreline. The hydraulic conductivity of these sediments can be estimated by performing constant or falling head tests on sediment samples in situ or in a lab.

2.1.2.2 Thermal Methods

Thermal methods exploit differences in temperature between groundwater and surface waters to quantify groundwater fluxes within a study area. Surface waters are generally colder than groundwater in the winter and warmer in the summer. Deep groundwater temperature is a relatively constant function of average annual air temperature at some depth (~ 10 metres or more) below ground surface (Stonestrom and Constantz, 2003; Figure 2.5). Groundwater flow investigations using measurements of water temperature can be completed from an airplane-mounted Thermal-Infrared-Multispectral Scanner (TIMS), down a borehole, or as a vertical profile through sediments.

A TIMS temperature analysis collects thermal images of bodies of fresh surface water or marine shorelines to estimate locations of groundwater discharge. Changes in the background temperature of surface water can identify locations of high groundwater discharge but this method cannot quantify a groundwater discharge rate (Banks et al., 1996). This method is very useful in preliminary investigations to guide the locations of future targeted groundwater/surface water investigations in places with high flux rates. Preliminary calculations suggested that flux rates in the Kelowna study area were not expected to produce the changes in surface water temperature required for success of this method.

Numerical modelling software is capable of quantifying groundwater flow in saturated or variably saturated porous sediments using coupled heat and groundwater flow equations. Various software packages (VS2DI, SWIM, HYDRUS, MODFLOW, FEFLOW, etc.) can be used to create one-, two- or three-dimensional models of groundwater flow and heat transport from temperature point measurements collected down a borehole or through sediments below the sediment/water interface (Healy, 2008). Borehole temperature measurements can be representative of conditions in the adjacent aquifer if vertical movement of water within the borehole is controlled (Anderson, 2005). Temperature changes due to water advection in a stream or lake bed can be tracked using temperature sensors placed at two or more depths within the sediment (Constantz, 2008). Impacts of groundwater advection on temperature gradients will vary with season and direction of groundwater flow (Table 2.2). Thermal profiling methods were originally selected for use on the Kelowna site but many of the flux rates through the sediment/water interface were quickly found to be smaller than the lower usable bound of ~1 x 10^{-7} $m^3/m^2/s$ (McGrath, 2010).

2.1.2.3 Chemical Methods

Chemical methods take advantage of chemical differences between groundwater and surface water. This may include electrical conductivity, isotopes, water quality or in marine environments, salinity. Tracers can be artificially added to a natural system to determine groundwater velocity. Measurements of deep groundwater chemistry, in-situ sediment water chemistry, and the chemistry of the overlying surface water body are typically combined using modelling to separate the contribution of groundwater to the surface water body.

2.1.2.4 Biological Methods

Biological community composition can be used to track groundwater discharge in some locations (Rosenberry et al., 2000). The presence or absence of certain biological indicator species can be used to locate groundwater discharge locations for further study. This method was not applicable at the Kelowna site due to the limited amount of nearshore vegetation and the dominance of invasive Eurasian Milfoil which is not useful as a groundwater discharge indicator species.

2.1.2.5 Numerical modelling

Regional numerical modelling can quantify groundwater recharge to, and discharge from, an aquifer using data from the natural system and finite-difference (eg: MODFLOW) or finite-element code (eg:. FEFLOW, etc.). Though time intensive, this technique can provide a powerful investigative tool if: there is an appropriate amount of data available, the problem is well defined, and care is taken to adequately translate the conceptual model of the groundwater flow system into the computer model program (Reilly and Harbaugh, 2004). The limitations of the selected computer program and any inherent assumptions of the model must be well understood to avoid creating unrealistic results.

Aquifer discharge rates to a lake can also be estimated by modelling two-dimensional transects along a flow line moving from shore into the lake. This simplified version of a regional model can be used to directly investigate the impacts of variably sized sediments (along the flow path or at the sediment/water interface) on the aquifer discharge rate (Munter and Anderson, 1981; Krabbenhoft and Anderson, 1986).

2.1.2.6 Water-balance estimations

Water-balance estimations calculate aquifer discharge or recharge using:

$$\sum Inflows - \sum outflows = \Delta S \qquad [3]$$

Where the sum of all water moving into an aquifer (*ΣInflows*) minus the sum of all water moving out of an aquifer (*ΣOutflows)* equals the change in groundwater storage (*ΔS*). Water-balance estimations are only useful if they accurately represent all inflows and outflows to a system.

2.1.2.7 Sampling design and results reporting

Measurements taken must cover the spatial and temporal variability at the study site to create a reasonable estimate of groundwater flow (LaBaugh and Rosenberry, 2008). Spatial variability investigations may include the installation of many individual point measurements or patterns of installations such as clusters of multiple point measurements or transects parallel or perpendicular to shore (Isiorho et al., 1996; Cherkauer and Carlson, 1997; Cox et al., 2007; Fryar et al. 2007; Kennedy et al., 2010; Ala-aho et al., 2013; Kidmose et al., 2013). Temporal variation can be investigated by taking more than one measurement at the same location (Shaw and Prepas, 1990b; Isiorho et al., 1996; Cox et al., 2007; Fryar et al., 2007). Control measurements should be collected to describe minimum equipment and measurement errors.

There are a wide variety of ways to report flows or fluxes within a study area. Overall flow rates within a study area can be estimated by integrating flux rates collected from transects installed perpendicular to the shoreline. These results can be reported as flow per unit of shoreline (Cable et al., 1997a) or be extrapolated out to an entire lake (Shaw and Prepas, 1990b). Change in repeated measurements over time at the same location can be graphed to visualize groundwater flow direction changes from groundwater recharge to groundwater discharge (Cherkauer and Carlson, 1997). Alternately, overall estimates of study area discharge have been reported as average flux within a study area (Schneider et al., 2005) or as a percentage of surface run off to support discussions on the significance of groundwater discharge within regional water budgets (Taniguchi et al., 2002). Groundwater flux has been graphically added to site maps (Schneider et al., 2005) and mapped as contoured seepage flux data across an entire lake (Boyle, 1994).

2.2 Site Background

2.2.1 Study Site

The study site is on the eastern side of Okanagan Lake adjacent to the City of Kelowna where a system of aquifers discharges to Okanagan Lake (Figure 1.2). The bedrock of Knox Mountain in the north (49˚54'22.54" N, 119˚29'42.01" W) and Okanagan Mountain Park in the south (49˚47'12.15" N, 119˚33'43.24" W) form the natural boundaries of the unconsolidated Kelowna aquifers. Okanagan Lake is a large, deep valley lake situated within the Okanagan Valley in the hilly to mountainous southern interior of British Columbia, Canada (Figure 2.6). The lake is approximately 120 x 3.5 km with a surface area of 351 km^2 (Summit Environmental Consultants Ltd., 2005) and a maximum depth of 232 m (Roed and Greenough, 2004). Water levels in Okanagan Lake are controlled to balance flood protection, water demand, fish needs, navigation, and recreational values by the B.C. Ministry of Forests, Lands and Natural Resource Operations (MFLNRO; previously the BC Ministry of Environment, MOE) as part of the regional Water Management Program (Symonds, 2000). The average lake elevation of 342 metres above sea level (masl) is significantly below the heights of 2000 masl reached in the nearby mountains.

The City of Kelowna covers approximately 200 km^2 of land and is the Okanagan's most populated area with over 100 000 inhabitants. Domestic water use in the Kelowna area is much higher than the national average (Okanagan Basin Water Board, 2011c). Eight-six percent (86%) of Okanagan water consumption is destined for outdoor seasonal applications such as agriculture, outdoor residential, and parks (Okanagan Basin Water Board, 2011b). Land use along the shoreline of the study area is primarily zoned for residential and public park use, interspersed with small industrial areas in the north and agricultural areas in the south. The majority of the shoreline is accessible to the public.

2.2.2 Climate

Precipitation within the Kelowna area is impacted by spatial and temporal distribution patterns. Spatially, precipitation is topographically driven with valley bottom areas receiving 380 mm of precipitation annually (Environment Canada, 2013a) while higher elevations receive over 1000 mm/yr (Golder Associates and Summit Environmental Consultants Ltd., 2009), (Figure 2.7). Seasonally, Kelowna receives the most rain in June and the lowest total precipitation in March (Figure 2.8; Environment Canada, 2013a). Snow makes up approximately ¼ of valley bottom precipitation. It sublimates to the atmosphere or is stored at surface until it is released to surface water or groundwater when temperatures exceed 0˚ Celsius. Inter-annual variability of total precipitation is +/- 60 mm (16%) within available data between 1994 and 2006 (Environment Canada, 2013b).

Evaporation rates from the mainstem lakes in the Okanagan have been estimated at between 400 – 1000 mm/year (Summit Environmental Consultants Ltd., 2009) and are currently under investigation by Environment Canada (Okanagan Basin Water Board, 2011c). Evaporation-driven lake level decreases tend to increase local hydraulic gradients and increase groundwater discharge to Okanagan Lake.

Biogeoclimatic zones in the Okanagan progress from Bunchgrass Zone (BG) on the valley floor to Ponderosa Pine (PP), Interior Douglas Fir (IDF), Interior Cedar Hemlock (ICH), Montane Spruce (MS), and Engelmann Spruce-Subalpine Fir (ESSF) at higher elevations (Summit Environmental Consultants Ltd., 2009). Potential evapotranspiration rates in the Okanagan have been calculated at higher than actual evapotranspiration rates at all elevations (Summit Environmental Consultants Ltd., 2009).

2.2.3 Hydrology

There are six major creeks within the study area, which are from north to south: Brandt's Creek, Mill (Kelowna) Creek, Fascieux Creek, Wilson Creek, Mission Creek, and Bellevue Creek (Figure 2.9). Mission Creek is the largest creek in the Okanagan and is estimated to contribute 2.5×10^8 m^3/year, or 28% of the total surface water inflow, to Okanagan Lake (Summit Environmental Consultants Ltd., 2009). Surface water flows in the Okanagan are highly seasonal with 86% of the total stream flow occurring between March and July with snowmelt contributing 75% of total streamflow (Summit Environmental Consultants Ltd., 2009). This strong seasonality allows hydrological processes to impact groundwater recharge and discharge rates within the study area. Groundwater discharge to creeks provides much of the surface flow during low flow times of year (November to March) and all of the surface flow when temperatures are below 0˚C. During the low flow period, creeks have a relatively small wetted perimeter and there is an accumulation of fines at the sediment/water interface. Groundwater recharge occurs when the hydraulic gradient is reversed by the rise in creek stage, driving water out of the creek and into the ground (Schwartz and Zhang, 2003) as well as in locations where creeks from bedrock upland areas first enter the valley floor (Welch and Allen, 2012). High volume flows also increase the "leakiness" of creeks as fine sediments are scoured and the size of the wetted perimeter expands. High surface water flows during freshet and storms transport the majority of the annual sediment contributions to Okanagan Lake.

No reports on surface seiche in Okanagan Lake have been completed to date. Equation 1 estimates a seiche period of 153 minutes (2.5 hrs) for the 120 km long Okanagan Lake. This is likely an overestimate as the loosely "s" shape of Okanagan Lake would create a maximum fetch of 60 kilometres (DataBC, 2013). The average seiche magnitude in Okanagan Lake is likely small as observed in other similarly sized lakes (< 1 cm, Laval and Imberger, 2003; "a few centimetres", Prigo et al., 1996) due to the low average wind speed (< 10 km/hr[1]; Windfinder, 2014). Winds associated with large storm events could create seiche events with larger magnitudes.

2.2.4 Geology

Okanagan Valley bedrock is comprised of Precambrian to Pleistocene aged materials excised deeply into a north to south oriented "V" shape by glacial activity (Roed and Greenough, 2004). Valley areas were subsequently infilled with up to 750 m of Pleistocene and recent sediments of glacial, glaciolacustrine and fluvial origin (Roed and Greenough, 2004; Figure 2.10). A geologic cross section through a portion of the study area (C-C' on Figure 2.6) outlines the basic stratigraphy in the Kelowna area (Figure 2.11). An important feature in the near surface is the silt and clay confining layer created by the presence of proglacial Lake Penticton approximately

[1] Corresponds to a "light breeze" on the Beaufort Wind Scale (National Oceanic and Atmospheric Administration, 2014).

11 000 years ago (Paradis et al., 2010). This low hydraulic conductivity layer forms an aquitard between the more recent fluvially deposited water-bearing deltaic silts, sands and gravels found at surface from the older glacial tills and interglacial gravels found lower in the profile.

The current bed of Okanagan Lake has been investigated using seismic reflection techniques (Eyles et al, 1990), but this study lacked ground truthing by drilling. The lake bed is comprised of less than 25 m to 60 m of interbedded silts and fine sands deposited during deglaciation (Eyles et al. 1990). Deeper portions of the lake, undisturbed by recent fluvial activity, are covered with modern lacustrine deposits comprised of approximately 50% silt and 50% clay (St. John, 1973). Deltaic building processes continue along the boundaries of Okanagan Lake at intersections with creeks (Figure 2.9). Sediment accumulation occurs constantly at these locations but peaks during high seasonal surface water flows when higher energy water can transport larger grain sizes and volumes of sediments from contributing basins. Dominant shoreline sediments within the study area range from fines to cobbles; depending on the prevailing sediment deposition regime and the presence of lake currents and/or wave activity at the site. Mission Creek and Bellevue Creek alluvial fans are still actively building, receiving up to boulder-sized sediments from glacial tills in their contributing basins. Sediments present within the near-shore of the study area are: silts to sands from Knox Mountain at the northern bound to the edge of the Mission Creek fan; a mix of clayey sand overlying sand, cobbles and boulders on the Mission Creek fan; and coarse cobbles over the southern Bellevue fan (Figure 2.7). The southern portion of the study area appears to be swept by strong shoreline currents and higher energy waves moving north from the south of Okanagan Lake.

2.2.5 Hydrogeology and Groundwater/Surface Water Interactions

Upland bedrock aquifers and unconsolidated valley aquifers are both present within the Kelowna area (Figure 2.6 and Figure 2.11). Upland bedrock aquifers receive recharge from precipitation and discharge directly to the lake, to valley aquifers as mountain block recharge, or more significantly, to surface water within the bedrock portion of stream valleys (Welch and Allen, 2012). The unconsolidated valley aquifers can be further divided into five confined aquifers, provincially known as BC Ministry of Environment aquifers 462, 463, 464, 465, and 466

(B.C. Ministry of Environment, 2013), and an unconfined aquifer which includes MOE unconfined aquifers 467 and 462 (Figure 2.6).

The Rutland Aquifer (MOE 464) is the largest confined aquifer in the area covering 68 km^2 with an average of 56 m thickness of interglacial gravel (Golder Associates and Summit Environmental Consultants Ltd., 2009). While the recharge areas for this aquifer have not been verified, one recharge area is possibly a gravelly area in Gallagher's Canyon at an elevation of 420 masl which interacts with a portion of Mission Creek (Figure 2.6), (Roed and Greenough, 2004). Water from the aquifer is suspected to discharge directly to Okanagan Lake or return upwards to the unconfined aquifer depending on the thickness of the confining layer along the flow path. Approximately 4.25×10^6 m^3/yr of groundwater was pumped out of the Rutland Aquifer for human use in 2004 (Roed and Greenough, 2004) which accounts for over half the total groundwater (8.5×10^6 m^3/yr) pumped within the Kelowna area (van der Gulik et al., 2010[2]). A low hydraulic conductivity ($K = 10^{-7}$ m/s; Golder Associates and Summit Environmental Consultants Ltd., 2009) glaciolacustrine and till layer 1 m to 85 m thick separates the confined aquifers from the fluvially deposited silt, sand and gravel aquifer at surface (Figure 2.11; Neilson-Welch and Allen, 2007). The unconfined aquifer receives recharge from seasonal creek losses, direct precipitation, irrigation returns, and urban infrastructure leakage while it provides irrigation water via wells and it discharges to creeks and to Okanagan Lake. Regionally, groundwater moves north to south but flow paths within the Kelowna area are dominantly east to west as groundwater moves through the unconsolidated aquifers, bounded by bedrock, en route to Okanagan Lake (Golder Associates and Summit Environmental Consultants Ltd., 2009; Smerdon and Allen, 2009).

Groundwater flow from the Kelowna aquifers into Okanagan Lake has recently been investigated using a numerical model, a water-balance estimation, and a series of Darcy flux calculations. The OBWB Phase II surface water background study did not directly calculate groundwater discharge to the lake at Kelowna but rather estimated the value as 4×10^6 m^3/year as the residual of its water-balance calculation (Summit Environmental Consultants

[2] 2003 total from major water purveyors, excludes private well users

Ltd., 2009). The Phase II groundwater report used Darcy flux calculations to estimate the Kelowna aquifer discharge to Okanagan Lake at 3.2 x 10^7 m^3/year; almost an order of magnitude higher than the surface water estimation (Golder Associates and Summit Environmental Consultants Ltd., 2009). The Smerdon and Allen (2009) Visual MODFLOW study was the first explicit attempt at quantifying groundwater flow within the Kelowna area but was hindered by a lack of available measured calibration data. This model estimated a discharge of 1.8 x 10^8 m^3/yr from the Kelowna aquifers to Okanagan Lake; an order of magnitude higher than the Phase II groundwater report. While methodology differences and a general lack of available measured calibration data may explain the variability of results, the range of results between the three reports clearly indicates a need for direct measurement of discharge from the Kelowna aquifers to Okanagan Lake.

2.2.6 Patterns of Groundwater Discharge

Groundwater discharge measured along the Kelowna shoreline has three possible origins: the bedrock bordering the study area, the unconfined aquifer, or the confined aquifers adjacent to Okanagan Lake. Bedrock bordering the study area only occurs in approximately 15-20% of the study area at Knox Mountain in the north and Okanagan Mountain Park in the south. Aquifers in these formations are expected to discharge to surface water flows or directly to the lake within the study area (Welch and Allen, 2012).

Flow from the unconfined aquifer is expected to discharge within the study area in a spatially and temporally variable pattern. Flow limitations imposed by the low conductivity sediments found below wave base in deeper water should theoretically decrease groundwater discharge in those areas, encouraging flow to discharge in shallower, more easily measureable areas of higher hydraulic conductivity sediments closer to the shoreline.

Flow from the confined aquifer to Okanagan Lake has not been thoroughly investigated to date. Artesian flow from the confined aquifers could potentially discharge into the unconfined aquifer upgradient of the shoreline or deeper in Okanagan Lake (Figure 2.12). Lake bathymetry and geological transects suggest the confined aquifers dip well below Okanagan Lake, promoting discharge of groundwater within the study area. This theory is also supported by the presence of low hydraulic conductivity modern lacustrine sediments on the bottom of Okanagan Lake (St. John, 1973) and the known existence of artesian flow conditions in Kelowna upgradient of the study area (Paradis et al., 2010; Figure 2.6). Geophysical transects completed by the Geological Survey of Canada (Paradis et al, 2010) suggest the confining layer thickens to over 100 m in some areas as it approaches the lake; further discouraging water from the confined aquifer from discharging into the deeper portions of Okanagan Lake.

A seasonal increase in groundwater discharge is expected to follow surface water freshet because of the substantial size and seasonal distribution of surface water flows within the study area (see Section 2.2.4 Hydrology). Groundwater flow through steep and gradual deltaic fan types is expected to increase by total volume and with distance from shore during high flow periods. Inter-annual variability is also expected because of differences in precipitation inputs from year to year.

2.3 Approach

2.3.1 Application of Previous and Historical Approaches to the Kelowna Site

Seepage meters provide temporally and spatially discrete data points. The majority of studies using seepage meters to investigate discharge of groundwater to a large surface water body report temporal or spatial change to flux values at point measurement locations rather than estimating groundwater discharge to an entire study area (Attanayake and Waller, 1988; Cable et al., 1997b; Schneider et al., 2005; Brodie et al., 2009; Rautio and Korkka-Niemi, 2011; Ala-aho et al., 2013; Rosenberry et al., 2013). The Kelowna lakeshore is too geologically complex to repeatedly collect one transect of point measurements perpendicular to the shoreline and extrapolate the results over the study area (Shaw and Prepas, 1990b). Limited access to deeper portions of the lake precludes the possibility of taking numerous transects perpendicular to the shoreline to produce a map of seepage flux (Cherkauer and Carlson, 1997) or a discharge rate per unit of shoreline (Cable et al., 1997a). The average seepage meter flux rate within the entire study (Schneider et al., 2005) cannot be used to estimate average discharge as this method ignores the temporal component of flow rates and weights the results to favour flows found during more active point measurement collection periods. An alternative method has been developed for the Kelowna study to ensure adequate spatial coverage of the study area while appropriately considering the temporal component of flow.

2.3.2 Approach Proposed for the Kelowna Groundwater Discharge Study

The wide range of results from recent modelling and water-balance estimations of flow from the Kelowna aquifers to Okanagan Lake (10^6 – 10^8 m^3/yr) identified a need for direct measurement of groundwater discharge on the site. A groundwater/surface water interactions methods review revealed seepage meters were the best fit for the study's primary flux measurement technique. The Lee (1977) seepage meter design relies upon manual installation either from shore in depths of up to 1.1 m or in deeper water with the use of SCUBA equipment. Measurements below wave base were expected to be more representative of actual groundwater flux rates as they are not affected by wave action. A new seepage meter design was undertaken to permit the installation of seepage meters from a boat (Appendix B). This was expected to provide access to depths between 1.1 m and 3.5 m without the use of SCUBA equipment.

Point measurements and transects were planned to inform the overall flow estimation; considering the temporally and spatially variable discharge of groundwater from the Kelowna aquifers to Okanagan Lake. The two (2) year investigation period was designed to allow for examination of inter-annual variation.

Discharge from the confined aquifer is poorly understood and is potentially routed through: the nearshore of Okanagan Lake via the unconfined aquifer; the deeper bottom sediments directly to Okanagan Lake; or most likely, a combination of the two routes. 2-D MODFLOW transects were planned to estimate the percentage of discharge from the confined aquifers being captured within the study area and allow the overall seepage meter discharge estimate to be scaled to be representative of total flow from the unconfined and confined aquifers to Okanagan Lake (Figure 2.12).

Final estimates of annual flow within the study area were then to be compared to other water budget parameters to inspect for relationships and to place the groundwater discharge estimate in a regional context.

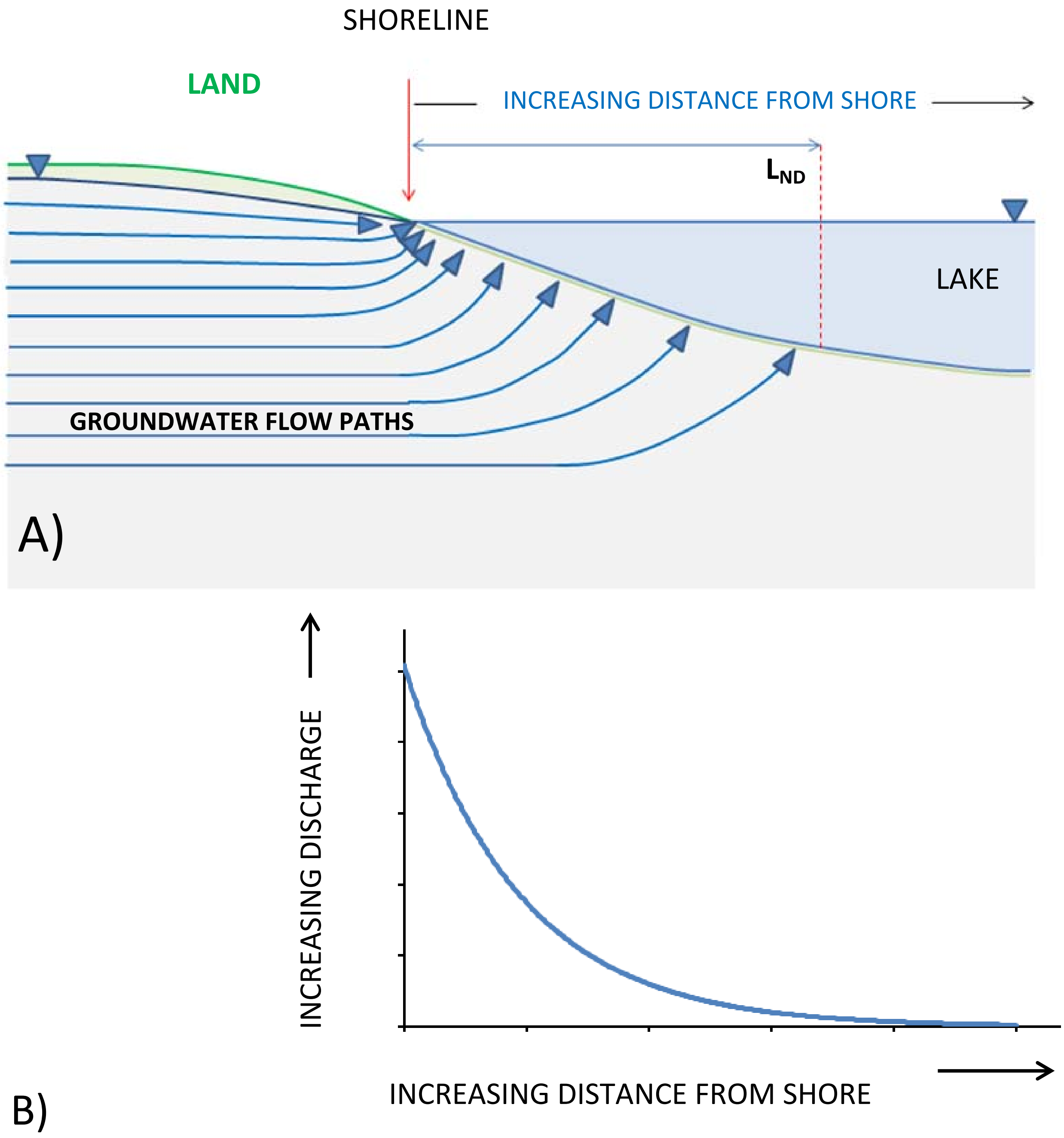


Figure 2.1 Movement of groundwater to a lake in an ideal system comprised of homogeneous and isotropic sediments: A) transect modified from Winter et al. (1998); B) Idealized discharge profile.

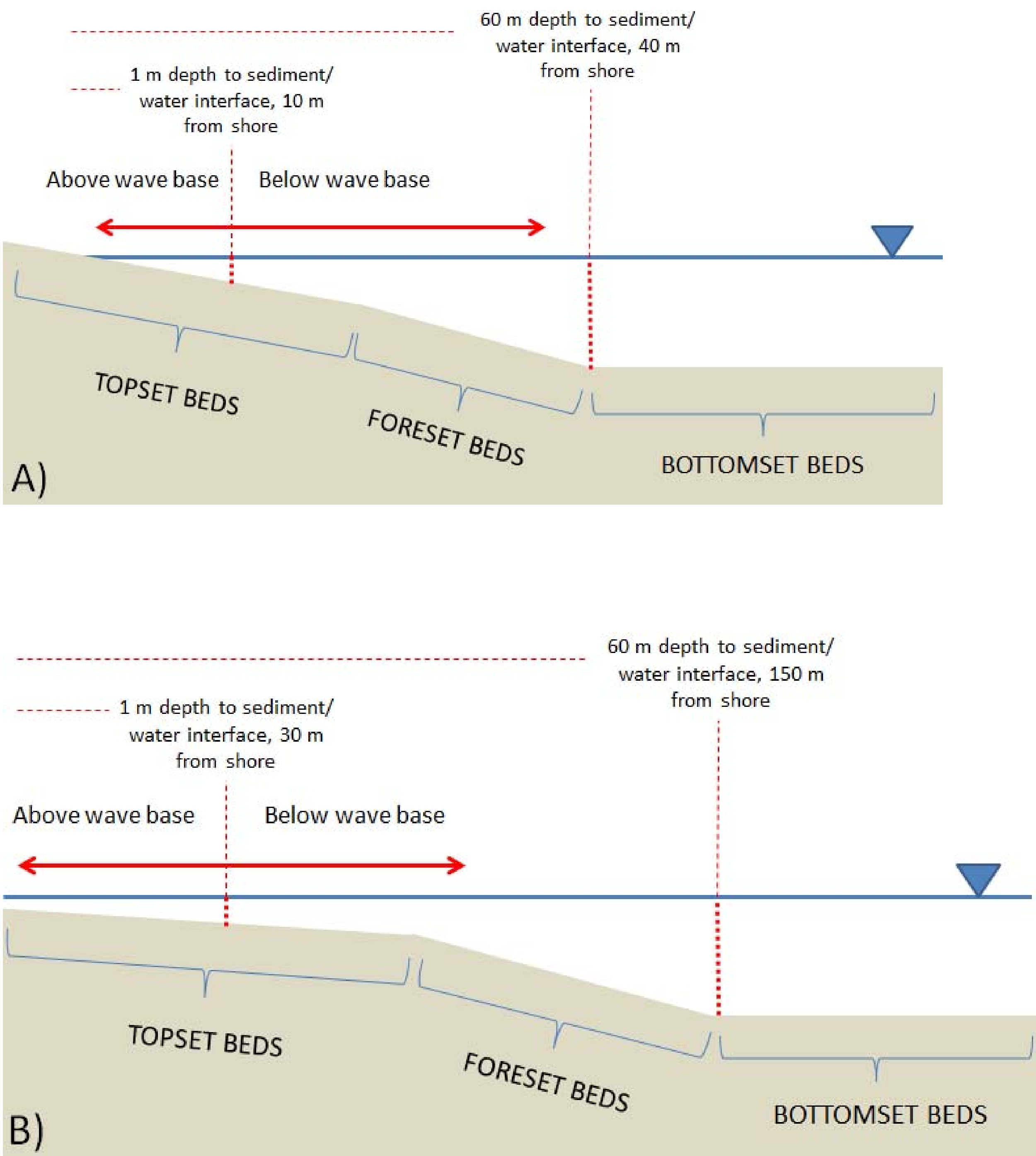


Figure 2.2 Idealized shoreline cross-sectional profiles with approximate depths and distances found at locations within the study area. A) Steep profile B) Shallow profile.

Figure 2.3 Physical measurement equipment: A) seepage meter (photo by N. Pyett), B) piezometer nest (photo by C. Baptie).

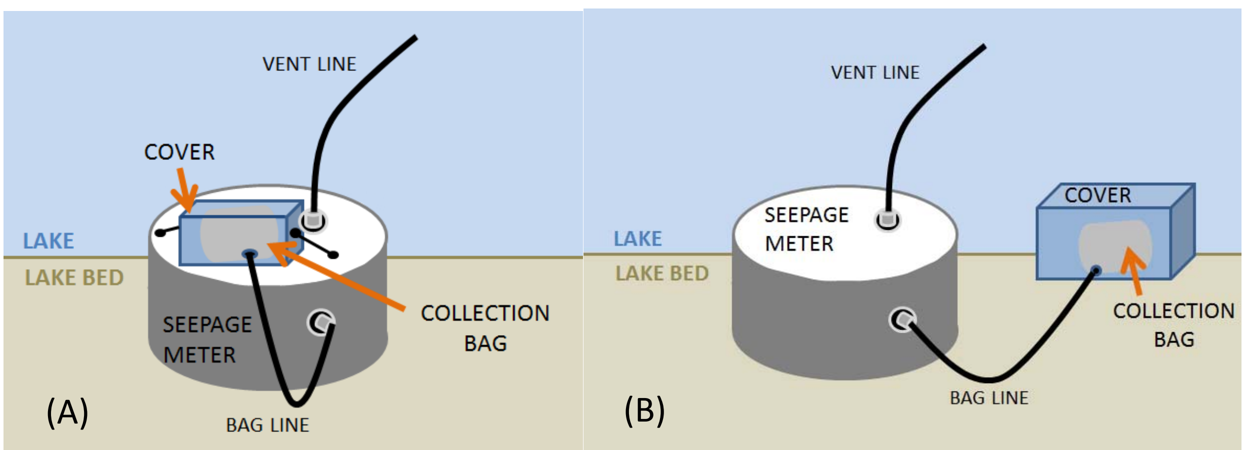


Figure 2.4 Seepage meter collection bag cover options: A) Enclosure in cover affixed to top of seepage meter; B) Enclosure in separate bag cover installed in lake bottom.

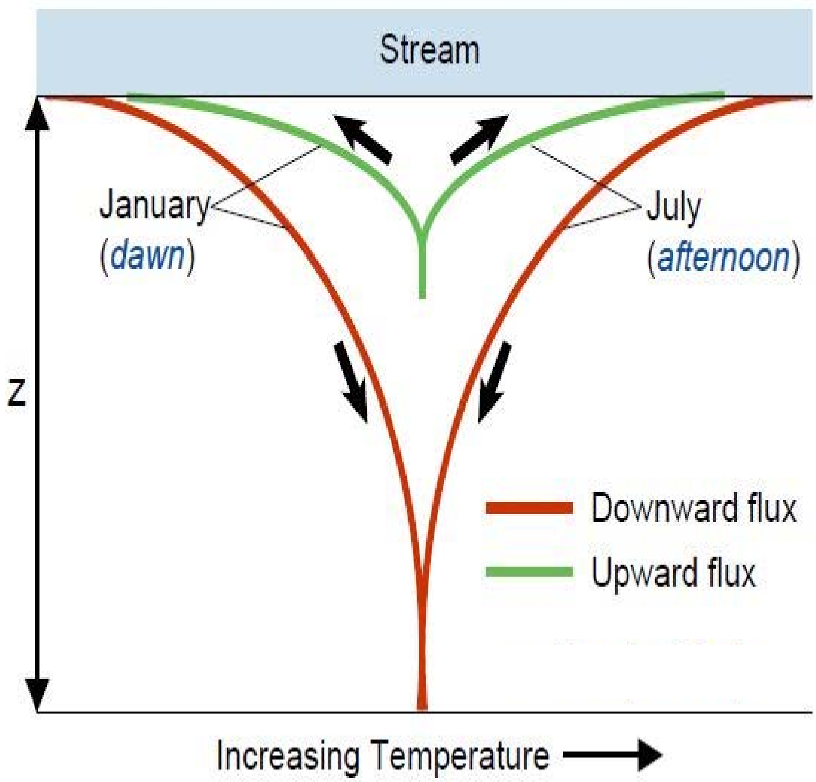


Figure 2.5 Sediment temperature profiles showing the effects of inter-annual temperature changes and the influence of groundwater flow direction (from Stonestrom and Constantz, 2003).

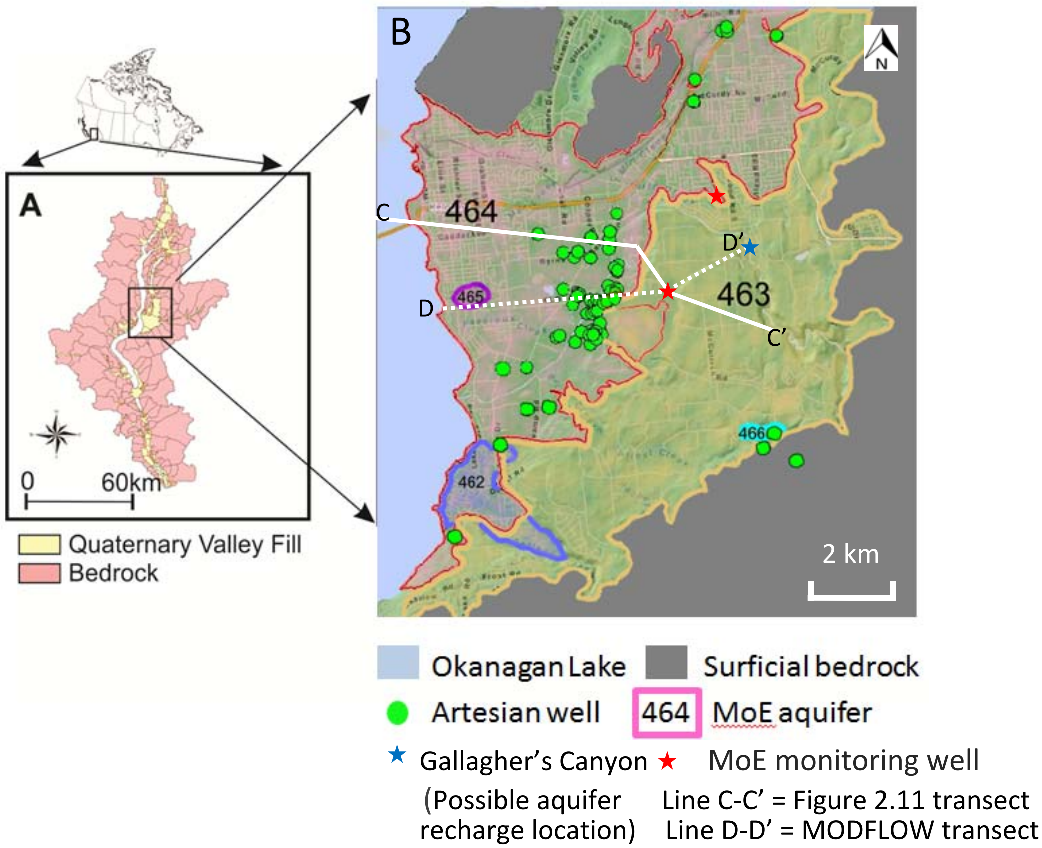
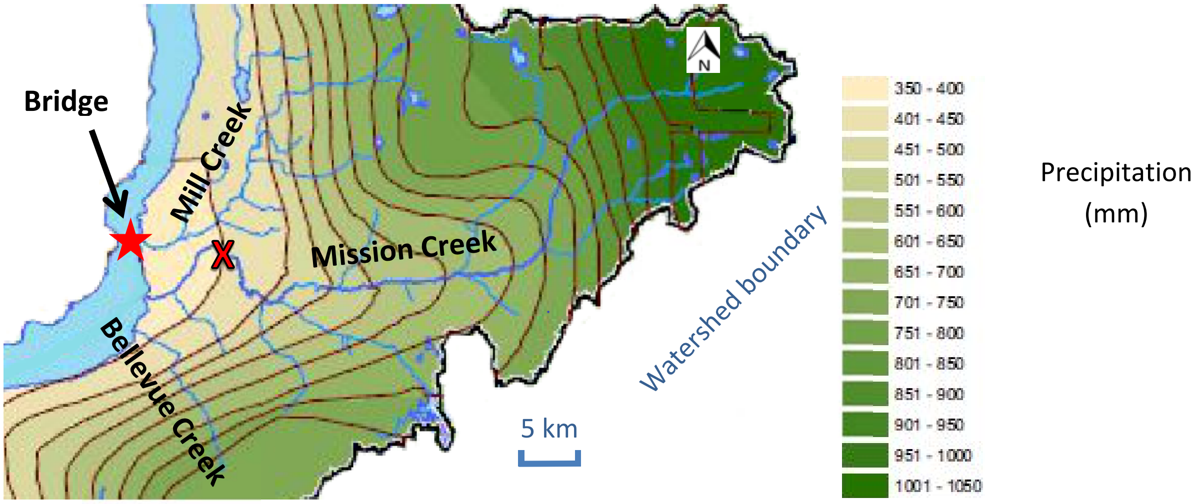


Figure 2.6 Overview of study location including: (A) location of Okanagan Basin and distribution of Quaternary valley fill sediment within the basin (adapted from Golder Associates and Summit Environmental Consultants Ltd., 2009); and (B) locations of surficial bedrock, confined aquifers, and artesian wells in the study area (adapted from DataBC, 2013).



X identifies the location of the Mission Creek hydrometric station (08NM166; 49° 52' 44'' N, 119° 24' 47'' W; 381 masl).

Figure 2.7 Spatial distribution of precipitation (adapted from Golder Associates and Summit Environmental Consultants Ltd., 2009).

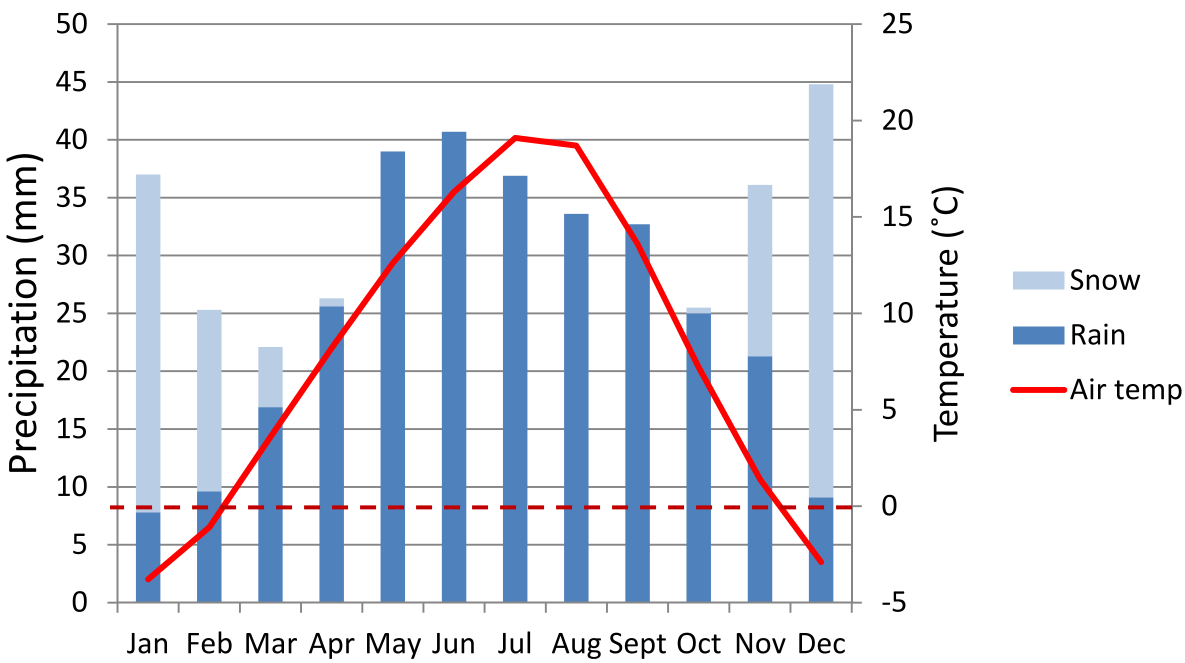


Figure 2.8 Annual precipitation distribution based on Environment Canada's 1971 – 2000 Climate Normals for climate station "Kelowna A" (Environment Canada, 2013a).

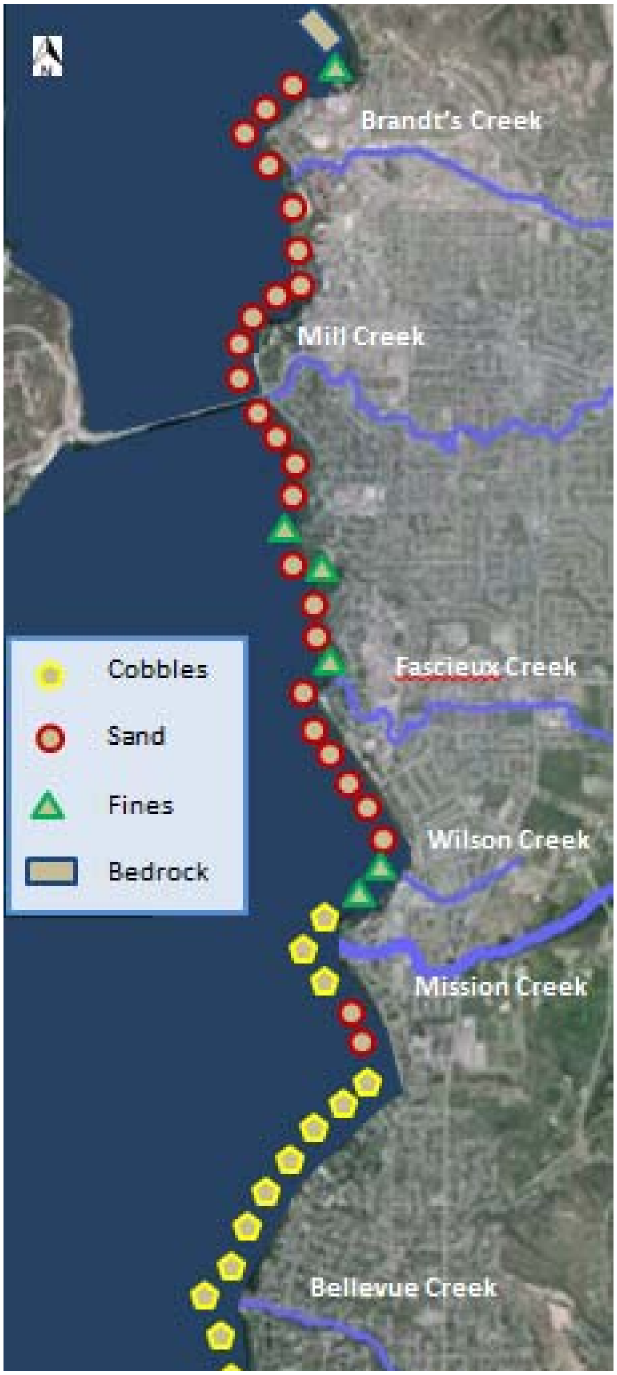


Figure 2.9 Major creeks located within the study area and the dominant shoreline sediment type.

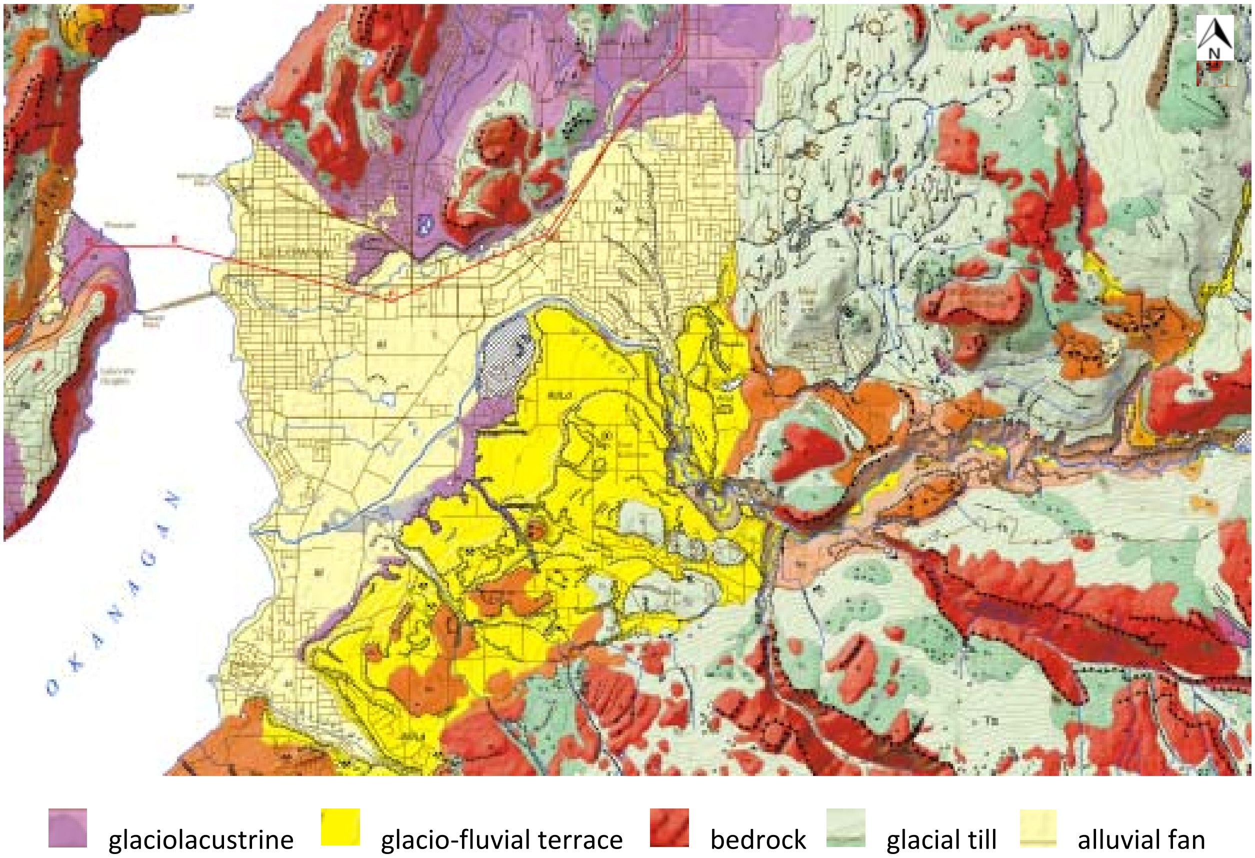


Figure 2.10 Surficial geology of Kelowna (from Geological Survey of Canada, Open File 6146 (Paradis, 2009).

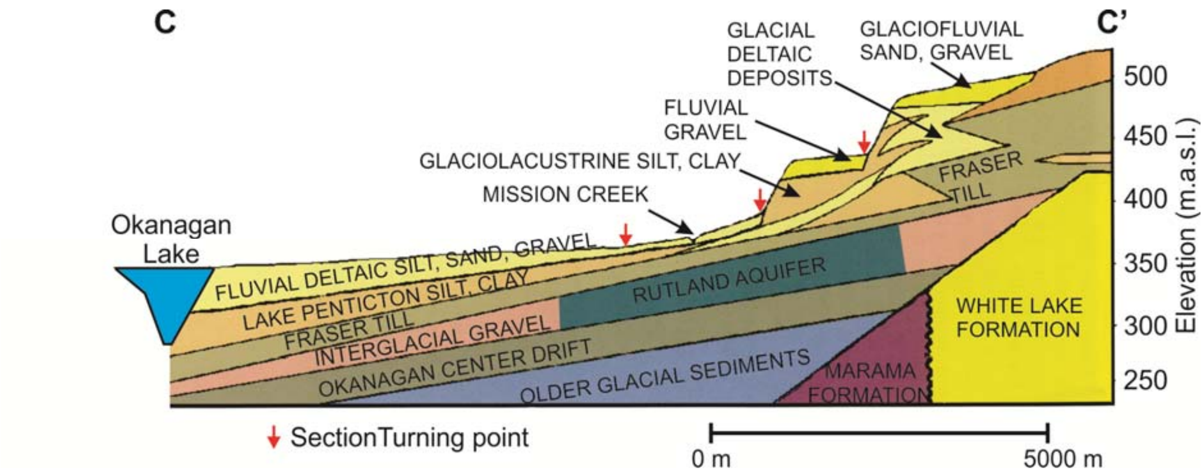


Figure 2.11 Transect of Kelowna geology marked C – C' on Figure 2.6 (adapted from Roed and Greenough (2004) for Pyett and Nichol (2013).

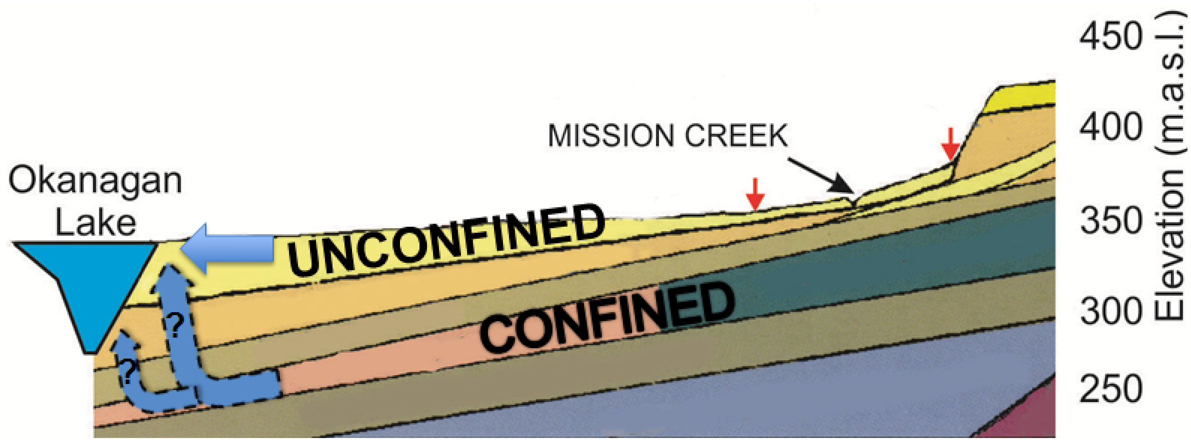


Figure 2.12 Potential paths for confined aquifer water discharge (simplification of Roed and Greenough (2004).

Table 2.1 Groundwater/surface water investigation methods

METHOD	DESCRIPTION	SELECTED FOR THIS PROJECT?
Physical: Seepage meters (Lee, 1977)	Groundwater flux measurement devices that cover a portion of the sediment/water interface in a body of water and directly measure the groundwater discharge through the use of a pre-loaded water collection bag. The collection of point measurements is specific to time and space so transect applications or repeated sampling of the exact same locations over time is common within the literature.	Yes
Physical: Gradient methods/ Piezometers (LaBaugh and Rosenberry, 2008)	Gradient methods use sediment hydraulic conductivity information and hydraulic gradient information (collected from wells or piezometers) to calculate estimations of groundwater flow. This method is regularly used as a comparison with other methods in groundwater discharge investigations.	Yes
Temperature: Thermal image analysis (Banks et al. 1996)	An airplane-mounted Thermal-Infrared-Multispectral Scanner (TIMS) can collect thermal images of bodies of fresh surface water and marine shorelines for estimations of groundwater discharge. This method is very useful in preliminary investigations to guide the locations of future targeted groundwater/surface water investigations in high groundwater discharge areas.	No[1]
Temperature: Temperature-depth profiles in a borehole (Anderson 2005)	Temperature point measurements can be collected at depth intervals in a borehole to produce temperature-depth profiles. Profiles from one or multiple boreholes can be repeated over time and modeled to quantify groundwater flow.	No[1]
Temperature: Thermal profiling (Constantz, 2008)	Groundwater recharge and discharge can be modeled using information from a series of temperature-depth profiles in the sediment beneath a surface water body. Movement of relatively cooler groundwater towards the surface would describe groundwater discharge during the summer season while movement of relatively warmer water from the surface towards the ground would describe groundwater recharge.	Yes[2]

Table 2.1 Groundwater/surface water investigation methods (continued)

METHOD	DESCRIPTION	SELECTED FOR THIS PROJECT?
Chemistry: Salinity (Oberdorfer, 2003)	Salinity measurements can be used in marine systems to separate fresh groundwater discharge from saline ocean water or brackish water recirculated through the nearshore by wave action.	No[1]
Chemistry: Water quality measurements/nitrate (Johannes and Hearn, 1985)	Groundwater containing high levels of nitrate or other contaminants can be tracked as it enters surface water bodies.	No[3]
Chemistry: Radon (Reich, 2009)	^{222}Rn is a chemically inert radioactive isotope added to groundwater during movement through rocks containing decaying uranium or thorium. Radon gas quickly volatilizes in surface waters so tracking its presence at the sediment-water surface can indicate the presence of groundwater discharge. Groundwater discharge rates can be quantified using mixing models which compare the sampling area radon concentrations to concentrations in the surface water body and in groundwater.	No[3]
Chemistry: Conductivity (LaBaugh and Rosenberry, 2008)	This method can be used when there is a measureable difference in specific conductance between surface water and groundwater. Transects of measurements can be collected by dragging sensors behind a boat.	No[1]
Chemistry: Dyes and Tracers (LaBaugh and Rosenberry, 2008)	Injection of materials into the groundwater or surface water and the collection of downgradient concentrations can assist in time-of-travel and dilution calculations quantifying groundwater flows. Materials selected for tracers should be readily detected at small concentrations (ie. fluorescent dyes) and should not harm the environment.	No[3]
Biology: Community Composition (Rosenberry et al., 2000)	The presence or absence of certain biological indicator species can be used to locate groundwater discharge locations.	No[1]

Table 2.1 Groundwater/surface water investigation methods (continued)

METHOD	DESCRIPTION	SELECTED FOR THIS PROJECT?
Numerical Modelling (Smith and Zawadski, 2003)	Estimating groundwater fluxes using finite-difference or finite-element code based options (ie. MODFLOW, FEFLOW, etc.) requires a great understanding of innate program assumptions and of the natural system being modelled. Incorrect parameter estimations can easily lead to a model that does not represent actual groundwater movement.	No[4]
Water-balance Techniques	Inflows to a system minus the outflows equal the change in groundwater storage. Systems assessments classified as "water-balance techniques" and can have varying levels of complexity.	No[4]

[1] not applicable to site

[2] initially selected, later eliminated (fluxes on the Kelowna site were found to be below method detection limits)

[3] not appropriate for the site

[4] previously attempted on this site

Table 2.2 The impact of groundwater fluxes on temperature gradients

Season (Canada)	Surface Temperature	Subsurface Temperature	GW Flow Direction	Impact on Temperature Gradient
Winter	Relatively cooler	Relatively warmer	DOWN	Steeper
Winter	Relatively cooler	Relatively warmer	UP	Shallower
Summer	Relatively warmer	Relatively cooler	DOWN	Steeper
Summer	Relatively warmer	Relatively cooler	UP	Shallower

CHAPTER 3: METHODS

Groundwater flux within the study area was investigated between June 2011 and November 2013 using seepage meters and gradient methods. Supportive modelling work was completed using Processing MODFLOW (Version 5.3.1; Simcore Software).

3.1 Gradient Methods

Small and large scale gradient methods were applied to the study site to: observe hydraulic heads affecting vertical flow just below the sediment/water interface, to better understand regional horizontal flow, and to facilitate Darcy flux calculations for direct volumetric comparison with seepage meter flux rates.

3.1.1 Shoreline Vertical Flux Calculations

Sixty-one (61) flux calculations were completed using:

- groundwater head measured in flexible tubing mini-piezometers screened at depths of 0.2 and 1.0 m below the sediment/water interface;
- lake levels; and
- hydraulic conductivities which were estimated from the literature based upon grain size or calculated by performing lab falling head tests on re-packed samples (Figure 3.1).

Further gradient method research in the study area was completed as a sub-study by a summer research assistant, Craig Baptie, as an undergraduate Honours thesis. Baptie (2012) used rigid standpipe piezometers installed at depths of 0.3 and 1.0 m below the sediment water interface. The sub-study included continuous gradient monitoring through the use of pressure transducers over three (3) trials lasting four (4), five (5) and seven (7) days, respectively. Vertical hydraulic conductivities were estimated using in situ falling head tests.

3.1.2 Large Scale Horizontal Flux Calculations

Lateral hydraulic gradient estimations were completed using:

- hydraulic head values in upgradient wells (Figure 3.2);
- the elevation of water in Okanagan Lake (Water Survey of Canada Station 08NM083); and
- horizontal hydraulic conductivity estimates produced by Golder Associates and Summit Environmental Consultants Ltd. (2009) for OBWB Phase II groundwater investigations.

3.2 Seepage Meters

Seepage meters (Appendix A) were manually installed within the nearshore study area (depths 0.2 - 1.1 m). Groundwater discharge from depths below wave base (1.1 – 3.5 m) was accessed by boat; installing an adjusted seepage meter into the sediment/water interface by applying even, twisting (clockwise and counter-clockwise), downward pressure to the top of a seepage meter with a "T" bar held in place by metal loops (Appendix B).

All meters were pre-loaded with one litre of lake water and given a 24 hour settling period prior to the start of a seepage meter trial. Trials were a minimum of 24 hours to integrate the effects of any hydraulic gradient changes due to wind-caused lake level changes (seiche). Trial times ranged in length between 24 hours to ten days (Figure 3.3). All seepage meter discharge bags were pre-loaded and measured after a trial using a 1000 ±5 mL graduated cylinder. Appendix C contains the seepage meter co-ordinates determined by a handheld GPS unit, raw data, and calculated flux rates for each point measurement, along with other supporting information.

3.2.1 Long-Term Stations

Three long-term station seepage meters were installed for the collection of weekly to biweekly flux measurements from September 2011 to August 2013 (Figure 3.3a). September 2011 to August 2012 is further referred to as "Study Year 1" and September 2012 to August 2013 is further referred to as "Study Year 2". Compression of adjacent sediment from researcher movement was minimized by varying the approach route and minimizing time spent at the seepage meters. Some measurements were prevented by ice impingement, human interference, or low lake levels. Secondary long-term stations were installed at Knox and Maude-Roxby locations between December 2011 and February 2012 because of low water level and ice impingement issues. Primary long-term stations were also sampled during this time period when possible. Secondary station data was eliminated from the record when five comparison trials in May of 2012 failed to relate fluxes between the two primary and secondary stations at both locations. The September – October period of 2011 and 2012 and the July – August period of 2012 and 2013 were selected for inter-annual variability comparisons because of minimal measurement loss at all three stations during these periods.

3.2.2 Cluster Measurements and Transects Parallel to the Shore

Clusters of three (3) seepage meters were placed into the sediment/water interface in close proximity (edges within 1 metre) within visually similar sediment, in equal depths of water, and in approximately equal distance from the shoreline. Seven (7) clusters were installed during high flow conditions (May – June 2013) and seven (7) clusters were installed during low flow conditions (end of September 2012 – April 2013), (Figure 3.3b). Cluster measurement data was examined for relationships between variability in flux and magnitude of flux, installation depth, sediment type, and installation distance from shore using a one sided analysis of variance (JMP 4, SAS 2002).

Coefficient of variation calculations were completed to normalize flow and investigate if the relationship is independent of mean flow in a cluster grouping:

$$CV = 100\% \frac{s}{\bar{Y}} \quad [4]$$

Where the coefficient of variation (*CV*) equals the standard deviation (*s*) divided by the mean ($\bar{Y}$) with answers reported as percentages (Whitlock and Schluter, 2009). Flux measurements with equal CVs would suggest flow magnitude is the primary driver of variation while unequal CVs would suggest another factor is responsible for the observed relationship.

Attempts at using transects parallel to the shoreline to investigate site scale heterogeneity were unsuccessful due to difficulties maintaining consistent depth and sediment conditions between the seepage meters.

3.2.3 Control Measurements

Two types of control measurements were attempted in this study. In Control Method 1, a standard seepage meter was installed over an impermeable barrier buried approximately fifteen (15) cm below the natural sediment/water interface. The installed seepage meter touched the mat-type barrier which extended past the edge of the seepage meter a minimum of five (5) cm in all directions creating a “no flow” control measurement. Control Method 2 used a standard seepage meter perforated with numerous holes approximately 5 cm in diameter to redirect groundwater discharge away from the collection bag, similar to Sebestyen and Schneider (2001) and Schneider et al. (2005), creating a “no capture” control measurement.

Four (4) “no flow” control measurements were installed near the Maude-Roxby long-term station (Figure 3.2a). Seven (7) “no capture” control measurements were installed with 2013 cluster measurements at various locations along the shoreline.

3.2.4 Method Comparison Trials

Seepage meters deployed from August 2011 to the beginning of August 2012 used collection bag covers installed at the sediment/water interface adjacent to the seepage meter; similar to the design used by Brodie et al., 2009 (Method 1; Figure 2.4b). The 68 L rectangular Rubbermaid bins selected as covers were later found to be easily washed away in moderate wave activity causing a loss of numerous measurements. A seepage meter cover change occurred in August 2012 to decrease the number of lost measurements and increase seepage meter cover ease of use. The alternate collection bag cover held the bag on top of the seepage meter, following the design used by the USGS (Method 2; Figure 2.4a). The impact of the method change on flux rates was determined using seven method comparison trials. Each trial included four (4) seepage meters run concurrently: two (2) with Method 1 collection bag covers and two (2) with Method 2 collection bag covers; all installed in visually similar sediment, the same distance from shore, and in the same depth of water. The percentage difference between Cover Method 1 and Cover Method 2 in each trial was used to calculate an overall average difference and standard deviation. Values within one standard deviation of the average were used to calculate the difference between the two methods. The percentage difference generated by these trials was applied to all data points collected using Method 1 covers to standardize the data set.

3.2.5 Transects Perpendicular to the Shore

Between August 21 and October 2, 2011, four transects were manually installed perpendicular to the shoreline for one to two day trials (Figure 3.3c). The Lakeshore and Royal transects were placed in locations with steep shoreline profiles, while the Maude-Roxby and Gyro transects were installed in locations with gradual shoreline profiles. Using a boat to access deeper water, six (6) transects were installed perpendicular to shore during lower flows (September – October 2012) and were repeated during high flows in May – June 2013 (Figure 3.3d). Locations were selected to cover the maximum amount of area below wave base. These boat-based transects were installed in large alluvial fans (average 2% gradient on sediment surface) with the exception of the Collett transect (5% gradient). All boat-based transects were planned as three seepage meter point measurements in length, dictated by equipment availability; however, the spring 2013 measurement at the Mission Creek and KLO transects had fewer than three points due to equipment failure at these locations. The number of measurements collected in boat accessed locations was maximized by using all available seepage meters. To compensate for the lack of concurrent data closer to shore, transects were temporally scaled and related to nearshore point measurements. This allowed the pattern of discharge observed at transect locations to be applied to geologically similar locations (ie. similar fan shape, shoreline profile, and/or depositional/erosional mechanism of development).

3.2.6 Point measurements

Seventy-four (74) point measurements were collected between August 2011 and July 2013 (Figure 3.3e), (Appendix C). Installation techniques varied slightly depending on the sediment type present at the trial location. Appendix A contains further information about site-specific techniques and the results of method comparison trials undertaken after the implementation of a seepage meter cover change during June 2012.

3.3 Overall Flow Calculation

Point measurements of flux ($m^3/m^2/s$) were collected across the study area, throughout the study period (Appendix C). Three (3) long-term stations provided data to temporally scale point measurement values to become representative of average annual flux at each point measurement location (Appendix D). The study area was divided into ten (10) separate sections ("discharge areas"); distinguished by observable geological/structural characteristics (ie. same fan, same shoreline profile, similar depositional/erosional mechanism of development), (Figure 3.4). Integration of transects of point measurements installed perpendicular to the shoreline in high and low flow conditions described changes in flux with distance from shore in five (5) of the ten (10) discharge areas (Appendix C). Integrated transects were related to nearshore point measurements to create spatial scaling factors for application in discharge areas not directly measured by perpendicular transects (Appendix D). Flow within each discharge area was calculated using an average of temporally scaled point measurements and either integrated perpendicular transects or spatial scaling factors (Appendix D). The average annual groundwater flow within the study area (m^3/year) was estimated by summing flows within the ten (10) discharge areas (Appendix D). A correction rate of 1.05 was applied to the final estimation to account for internal friction within the seepage meters.

3.3.1 Temporal Scaling

Daily long-term station values of flux ($q_{LT\,n}$, $m^3/m^2/s$) were calculated by linearly interpolating between measured flux rates within the long-term record (Appendix D). The average daily flux value ($q_{LT\,avg}$, $m^3/m^2/s$) across the study period was determined for each long term station. Multipliers ($mult_n$, no units) for each day (n) within the study period were created to scale point measurement flux rates ($m^3/m^2/s$) to be representative of flow over the study period (Equation 4):

$$mult_n = \frac{q_{LT\,avg}}{q_{LT\,n}} \qquad [5]$$

Where the multiplier ($mult_n$) for a specific day within the study period equals the average of all daily flux rates ($q_{LT\,avg}$, $m^3/m^2/s$) divided by the flux on day (n), ($q_{LT\,n}$, $m^3/m^2/s$).

Inter-annual variation was investigated by creating additional sets of daily multipliers using Study Year 1 and Study Year 2 data separately (Appendix D).

3.3.2 Spatial Flux Integration and Scaling

Estimates of integrated flow over one metre of shoreline were calculated using transects perpendicular to the shoreline below wave base plus one nearshore measurement:

$$Q_{tot,i} = Q_1 + Q_2 + \cdots + Q_{final} \qquad [6]$$

Where the total integrated flow of the transect at position i along the shoreline ($Q_{tot,i}$, m^3/s) equals the sum of the flows associated with each point measurement in the transect (Figure 3.5). Each flux point measurement (q_1 to q_{final}, $m^3/m^2/s$) becomes a flow (Q_1 to Q_{final}, m^3/s) by being applied to an area (A_1 to A_{final}, m^2). The first point measurement, q_1, was the spatially and temporally closest nearshore point measurement. The q_1 measurement represents the flux closest to shore and was applied to an area one metre (1 m) wide from the shoreline to half the distance between the first and second seepage meter:

$$Q_1 = q_1\left(1 \times (l_1 + \left(\tfrac{1}{2}(l_2 - l_1)\right))\right) \qquad [7]$$

Where l_1 is the distance (m) from shore of the flux measurement q_1 and l_2 is the distance (m) from shore of the flux measurement q_2. All middle flux measurements in a transect (q_2 to $q_{final\text{-}1}$) were applied to areas one meter (1 m) wide by half the distance between the two closest point measurements patterned after Equation 7:

$$Q_2 = q_2(1 \times \left(\left(\tfrac{1}{2}(l_2 - l_1)\right) + \left(\tfrac{1}{2}(l_3 - l_2)\right)\right) \qquad [8]$$

The point measurement farthest from shore (q_{final}) was a special case with an area one metre (1 m) wide by half the distance between q_{final} and $q_{final\text{-}1}$ to L_{ND}:

$$Q_i = (1 \times \left(\left(\tfrac{1}{2}(l_{final} - l_{final-1})\right) + (l_{ND} - l_{final})\right) \qquad [9]$$

L_{ND} was selected as the endpoint of the transect to ensure capture of all flow within the study area. If L_{ND} could not be directly visualized, the pattern of flow decrease with distance from shore was extended to provide a reasonable approximation.

Integrated transects were related to nearshore point measurements to estimate the percentage of total flow captured within the nearshore area. These "spatial scaling factors" were used to estimate flux rates in deeper portions of the lake in sections of the study area that were not directly measured by perpendicular transects (Appendix D).

3.4 2-D MODFLOW Modelling

A 2-D, steady state Processing MODFLOW model was created to investigate the impacts of varying sediment hydraulic conductivity on the percentage of total aquifer discharge collected within the study area. The 194 x 150 cell model represented an idealized section approximately 10 km long x 1 m wide starting in South-East Kelowna and moving along a flow line to Okanagan Lake (Figure 2.6). This cross sectional model included portions of the unconfined aquifer, the confining layer, and the confined aquifer. Geology was based upon the cross section created by Roed and Greenough (2004); which integrated the work of Lowen and Letvak (1981) and Nasmith (1962). The transect was further modified to incorporate the new seismic data available from Pugin and Pullan (2009). Cells representing Okanagan Lake and the lower and upper elevation portions of Mission Creek were set as fixed potentiometric heads at 342 masl, 356 masl and 420 masl, respectively, based on elevation data from site visits or estimated using DataBC (Figures 3.6 and 3.7). The dimensions and the positions of the geologic layers within the model were produced by spatially translating a bathymetric map of Okanagan Lake, seismic data, and land elevation information (Appendix F). Water budget zones were created to track water moving across the model and included:

- Zone 1: Upper Mission Creek;
- Zone 2: Lower Mission Creek;
- Zone 3: Okanagan Lake nearshore (x = 0 – 150 m);
- Zone 4: Okanagan Lake nearshore (x = 151 – 300 m); and
- Zone 5: Okanagan Lake deep (x > 300 m).

Zones 3 and 4 represent lakebed within the study area while Zone 5 represents lakebed further out into Okanagan Lake. Hydraulic conductivity values were obtained from local and literature sources. Hydraulic conductivity values from Golder Associates and Summit Environmental Consultants Ltd. (2009) for the unconfined aquifer (~ 10^{-4} m/s), the confining layer (~10^{-7} m/s), and the confined aquifer (~10^{-3} m/s) were used as mid-range values for the sensitivity analysis. The range of hydraulic conductivity values used within the twenty-four (24) model scenarios were 1 x 10^{-4} – 1 x 10^{-9} m/s in the confining layer and 1 x 10^{-2} – 1 x 10^{-5} m/s in the confined aquifer (Figure 3.6). The unconfined aquifer layer was held at 1 x 10^{-4} m/s. An additional eighteen (18) scenarios investigated the impact of a lower hydraulic conductivity lakebed below wave base holding the hydraulic conductivity of the unconfined aquifer and confined aquifer at 1 x 10^{-4} m/s and 1 x 10^{-3} m/s, respectively while varying the K of the confining layer (1 x 10^{-4} – 1 x 10^{-9} m/s) and the two metre thick lakebed layer (10^{-7} m/s – 10^{-9} m/s).

Scenarios were run using the MODFLOW DE45 solver after an initial solver experiment using baseline scenario data found PCG2 and SSOR to repeatedly fail. The SIP solver was also able to produce results comparable to DE45 but required longer iterations. None of the solvers were able to produce a result in scenarios in which the lower hydraulic conductivity lakebed layer was present and the confining layer had a hydraulic conductivity value lower than 10^{-7} m/s.

CHAPTER 3: FIGURES AND TABLES

A star (✱) marks the east side of the W.R. Bennett bridge (49˚52’51” N, 119˚30’16” W) on each of the following maps to assist with visualization of the study area.

Figure 3.1 Site scale gradient method investigation locations: A) Knox; B) Maude-Roxby; C) Gyro; and D) Lakeshore (DataBC, 2013).

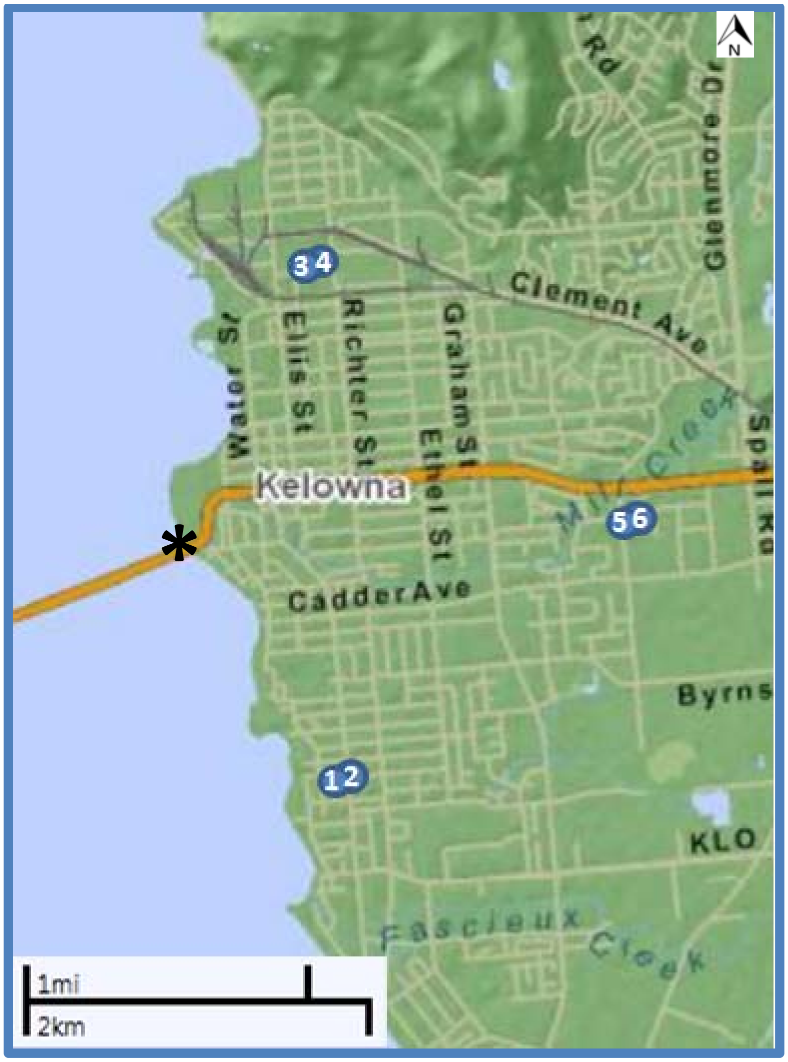


Figure 3.2 Locations of wells used in large scale horizontal flux calculations (Wells 2, 4, and 6 were adjusted slightly to allow for visualization), (DataBC, 2013).

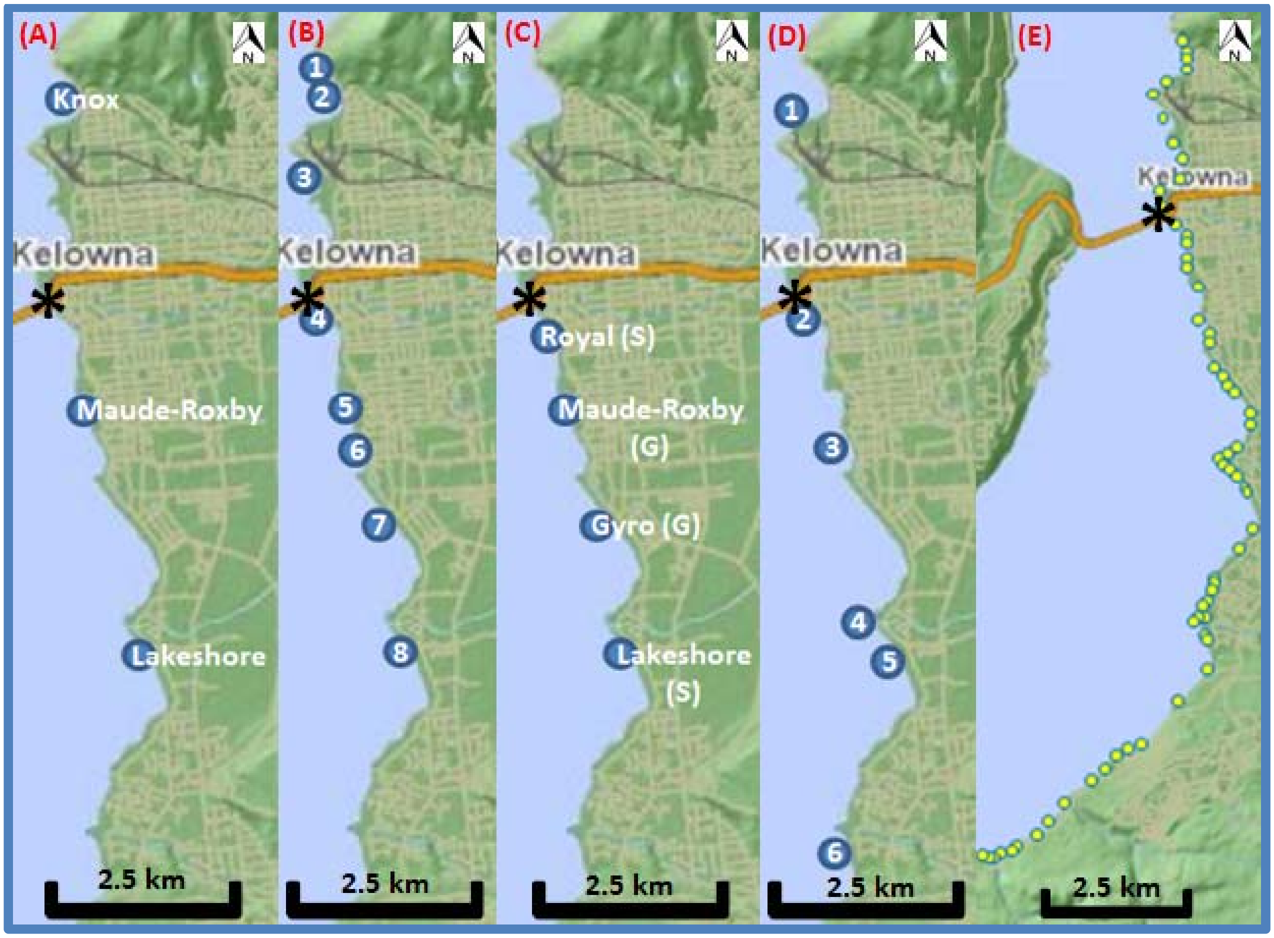


Figure 3.3 Seepage meter sampling locations: A) long-term stations; B) cluster measurements; C) transects perpendicular to shore taken in 2011 in areas of steep (S) and gradual (G) lake bottom profiles; D) Transects perpendicular to shore taken by boat in 2012/13; and E) point measurements DataBC, 2013).

Figure 3.4 Study area shoreline sections determined by observable geological and structural characteristics (DataBC, 2013).

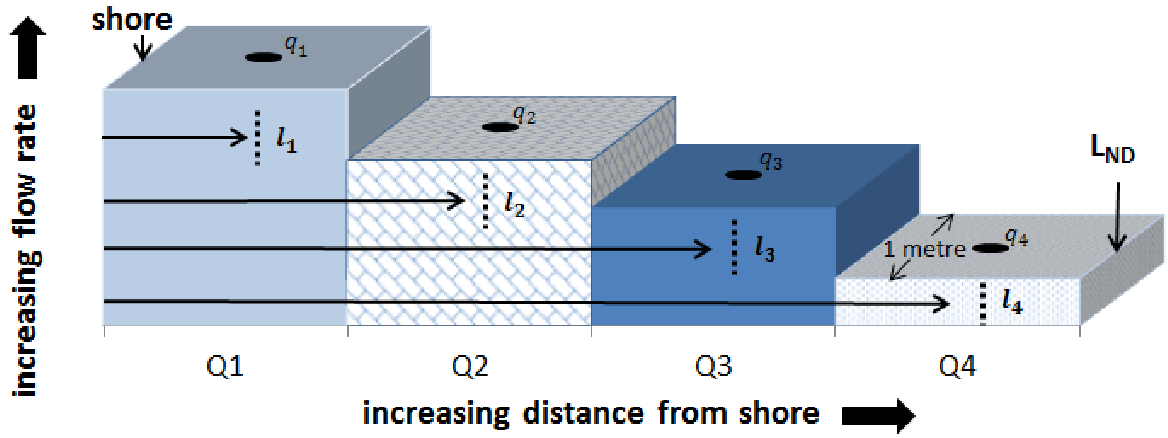


Figure 3.5 Methodology used for calculating estimated integrated flow in transects installed perpendicular to the shoreline (Equations 6 – 9).

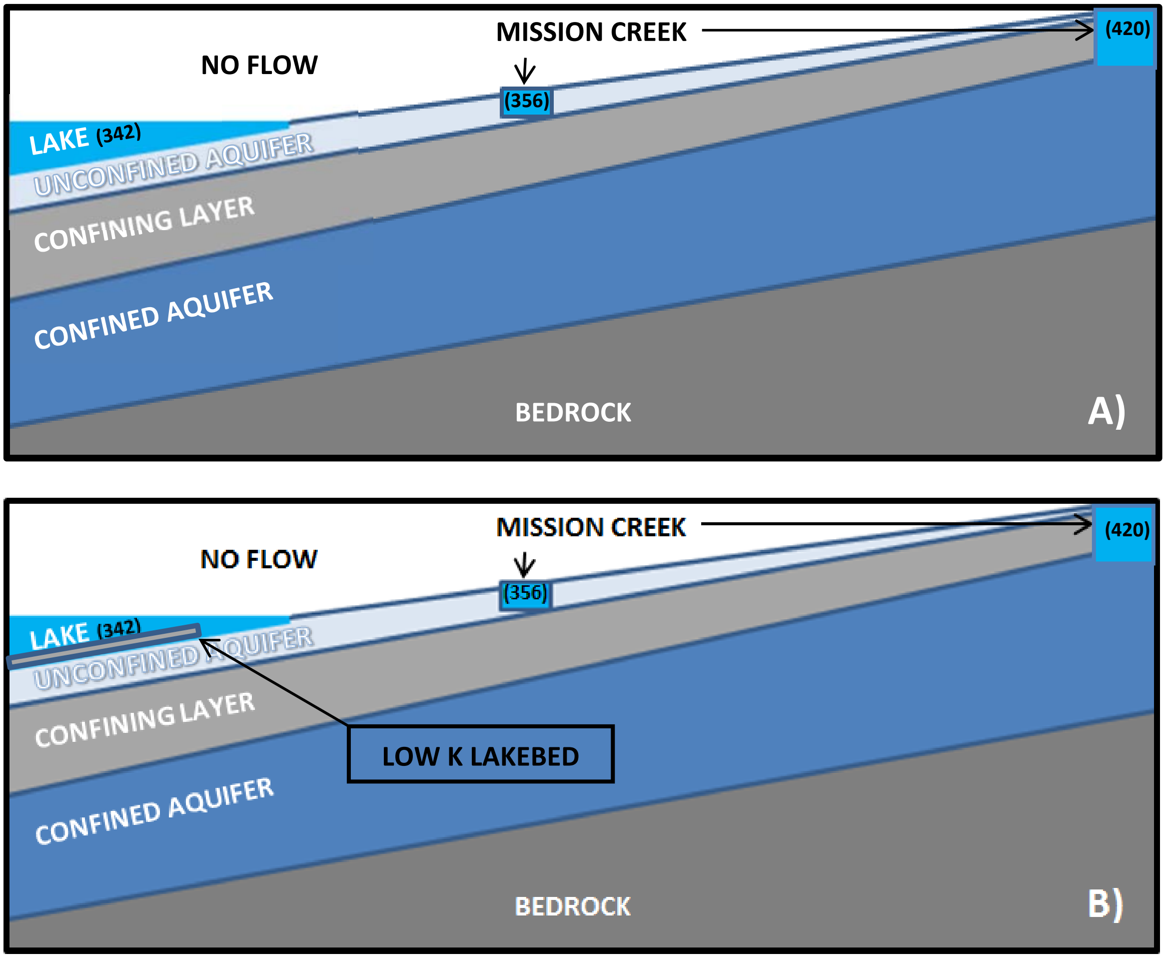


Figure 3.6 Idealized MODFLOW transects (9.7 km long by 100 m high) used in modelling. Elevations of surface water bodies shown in masl in brackets. A) Scenario 1 to Scenario 24: No low conductivity lakebed sediments in place. B) Scenario 25 – Scenario 42: Low conductivity lakebed sediments in place below wavebase (8 m depth) in the lake.

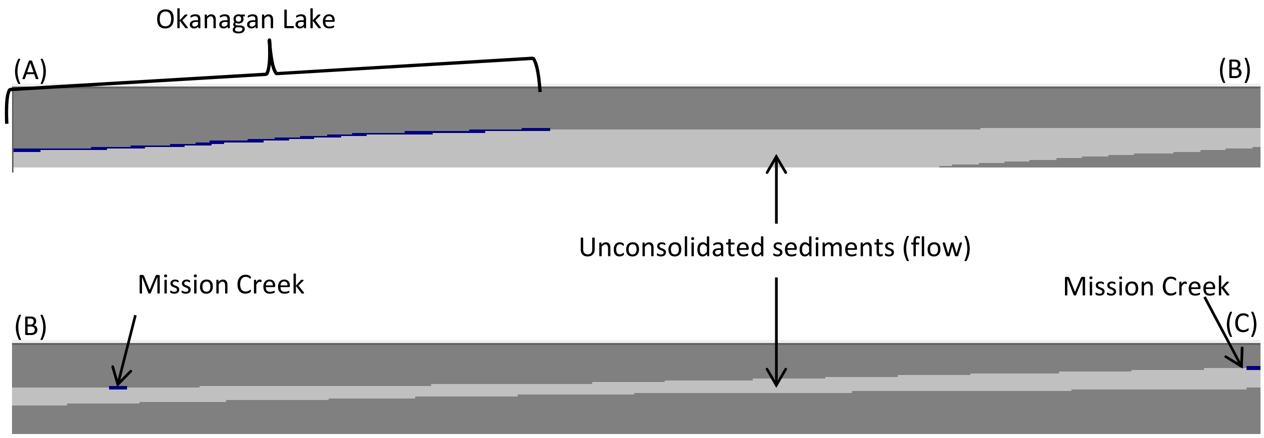


Figure 3.7 Basic model grid layout separated into the downstream section (A-B) and the upstream section (B-C). Combined, the model is 9.7 km long by 100 m high. Grey colouring indicates areas of “no flow” (air and bedrock).

CHAPTER 4: RESULTS

This section reviews the climate and water level conditions observed during the study period before reporting on the results of control measurements and investigations into the spatial and temporal distribution of groundwater flux within the study area. After using the above information to calculate the Kelowna aquifer discharge captured within the study area, the MODFLOW transect modelling results estimated the study area's contribution to the total flow moving from the Kelowna aquifers to Okanagan Lake.

4.1 Climate and Water Levels

Okanagan Lake levels (Hydrometric station 08NM083) ranged from 341.5 – 342.6 masl over the study period with an average of 341.9 masl (Environment Canada, 2013c). Annual precipitation rates for 2011-2013 in Kelowna were 231 mm, 328 mm, and 381 mm, respectively (Environment Canada, 2014a). These precipitation rates are 60%, 85%, and 99% of the 1981 – 2010 "Climate Normal" value of 386.9 mm (Environment Canada, 2014b). Maximum daily precipitation and wind speeds reported for the period of 1981 – 2010 were not exceeded during the study period (Environment Canada, 2014a and 2014b). Appendix E provides the locations of more detailed information on Okanagan Lake water levels, precipitation and potential evapotranspiration rates as well as hydrometric and groundwater data to support discussion in Chapter 5.

4.2 Control Measurements

Four (4) "no flow" and seven (7) "no capture" control measurements were collected between June 2012 and September 2013 (Table 4.1). The "no flow" control measurements reported flux values higher than adjacent seepage meter measurements in all but one case. Four of seven "no capture" control measurements reported an average of ±40 mL of water collected over 3 – 5 days representing an average equipment related error of 5.0 x 10^{-10} $m^3/m^2/s$. Three of the "no capture" control measurements were excluded from the record due to suspected human or animal interference.

4.3 Cover Method Comparison

Measurements from seepage meters with the Method 1 covers were 236% higher than measurements collected from seepage meters with Method 2 covers (Table 4.2). Method 2 also showed a substantial reduction in measurement variability with average standard deviation values decreasing from 53% to 19% of the mean flux rate. Point measurements collected from September 2011 – August 11, 2012 were reduced by 236% prior to inclusion in the data record.

4.4 Cluster Measurements

The cluster measurements found high spatial variability between the individual point measurements comprising a cluster (intra-cluster variability) with an average percentage difference of 68% across all forty-two (42) cluster measurements (Table 4.3). Individual flux rates ranged from -5.8×10^{-10} $m^3/m^2/s$ to 8.0×10^{-9} $m^3/m^2/s$ with cluster averages between 1.6×10^{-10} $m^3/m^2/s$ to 3.9×10^{-9} $m^3/m^2/s$. The only statistically significant relationship was change in intra-cluster variability with change in flux ($P > 0.001$) which had a linear relationship ($R^2 = 0.77$). The relationship of variance to flux rate was used to apply an estimate of variability to each of the point measurements collected within the study. Though cluster measurements were collected in high and low flow conditions across a range of sediment types, only 62% of the point measurements receiving variability estimates fell within the range of flux rates created by individual point measurements used within clusters. Twenty-one (21) individual measurements were above cluster measurement bounds. Site scale sediment heterogeneities may have introduced up to 4.5×10^5 m^3/year of uncertainty into the overall flow calculation.

4.5 Long-Term Stations

The long-term station flux rates changed by two to three orders of magnitude (10^{-11} to $10^{-9}/10^{-8}$ $m^3/m^2/s$) over each annual cycle (Figure 4.1). Human interference and equipment difficulties led to several gaps in the record including a four month break between March and June 2012 at the Lakeshore long-term station and an April 2012 and February to April 2013 break at the Maude-Roxby station. The November 2011 to February 2012 break in the Knox and Maude-Roxby long-term station records was due to ice impingement and is not expected to have a large influence on the overall flow calculation due to the low flows expected in that period.

Multipliers used to scale point measurements to be representative of annual flux based on the long-term station data (Equation 4) are available in Appendix B.

4.6 Transects Perpendicular to the Shoreline

The 2011 perpendicular transects at Lakeshore, Royal and Gyro locations were installed in sand while the Maude-Roxby location varied between silt and fine gravel. All four transects were installed within wave base. Steep and gradual shoreline transects did not demonstrate an exponential or linear decrease in specific discharge with increasing distance from shore (Figure 4.2, Table 4.4). Estimates of flow integrated from shore to the point of non-detection (L_{ND}) using Equation 5 and temporally scaled flux rates produced flows ranging from 1.9 x 10^{-8} m^3/s at Royal to 4.2 x 10^{-7} m^3/s at Maude-Roxby.

The 2012 "low flow" boat transects, installed in sandy silt to sand, generally followed the expected pattern of a reduction in flow with distance from shore with the exception of the transect placed on the south side of the Mission Creek fan (Figure 4.3). An 81% - 104% reduction in flows from the estimated nearshore measurements to the point farthest from shore created a reasonable estimation of L_{ND} in all six transects (Table 4.5). This distance ranged from less than 60 m at Collett to approximately 375 m in the KLO transect. Flow discharge also decreased more quickly at the Collett location with a 1.5% average decrease in flux per metre from shore (total flow over total distance) compared to the 0.4% average decrease in flux per metre across all six transects.

The May/June 2013 ("high flow") boat transects did not clearly decrease with distance from shore except for the Collett and Manhattan locations (Figure 4.4). Transects collected in proximity to the outflow of Mill Creek and Mission Creek showed an increase in discharge with distance from shore; a reverse of the discharge pattern found in low flow conditions. The pattern of flux collected from the southern portion of the Mission Creek fan was constant between high and low flow conditions. Equipment loss limited transects to the inclusion of only two points at the KLO and Mission Creek mouth locations. The points on the KLO fan showed a large increase in flow across the fan in the high flow period. The Mission Creek fan transect is a blend of two, two-point transects due to a single seepage meter failing in two subsequent flux investigations. Integrations of “high flow” transects (Equation 6) show an increase in total discharge in high flow conditions at all locations except for Manhattan which experienced a 20% reduction in total estimated flow (Table 4.6).

The twelve (12) boat transects provided a description of flux changes with distance from shore in five (5) of ten (10) shoreline sections within the study area (Figure 3.4). The remaining five (5) sections were scaled using flux patterns in geologically similar areas (Appendix C).

4.7 Point Measurements

Seventy-four (74) point measurements were collected between August 2011 and July 2013 (Appendix C). Sixteen (16) of the points were eliminated from the overall flow calculation due to:

1) Collection outside the operation of the long-term stations;
2) Collection of negative point measurement values;
3) Collection during a period of extremely low long-term station flux rates; or
4) Collection during a period with minimal long-term station data.

Six (6) point measurements were collected in August 2011 placing them outside of the operational range of the long-term stations. Temporal multipliers were not available to scale these point measurements so they were excluded from the overall flow calculation. Negative point measurements cannot be scaled to be representative of flow over the entire study period excluding four (4) point measurements from the record. Extremely low long-term station flux rates produced extremely high temporal multipliers. Two (2) point measurements collected during periods of low flow became unrealistically high flux rates (10^{-5} $m^3/m^2/s$) and were removed from the record. Four (4) point measurements were excluded from the record because they were collected over two (2) weeks away from any directly measured long-term station daily flux rate.

The eleven (11) out of fourteen (14) cluster measurement averages complied with the inclusion criteria and were added to the fifty-eight (58) remaining point measurements to provide additional values to support the overall flow calculation.

4.8 Overall Flow Estimation

The estimated flow discharged from the Kelowna aquifers to Okanagan Lake within the study period was 3.7×10^5 m^3/yr (after the application of the 1.05 seepage meter correction factor).

4.9 Inter-Annual Variation in Flux

Fluxes observed in the September – October period in 2012 were 87%, 48%, and 29% of fluxes observed in September – October 2011 in the Knox, Maude-Roxby, and Lakeshore long-term stations, respectively (Table 4.7). The comparison of the July – August 2012 and 2013 portions of the record found Knox and Maude-Roxby long-term station flux rates decreased by 84% and 92%, respectively, while the Lakeshore long-term station flux rate increased by 154%. These are discrete comparisons and cannot be considered to be cumulative year to year change.

The application of temporal multipliers created to investigate inter-annual variation to point measurement and cluster data found Year 2 flows (2.90×10^5 m^3/yr) within the study area were estimated to be only 70% of Year 1 flows (4.13×10^5 m^3/yr).

4.10 Gradient Methods

Shoreline vertical flux calculations indicated the hydraulic gradient was in the same direction as the flow direction established by adjacent seepage meters in 38 out of 61 trials (62%; Table 4.8), though comparison of measured to calculated groundwater flux rates showed poor agreement in all measurements. Baptie (2012) also reported poor agreement between flux rate and direction in seepage meter measurements and gradient methods.

The hydraulic gradient direction predicted by the large scale horizontal flux calculations matched the flux direction of temporally similar seepage meter data in nine out of twelve (9/12; 75%) calculations (Table 4.9). In two of the remaining calculations, the seepage meter flux rates were below the method detection limit. Difficulties correlating flux magnitudes between the two methods are presumably due to the use of estimated hydraulic conductivity values in the large scale horizontal flux calculations.

4.11 MODFLOW Modelling

Twenty-four (24) MODFLOW scenarios investigated the impact of various combinations of subsurface sediment hydraulic conductivity on the percentage of total aquifer discharge captured within the nearshore (0 – 150 m from the shoreline = Zone 3; 151 – 300 m from the shoreline = Zone 4) and deeper portions of Okanagan Lake (>300 m from the shoreline = Zone 5), (Table 4.10). The DE45 solver was able to solve all twenty-four (24) scenarios. The percentage of total flow captured within the nearshore of the study area ranged from 26 – 100% with a mean of 72% (Table 4.10).

Several patterns were observed in the data (Figure 4.5):

- Decreasing the hydraulic conductivity in the confining layer decreases total discharge;
- Decreasing the hydraulic conductivity in the confined layer decreases the total discharge; and
- Decreasing the hydraulic conductivity in the confined layer increases the proportion of water captured within the nearshore.

Eighteen (18) additional scenarios investigated the impacts of the presence of a two metre thick low hydraulic conductivity lakebed layer below wave base. The DE45 solver was unable to solve six (6) scenarios in which an extremely low hydraulic conductivity (10^{-8} – 10^{-9} m/s) confining layer was coupled with a low hydraulic conductivity (10^{-7} – 10^{-9} m/s) lakebed layer. The SIP solver was also not able to resolve these scenarios with any degree of confidence. In the remaining twelve (12) scenarios, the DE45 solver was able to solve all scenarios and the percentage of total flow captured within the nearshore of the study area ranged from 56-100% with a mean of 87%.

Patterns observed within this dataset included (Figure 4.5):

- Decreasing the hydraulic conductivity in the confining layer decreases the total discharge;
- Decreasing the hydraulic conductivity of the lakebed layer increases the proportion of water captured within the nearshore;
- Increasing the hydraulic conductivity in the confining layer increases the proportion of water captured within the nearshore; and
- Changing the hydraulic conductivity of the lakebed layer has no effect on the total amount of water that moves into the lake.

The hydraulic conductivity scenario expected to most closely represent reality (based on previous report data) includes a low hydraulic conductivity lakebed layer below wave base (unknown K) and an unconfined aquifer, confining layer and confined aquifer of 10^{-4} m/s, 10^{-7} m/s and 10^{-3} m/s, respectively. Scenarios matching these criteria (Scenarios 28, 32 and 36) result in 56 - 96% of the total flow being captured within the nearshore study area.

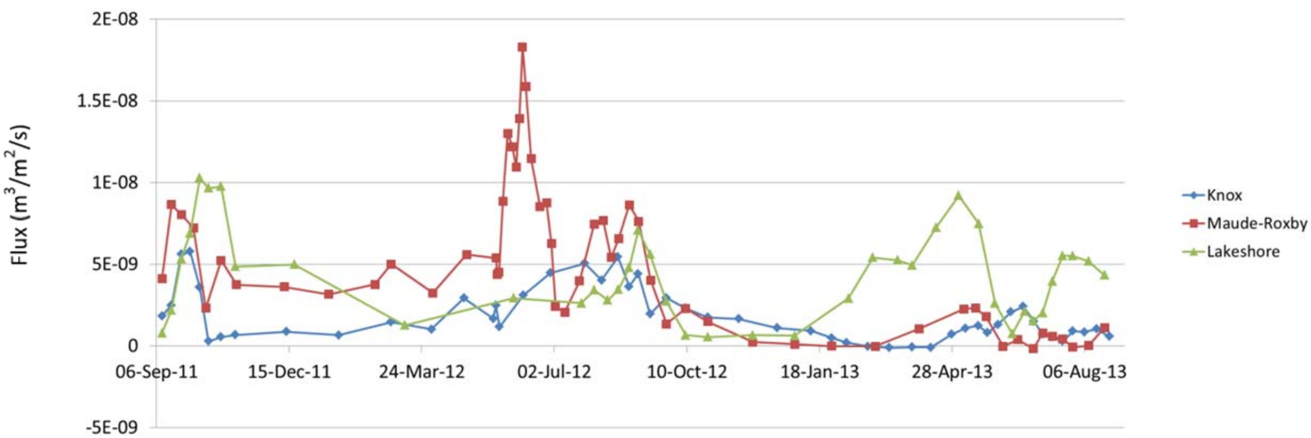


Figure 4.1 Long-term station flux rates over the study period

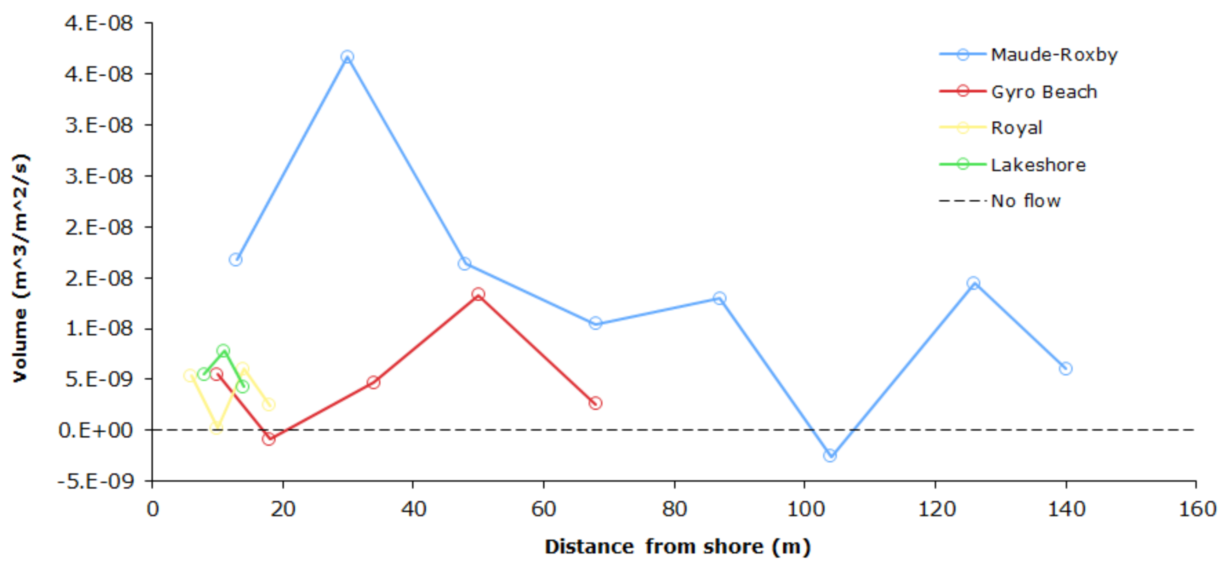


Figure 4.2 Flux rates observed in transects manually installed perpendicular to the shoreline in 2011

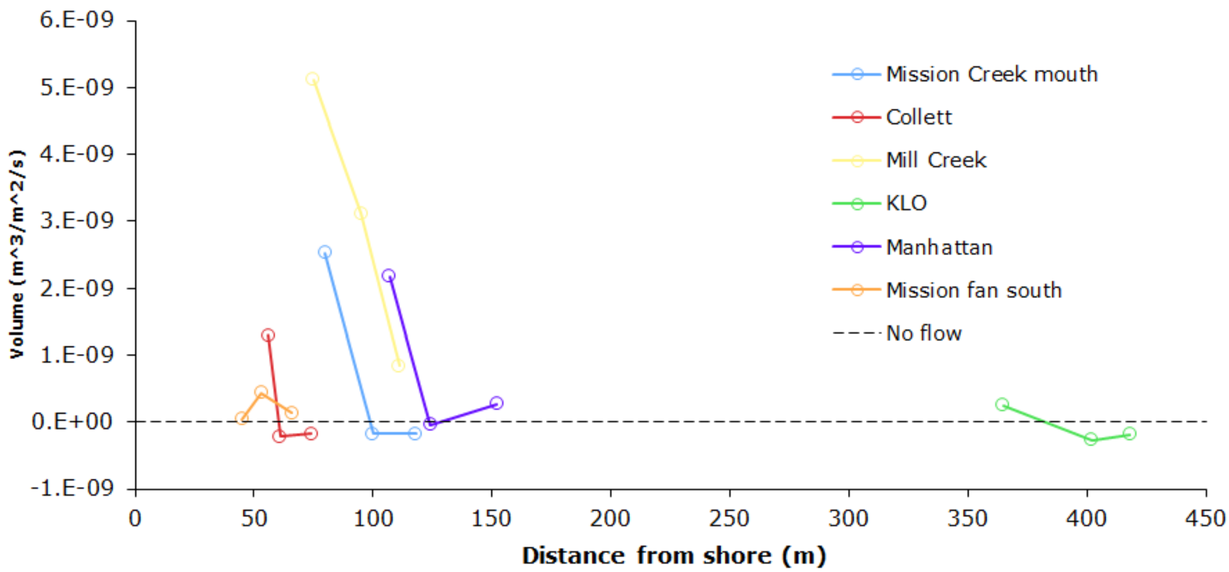


Figure 4.3 Flux rates observed in transects installed perpendicular to the shoreline from a boat in low flow conditions (September - October, 2012)

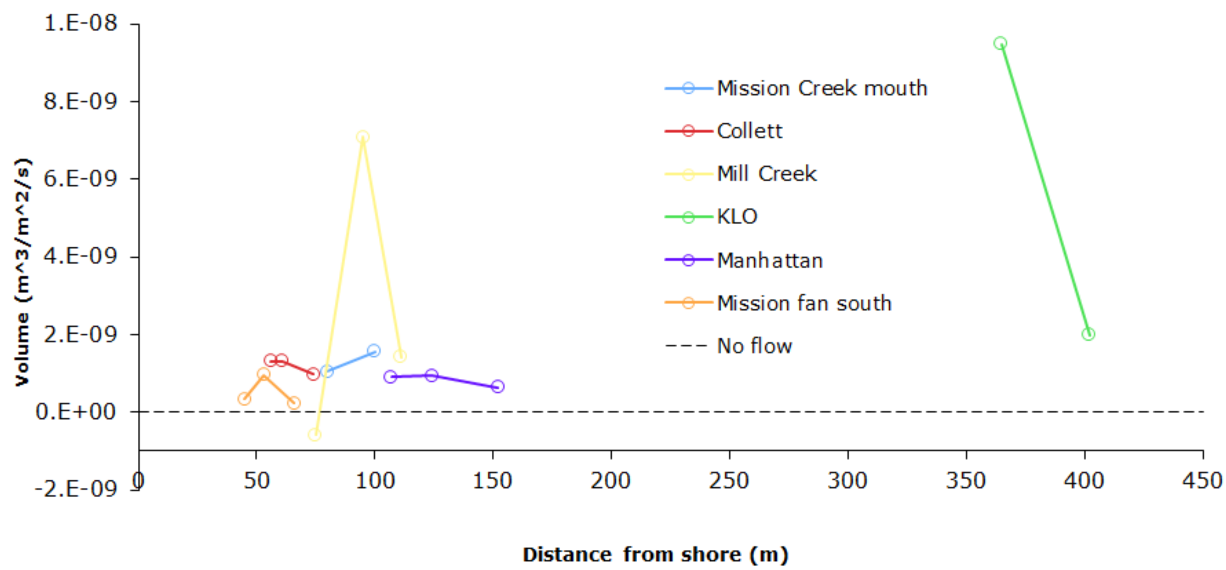


Figure 4.4 Flux rates observed in transects installed perpendicular to the shoreline from a boat in high flow conditions (May - June, 2013)

NO LAKEBED LAYER

$\downarrow K_{confining} = \downarrow discharge_{TOTAL}$

$\downarrow K_{confined} = \downarrow discharge_{TOTAL}$

$\downarrow K_{confined} = \uparrow discharge_{NEARSHORE}$

LAKEBED LAYER

$\downarrow K_{confining} = \downarrow discharge_{TOTAL}$

$\downarrow K_{confining} = \downarrow discharge_{NEARSHORE}$

$\downarrow K_{lakebed} = \uparrow discharge_{NEARSHORE}$

$\Delta K_{lakebed} = \not\Delta\ discharge_{TOTAL}$

Figure 4.5 Patterns observed in MODFLOW scenario outputs

Table 4.1 Control measurements

Method	Included in method error calculation?	Flux Rate ($m^3/m^2/s$)
“no flow”	No[1]	-2.14×10^{-9}
“no flow”	No[1]	7.03×10^{-10}
“no flow”	No[1]	3.65×10^{-9}
“no flow”	No[1]	2.97×10^{-9}
“no capture”	**Yes**	$\mathbf{-3.36 \times 10^{-10}}$
“no capture”	**Yes**	$\mathbf{5.66 \times 10^{-10}}$
“no capture”	**Yes**	$\mathbf{5.94 \times 10^{-10}}$
“no capture”	No[2]	3.22×10^{-9}
“no capture”	No[2]	2.06×10^{-9}
“no capture”	**Yes**	$\mathbf{5.00 \times 10^{-10}}$
“no capture”	No[2]	2.57×10^{-9}
Seepage meter method error average:		4.99×10^{-10}

[1] method malfunction

[2] suspected/known human or animal interference

Table 4.2 Results from the discharge bag cover method comparison experiments

Trial Location	Flux ($m^3/m^2/s$)		Average Flux ($m^3/m^2/s$)		Change	Standard Deviation ($m^3/m^2/s$)	
	Method 1	Method 2	Method 1	Method 2	(%)	Method 1	Method 2
Knox	1.77E-09 7.95E-09	3.45E-09 3.51E-09	4.86E-09	3.48E-09	140	4.37E-09	4.17E-11
West Ave	2.69E-08 1.84E-08	1.64E-09 2.03E-09	2.26E-08	1.84E-09	1233	5.97E-09	2.80E-10
Maude-Roxby	1.65E-09 2.28E-09	5.90E-10 8.19E-10	1.97E-09	7.04E-10	279	4.48E-10	1.62E-10
KLO	-6.36E-10 2.15E-09	0.00E+00 5.33E-10	7.57E-10	2.67E-10	284	1.97E-09	3.77E-10
Mill Creek N	6.18E-09 3.31E-09	1.97E-09 1.12E-09	4.74E-09	1.55E-09	306	2.03E-09	6.00E-10
Mill Creek S	6.00E-09 9.72E-10	[1] 1.12E-09	3.49E-09	1.12E-09	312	3.55E-09	n/a
Gyro	1.65E-09 [1]	1.79E-09 [1]	1.65E-09	1.79E-09	92	n/a	n/a

[1] measurement loss resulting in one point averages (light text).

Table 4.3 Estimates of average flux rate and variability determined from three point cluster measurements (raw data available in Appendix C)

LOCATION	FIG 3.3 NO.	LOW FLOW CLUSTERS AVG FLUX $m^3/m^2/s$	LOW FLOW CLUSTERS ST. DEV $m^3/m^2/s$	LOW FLOW CLUSTERS ERROR %	HIGH FLOW CLUSTERS AVG FLUX $m^3/m^2/s$	HIGH FLOW CLUSTERS ST. DEV $m^3/m^2/s$	HIGH FLOW CLUSTERS ERROR %
Poplar Point	1	2.46×10^{-9}	2.29×10^{-9}	71.4	3.73×10^{-9}	3.14×10^{-9}	64.1
Knox	2	1.25×10^{-9}	8.77×10^{-10}	51.7	1.18×10^{-9}	2.02×10^{-10}	12.7
Half Moon Bay	3	5.70×10^{-10}	6.30×10^{-10}	84.8			
Mill Creek	4	1.56×10^{-10}	4.25×10^{-10}	200.0	3.02×10^{-9}	1.85×10^{-9}	42.0
KLO Rd.	5	2.48×10^{-10}	8.04×10^{-10}	247.0	2.29×10^{-9}	4.18×10^{-10}	13.8
Maude-Roxby	6				2.24×10^{-9}	2.16×10^{-9}	65.8
Gyro Beach	7	1.39×10^{-9}	1.28×10^{-9}	70.7	5.35×10^{-9}	3.59×10^{-9}	50.9
Mission Creek	8	3.89×10^{-9}	3.90×10^{-9}	70.8	1.95×10^{-9}	1.25×10^{-9}	49.1

Table 4.4 Estimates of groundwater flux from 2011 seepage meter transects installed perpendicular to the shoreline

LOCATION	START DATE	TIME ($x 10^4$ sec)	VOLUME ($x 10^{-3}$ m^3)	FLUX [1] ($m^3/m^2/s$)	DEPTH TO SEDIMENT/ WATER INTERFACE (m)	DISTANCE FROM SHORE (m)
Royal	08-Sep-11	15.5	0.22	5.34×10^{-9}	0.69	6
		15.5	0.01	2.43×10^{-10}	0.72	10
		15.5	0.25	6.07×10^{-9}	0.77	14
		15.5	0.10	2.43×10^{-9}	0.84	18
Maude-Roxby	21-Aug-11	7.0	0.31	1.68×10^{-8}	0.47	13
		7.1	0.69	3.67×10^{-8}	0.56	30
		7.1	0.31	1.64×10^{-8}	0.43	48
		7.2	0.20	1.04×10^{-8}	0.60	68
		7.3	0.25	1.30×10^{-8}	0.65	87
		7.4	-0.05	-2.56×10^{-9}	0.60	104
		7.4	0.29	1.45×10^{-8}	0.62	126
		7.5	0.12	6.05×10^{-9}	0.65	140
Gyro	17-Sep-11	8.9	0.13	5.51×10^{-9}	0.65	10
		8.8	-0.02	-8.56×10^{-10}	0.66	18
		8.8	0.11	4.72×10^{-9}	0.71	34
		8.8	0.31	1.33×10^{-8}	0.84	50
		8.7	0.06	2.58×10^{-9}	0.99	68
Lakeshore	30-Sep-11	15.4	0.23	5.51×10^{-9}	0.91	8
		15.4	0.32	7.83×10^{-9}	0.97	11
		15.4	0.18	4.28×10^{-9}	1.07	14

[1] Method scaled flux rates (flux/(average difference between Cover Method 1 and Cover Method 2))

Table 4.5 Groundwater flux rates estimated from 2012 “low flow” seepage meter transects installed perpendicular to the shoreline

LOCATION	START DATE	TIME ($x 10^4$ sec)	VOLUME ($x 10^{-3}$ m^3)	FLUX ($m^3/m^2/s$)	DEPTH TO SEDIMENT/ WATER INTERFACE (m)	DISTANCE FROM SHORE (m)
Manhattan	03-Oct-12	42.3	0.25	2.18×10^{-9}	1.62	107
		42.2	-0.01	-4.45×10^{-11}	1.71	124
		42.2	0.03	2.67×10^{-10}	2.07	152
Mill	25-Sep-12	32.4	0.44	1.30×10^{-9}	1.10	75
		39.8	0.33	-2.23×10^{-10}	1.57	95
		39.8	0.09	-1.79×10^{-10}	1.91	111
KLO	25-Sep-12	41.0	0.03	2.48×10^{-10}	1.34	365
		41.0	-0.03	-2.75×10^{-10}	1.42	402
		41.0	-0.02	-1.83×10^{-10}	1.33	418
Mission Creek mouth	11-Sep-12	43.1	0.29	2.53×10^{-9}	1.8	80
		43.1	-0.02	-1.74×10^{-10}	1.95	100
		43.1	-0.02	-1.75×10^{-10}	2.86	118
Mission Creek fan	03-Oct-12	43.1	0.01	4.37×10^{-11}	1.24	45
		43.0	0.05	4.37×10^{-10}	1.40	53
		43.0	0.02	1.31×10^{-10}	1.85	66
Collett	11-Sep-12	42.0	0.15	1.30×10^{-9}	1.85	56
		42.1	-0.03	-2.23×10^{-10}	2.36	61
		42.1	-0.02	-1.79×10^{-10}	3.47	74

Table 4.6 Groundwater flux rates estimated from 2013 "high flow" seepage meter transects installed perpendicular to the shoreline

LOCATION	START DATE	TIME (x 10^4 sec)	VOLUME (x 10^{-3} m^3)	FLUX ($m^3/m^2/s$)	DEPTH TO SEDIMENT/ WATER INTERFACE (m)	DISTANCE FROM SHORE (m)
Manhattan	14-Jun-13	35.6	0.09	8.98×10^{-10}	1.91	107
		35.5	0.09	9.44×10^{-10}	1.98	124
		35.3	0.06	6.39×10^{-10}	2.10	152
Mill	10-Jun-13	23.3	-0.04	-5.96×10^{-10}	1.80	75
		23.4	0.44	7.08×10^{-9}	1.84	95
		23.4	0.09	1.41×10^{-9}	2.13	111
KLO	10-Jun-13	17.9	0.45	9.48×10^{-9}	1.91	365
		17.8	0.09	1.41×10^{-9}	2.01	418
Mission Creek mouth	30-May-13	42.2	0.12	1.05×10^{-9}	1.94	80
		42.0	0.18	1.57×10^{-9}	2.21	118
Mission Creek fan	24-May-13	45.1	0.04	3.42×10^{-10}	1.98	45
	05-Jun-13	31.8	0.09	9.51×10^{-10}	1.96	53
		32.0	0.02	2.35×10^{-10}	2.33	66
Collett	05-Jun-13	60.5	0.10	1.31×10^{-9}	2.17	56
		60.7	0.10	1.31×10^{-9}	2.98	61
		60.9	0.08	9.82×10^{-10}	3.86	74

Table 4.7 Inter-annual comparison of flux measurements observed at long-term stations

	Flux at Long-Term Stations		
	Knox ($m^3/m^2/s$)	Maude-Roxby ($m^3/m^2/s$)	Lakeshore ($m^3/m^2/s$)
Sept - Oct 2011	1.65E-07	3.20E-07	3.58E-07
Sept - Oct 2012	1.43E-07	1.55E-07	1.04E-07
Percentage of 2011 fluxes observed in 2012	87%	48%	29%
July - Aug 2012	2.60E-07	2.67E-07	1.53E-07
July - Aug 2013	4.06E-08	2.07E-08	2.34E-07
Percentage of 2012 fluxes observed in 2013	16%	8%	153%

Table 4.8 Shoreline vertical flux calculation parameters and results

Date of Measurement (dd/mmm/yr)	Map Identifier (Figure 3.1)	Piezometer Nest Number	Screen Depth Below Sediment/Water Interface(m)	Comparison to Lake Water Level (m)	Gradient to OK Lake (h_1-h_2/Δl)	Hydraulic Conductivity (m/s)[1]	Flux ($m^3/m^2/s$)	Seepage Meter Measurement Dates	Flux Average ($m^3/m^2/s$)	Same flux direction?
17-Sep-11	A	1	0.20	0.025	0.125	1.00E-05	1.25E-06	18-Sep-11	-3.477E-10	NO
			1.00	0.004	0.004	1.00E-05	4.00E-08	18-Sep-11	-3.477E-10	NO
	B	3	0.17	-0.005	-0.029	1.00E-05	-2.94E-07	18-Sep-11	7.0951E-09	NO
	C	1	0.30	0.002	0.007	1.50E-04	1.00E-06	21-Sep-11	1.5011E-08	YES
		2	1.00	0.001	0.001	1.50E-04	1.50E-07	21-Sep-11	1.5011E-08	YES
18-Sep-11	A		0.20	0.118	0.590	1.00E-05	5.90E-06	18-Sep-11	-3.477E-10	NO
			1.00	-0.003	-0.003	1.00E-05	-3.00E-08	18-Sep-11	-3.477E-10	YES
	B		0.20	-0.005	-0.025	1.00E-05	-2.50E-07	18-Sep-11	7.0951E-09	NO
			1.00	0.000	0.000	1.00E-05	0.00E+00	18-Sep-11	7.0951E-09	NO
24-Sep-11	A		0.20	0.067	0.335	1.00E-05	3.35E-06	24-Sep-11	7.103E-09	YES
			1.00	0.056	0.056	1.00E-05	5.60E-07	24-Sep-11	7.103E-09	YES
	B		0.20	0.002	0.010	1.00E-05	1.00E-07	24-Sep-11	1.5266E-08	YES
			1.00	-0.001	-0.001	1.00E-05	-1.00E-08	24-Sep-11	1.5266E-08	NO
	D		0.20	-0.002	-0.010	1.50E-04	-1.50E-06	24-Sep-11	4.3972E-09	NO
			1.00	-0.025	-0.025	1.50E-04	-3.75E-06	24-Sep-11	4.3972E-09	NO
02-Oct-11	A		0.20	0.027	0.135	1.00E-05	1.35E-06	02-Oct-11	1.0062E-08	YES
			1.00	-0.010	-0.010	1.00E-05	-1.00E-07	02-Oct-11	1.0062E-08	NO
	B		0.20	-0.005	-0.025	1.00E-05	-2.50E-07	02-Oct-11	1.79E-09	NO
			1.00	-0.006	-0.006	1.00E-05	-6.00E-08	02-Oct-11	1.79E-09	NO
	D		0.20	0.001	0.005	1.50E-04	7.50E-07	02-Oct-11	6.4522E-09	YES
			1.00	0.034	0.034	1.50E-04	5.10E-06	02-Oct-11	6.4522E-09	YES
08-Oct-11	A		0.20	0.059	0.295	1.00E-05	2.95E-06	08-Oct-11	1.7604E-10	YES
			1.00	-0.001	-0.001	1.00E-05	-1.00E-08	08-Oct-11	1.7604E-10	NO
	B		0.20	-0.008	-0.040	1.00E-05	-4.00E-07	02, 16-Oct-11	3.216E-09	NO
			1.00	0.004	0.004	1.00E-05	4.00E-08	02, 16-Oct-11	3.216E-09	YES
	D		0.20	-0.018	-0.090	1.50E-04	-1.35E-05	08-Oct-11	9.8651E-09	NO
			1.00	0.010	0.010	1.50E-04	1.50E-06	08-Oct-11	9.8651E-09	YES

Table 4.8 Shoreline vertical flux calculation parameters and results (continued)

Date of Measurement (dd/mmm/yr)	Map Identifier (Figure 3.1)	Piezometer Nest Number	Screen Depth Below Sediment/Water Interface(m)	Comparison to Lake Water Level (m)	Gradient to OK Lake (h_1-h_2/Δl)	Hydraulic Conductivity (m/s)[1]	Flux ($m^3/m^2/s$)	Seepage Meter Measurement Dates	Flux Average ($m^3/m^2/s$)	Same flux direction?
16-Oct-11	A		0.20	0.017	0.085	1.00E-05	8.50E-07	16-Oct-11	4.9526E-10	YES
			1.00	0.023	0.023	1.00E-05	2.30E-07	16-Oct-11	4.9526E-10	YES
	B		0.20	0.030	0.150	1.00E-05	1.50E-06	16-Oct-11	4.6427E-09	YES
			1.00	0.001	0.001	1.00E-05	1.00E-08	16-Oct-11	4.6427E-09	YES
	D		0.20	-0.001	-0.005	1.50E-04	-7.50E-07	16-Oct-11	1.4525E-08	NO
			1.00	-0.022	-0.022	1.50E-04	-3.30E-06	16-Oct-11	1.4525E-08	NO
22-Oct-11	A		0.20	0.023	0.115	1.00E-05	1.15E-06	22-Oct-11	1.6802E-10	YES
			1.00	0.058	0.058	1.00E-05	5.80E-07	22-Oct-11	1.6802E-10	YES
	B		0.20	0.001	0.005	1.00E-05	5.00E-08	22-Oct-11	5.0822E-10	YES
			1.00	0.002	0.002	1.00E-05	2.00E-08	22-Oct-11	5.0822E-10	YES
	D		0.20	-0.010	-0.050	1.50E-04	-7.50E-06	22-Oct-11	4.6034E-09	NO
			1.00	-0.005	-0.005	1.50E-04	-7.50E-07	22-Oct-11	4.6034E-09	NO
05-Nov-11	A		0.20	0.219	1.095	1.00E-05	1.10E-05	05-Nov-11	9.9053E-10	YES
			1.00	0.144	0.144	1.00E-05	1.44E-06	05-Nov-11	9.9053E-10	YES
	B		0.20	0.000	0.000	1.00E-05	0.00E+00	05-Nov-11	1.0529E-08	NO
			1.00	-0.005	-0.005	1.00E-05	-5.00E-08	05-Nov-11	1.0529E-08	NO
	D		0.20	0.007	0.035	1.50E-04	5.25E-06	05-Nov-11	1.014E-08	YES
			1.00	0.065	0.065	1.50E-04	9.75E-06	05-Nov-11	1.014E-08	YES
18-Nov-11	A		0.20	0.010	0.050	1.00E-05	5.00E-07	18-Nov-11	8.8487E-10	YES
			1.00	0.023	0.023	1.00E-05	2.30E-07	18-Nov-11	8.8487E-10	YES
	D		0.20	-0.195	-0.975	1.50E-04	-1.46E-04	18-Nov-11	-1.782E-10	YES
			1.00	-0.199	-0.199	1.50E-04	-2.99E-05	18-Nov-11	-1.782E-10	YES
27-Nov-11	A		0.20	-0.031	-0.155	1.00E-05	-1.55E-06	18-Nov-11	8.8487E-10	NO
			1.00	0.112	0.112	1.00E-05	1.12E-06	18-Nov-11	8.8487E-10	YES
	D		0.20	-0.058	-0.290	1.50E-04	-4.35E-05	18-Nov-11	8.8487E-10	NO
			1.00	0.030	0.030	1.50E-04	4.50E-06	18-Nov-11	8.8487E-10	YES

Table 4.8 Shoreline vertical flux calculation parameters and results (continued)

Date of Measurement (dd/mmm/yr)	Map Identifier (Figure 3.1)	Piezometer Nest Number	Screen Depth Below Sediment/Water Interface(m)	Comparison to Lake Water Level (m)	Gradient to OK Lake (h_1-h_2/Δl)	Hydraulic Conductivity (m/s)[1]	Flux ($m^3/m^2/s$)	Seepage Meter Measurement Dates	Flux Average ($m^3/m^2/s$)	Same flux direction?
14-Feb-12	A		1.00	0.023	0.023	1.00E-05	2.30E-07	14-Feb-12	7.5575E-10	YES
	B		1.00	0.015	0.015	1.00E-05	1.50E-07	14-Feb-12	9.1868E-09	YES
03-Mar-12	A		0.20	0.028	0.140	1.00E-05	1.40E-06	03-Mar-12	3.6142E-10	YES
			1.00	0.031	0.031	1.00E-05	3.10E-07	03-Mar-12	3.6142E-10	YES
	B		1.00	0.019	0.019	1.00E-05	1.90E-07	03-Mar-12	2.0014E-09	YES
15-Mar-12	A		0.20	0.021	0.105	1.00E-05	1.05E-06	15-Mar-12	3.2505E-09	YES
			1.00	0.029	0.029	1.00E-05	2.90E-07	15-Mar-12	3.2505E-09	YES
	B		1.00	0.026	0.026	1.00E-05	2.60E-07	15-Mar-12	3.8235E-09	YES

[1] Falling head tests were unsuccessfully attempted on re-packed sediment samples from Knox (Site A), Maude-Roxby (Site B), and Lakeshore (Site D). Creation of preferential flow paths generated unrealistically high hydraulic conductivity values (ie. 0.04 m/s for a fine sand). Textbook values were substituted. Hydraulic conductivity values for Gyro Beach (Site C) were adopted from in situ falling head tests completed by Baptie (2012) as part of a supportive undergraduate research project.

Table 4.9 Large scale horizontal flux calculation parameters and results

Date of Measurement (dd/mmm/yr)	Map Identifier (Figure 3.1)	Midpoint Screen Elevation (masl)	Groundwater head (masl)	Distance to OK Lake (m)	Hydraulic Conductivity (m/s)[1]	OK Lake Elevation (masl)	Gradient (h_1-h_2/Δl)	Flux ($m^3/m^2/s$)	Seepage Meter Measurement Dates	Flux Average ($m^3/m^2/s$)	Same flux direction?	Same flux magnitude?
12-Sep-12	1	342.04	342.50	289	1.00E-05	341.94	0.0019	1.93E-08	11-Sep-12, 23-Sep-12	2.04E-10	YES	NO
	2	341.99	342.51	287	1.00E-05	341.94	0.0020	1.97E-08	11-Sep-12, 23-Sep-12	2.04E-10	YES	NO
01-Oct-12	1	342.04	342.46	289	1.00E-05	341.86	0.0021	2.09E-08	23-Sep-12, 10-Oct-12	3.17E-09	YES	NO
	2	341.99	342.48	287	1.00E-05	341.86	0.0022	2.16E-08	23-Sep-12, 10-Oct-12	3.17E-09	YES	NO
26-Oct-12	3	341.44	341.83	649	1.00E-05	341.76	0.0001	1.16E-09	24-Oct-12, 12-Nov-12	1.87E-09	YES	YES
	4	341.65	341.69	655	1.00E-05	341.76	-0.0001	-9.92E-10	24-Oct-12, 12-Nov-12	1.87E-09	NO	[2]
05-Nov-12	5	352.1	353.31	2360	1.00E-05	341.80	0.0049	4.88E-08	24-Oct-12, 12-Nov-12	4.14E-10	YES	NO
	6	352.5	353.42	2360	1.00E-05	341.80	0.0049	4.93E-08	24-Oct-12, 12-Nov-12	4.14E-10	YES	NO
12-Feb-13	1	342.04	342.65	289	1.00E-05	341.68	0.0033	3.35E-08	03-Feb-13, 29-Apr-13	-1.32E-10	NO	[2]
	2	341.99	342.66	287	1.00E-05	341.68	0.0034	3.39E-08	03-Feb-13, 29-Apr-13	-1.32E-10	NO	[2]
29-May-13	1	342.04	342.74	289	1.00E-05	342.38	0.0012	1.22E-08	25-May-13, 31-May-13	9.05E-10	YES	NO
	2	341.99	342.73	287	1.00E-05	342.38	0.0012	1.21E-08	25-May-13, 31-May-13	9.05E-10	YES	NO

[1]Hydraulic conductivities estimated using textbook values and well log descriptions

[2]Flux magnitude was not assessed if flux directions were opposing in the two methods

Table 4.10 MODFLOW scenario results summary

Scenario No.	Hydraulic Conductivity (m/s)			Model Volumetric Budget (m^3)				Zone 3 (0 - 150 m from shoreline)		Zone 4 (151- 300 m from shoreline)		Zone 5 (>300 m from shoreline)		Sum of Nearshore (zone 3+4)
	unconfined	confining	confined	Water in	Water out	Water leaving at lake (% of total)	Water leaving at the lake	Discharge at the lake	% of total discharge to the lake	Discharge at the lake	% of total discharge to the lake	Discharge at the lake	% of total discharge to the lake	
1	1.00E-04	1.00E-04	1.00E-02	6.69E-01	6.69E-01	51	3.43E-01	7.80E-02	23	5.54E-02	16	2.09E-01	61	39
2	1.00E-04	1.00E-05	1.00E-02	5.45E-01	5.45E-01	78	4.23E-01	7.01E-02	17	4.15E-02	10	3.12E-01	74	26
3	1.00E-04	1.00E-06	1.00E-02	3.38E-01	3.38E-01	83	2.80E-01	5.68E-02	20	1.86E-02	7	2.05E-01	73	27
4	1.00E-04	1.00E-07	1.00E-02	1.03E-01	1.03E-01	73	7.48E-02	2.90E-02	39	3.65E-03	5	4.22E-02	56	44
5	1.00E-04	1.00E-08	1.00E-02	2.43E-02	2.43E-02	61	1.49E-02	9.60E-03	64	4.37E-04	3	4.90E-03	33	67
6	1.00E-04	1.00E-09	1.00E-02	3.86E-03	3.85E-03	66	2.54E-03	1.99E-03	78	4.75E-05	2	5.05E-04	20	80
7	1.00E-04	1.00E-04	1.00E-03	7.66E-02	7.66E-02	38	2.90E-02	1.54E-02	53	6.72E-03	23	6.86E-03	24	76
8	1.00E-04	1.00E-05	1.00E-03	7.07E-02	7.07E-02	49	3.44E-02	1.34E-02	39	5.87E-03	17	1.51E-02	44	56
9	1.00E-04	1.00E-06	1.00E-03	6.14E-02	6.14E-02	65	3.98E-02	1.24E-02	31	3.38E-03	8	2.41E-02	60	40
10	1.00E-04	1.00E-07	1.00E-03	4.41E-02	4.41E-02	68	3.00E-02	1.26E-02	42	1.48E-03	5	1.60E-02	53	47
11	1.00E-04	1.00E-08	1.00E-03	2.10E-02	1.83E-02	53	1.11E-02	7.21E-03	65	3.20E-04	3	3.56E-03	32	68
12	1.00E-04	1.00E-09	1.00E-03	7.53E-03	3.38E-03	30	2.25E-03	1.76E-03	78	4.21E-05	2	4.49E-04	20	80
13	1.00E-04	1.00E-04	1.00E-04	9.29E-03	9.29E-03	41	3.78E-03	3.33E-03	88	4.44E-04	12	9.92E-14	0	100
14	1.00E-04	1.00E-05	1.00E-04	8.14E-03	8.14E-03	43	3.50E-03	2.73E-03	78	4.74E-04	14	2.98E-04	9	91
15	1.00E-04	1.00E-06	1.00E-04	7.82E-03	7.82E-03	47	3.69E-03	2.43E-03	66	3.71E-04	10	8.90E-04	24	76
16	1.00E-04	1.00E-07	1.00E-04	7.33E-03	7.33E-03	55	4.00E-03	2.48E-03	62	1.92E-04	5	1.33E-03	33	67
17	1.00E-04	1.00E-08	1.00E-04	6.07E-03	6.07E-03	60	3.66E-03	2.60E-03	71	9.35E-05	3	9.61E-04	26	74
18	1.00E-04	1.00E-09	1.00E-04	2.74E-03	2.74E-03	69	1.89E-03	1.53E-03	81	3.20E-05	2	3.33E-04	18	82
19	1.00E-04	1.00E-04	1.00E-05	2.22E-03	2.22E-03	63	1.40E-03	1.35E-03	96	4.71E-05	3	3.13E-06	0	100
20	1.00E-04	1.00E-05	1.00E-05	1.73E-03	1.73E-03	56	9.64E-04	9.39E-04	97	2.26E-05	2	2.68E-06	0	100
21	1.00E-04	1.00E-06	1.00E-05	1.63E-03	1.63E-03	56	9.13E-04	8.68E-04	95	2.95E-05	3	1.62E-05	2	98
22	1.00E-04	1.00E-07	1.00E-05	1.58E-03	1.58E-03	57	9.07E-04	8.34E-04	92	2.27E-05	2	4.99E-05	5	95
23	1.00E-04	1.00E-08	1.00E-05	1.48E-03	1.48E-03	61	9.01E-04	8.17E-04	91	1.20E-05	1	7.16E-05	8	92
24	1.00E-04	1.00E-09	1.00E-05	1.24E-03	1.24E-03	72	8.95E-04	8.18E-04	91	8.28E-06	1	6.91E-05	8	92
25[1]	1.00E-04	1.00E-04	1.00E-03	7.66E-02	7.66E-02	38	2.89E-02	1.72E-02	60	1.00E-02	35	1.61E-03	6	94
26[1]	1.00E-04	1.00E-05	1.00E-03	7.07E-02	7.07E-02	48	3.38E-02	1.64E-02	48	1.12E-02	33	6.28E-03	19	81
27[1]	1.00E-04	1.00E-06	1.00E-03	6.08E-02	6.08E-02	63	3.86E-02	1.41E-02	37	8.05E-03	21	1.64E-02	43	57
28[1]	1.00E-04	1.00E-07	1.00E-03	4.38E-02	4.38E-02	67	2.95E-02	1.28E-02	43	3.69E-03	12	1.31E-02	44	56
29[2]	1.00E-04	1.00E-04	1.00E-03	7.66E-02	7.66E-02	38	2.88E-02	1.77E-02	61	1.08E-02	38	2.82E-04	1	99
30[2]	1.00E-04	1.00E-05	1.00E-03	7.06E-02	7.06E-02	46	3.24E-02	1.83E-02	56	1.28E-02	40	1.29E-03	4	96
31[2]	1.00E-04	1.00E-06	1.00E-03	5.98E-02	5.98E-02	60	3.62E-02	1.75E-02	48	1.36E-02	38	5.11E-03	14	86
32[2]	1.00E-04	1.00E-07	1.00E-03	4.26E-02	4.26E-02	65	2.78E-02	1.36E-02	49	7.65E-03	28	6.51E-03	23	77
33[3]	1.00E-04	1.00E-04	1.00E-03	7.66E-02	7.66E-02	38	2.88E-02	1.78E-02	62	1.10E-02	38	3.63E-05	0	100
34[3]	1.00E-04	1.00E-05	1.00E-03	7.06E-02	7.06E-02	47	3.33E-02	1.87E-02	56	1.44E-02	43	1.56E-04	0	100
35[3]	1.00E-04	1.00E-06	1.00E-03	5.94E-02	5.94E-02	59	3.52E-02	1.88E-02	54	1.56E-02	44	6.72E-04	2	98
36[3]	1.00E-04	1.00E-07	1.00E-03	4.14E-02	4.14E-02	63	2.61E-02	1.44E-02	55	1.05E-02	40	1.16E-03	4	96

[1] Lakebed layer hydraulic conductivity = 10^{-7} m/s; [2] Lakebed layer hydraulic conductivity = 10^{-8} m/s; [3] Lakebed layer hydraulic conductivity = 10^{-9} m/s

CHAPTER 5: DISCUSSION

In the following section, error, variability, and groundwater flow estimation calculations are further clarified and justified including several sensitivity analyses. Results are interpreted and set in a regional context by examining potential influences on groundwater discharge such as precipitation, evaporation, surface water levels, groundwater levels, and pumping rates. Factors potentially impacting future water availability in the Kelowna area are also discussed including patterns historical groundwater levels, the impact of pumping on surface water levels, climate change, and the shifting regulatory environment.

5.1 Error and Variability Calculations

5.1.1 Control Measurements

Individual seepage meters were not monitored during their entire twenty-four (24) hour to ten (10) day deployment and so may have been subject to human or animal interference, currents, unusual storm activity, or influences from local biota in addition to leakage or measurement errors. Point measurements were eliminated from the record if they exhibited any obvious signs of interference or damage such as animal teeth marks, loss of the seepage bag cover or gross movement of a seepage meter from its original positioning. Control measurements attempt to quantity the average impacts of normal variability caused by currents, waves, and seepage meter design on flux measurements. Each individual point measurement may experience more or less of these influences.

The “no flow” measurements presumably returned flows higher than adjacent seepage meters in most cases due to the loosening effect on the sediment produced by the installation of the impermeable barrier. In Cable et al. (1997b), impermeable barriers were installed on top of the sediment water interface in “kiddie pools” filled with coastal sand, decreasing the depth to sediment/water interface by 10 – 15 cm at those locations. Flat impermeable barriers were selected for the Maude-Roxby location to eliminate the artificial decrease in the depth to the sediment/water interface and to reduce the seepage meter shielding provided by the “kiddie pool” walls. Repacking the sediment to the same density after the mat-style impermeable barrier installation proved impossible, allowing the control meter greater movement with wave action producing pressure effects that artificially increased the flow of water into the groundwater collection bag. The “no flow” control measurements were eliminated from the estimation of error because they were not deemed to be representative of conditions experienced by the standard seepage meters.

The “no capture” control method, based on Sebestyen and Schneider (2001) and Schneider et al. (2005), does not represent conditions identical to seepage meter experiments. The holes meet the objective of redirecting groundwater flow away from the collection bag but may influence wave interactions with the meter or not adequately mimic the buildup of pressure possible within a sealed seepage meter during periods of groundwater inflow. The exact impacts of pressure and wave differences on seepage meters in a natural nearshore environment could not be described without the completion of a comparison trial with “no flow” control meters. The “no capture” control measurements were used as the “controls” as the “no flow” control measurement trials were unsuccessful.

Within the literature, seepage meter method errors are often ignored, discussed but not quantified, or directly included within variability assessments of repeated measurements over time (Attanayake and Waller, 1988; Boyle, 1994; Cable et al., 1997a; Kidmose et al., 2011; Ala-aho et al., 2013). The control measurement average of 4% of average flux rates found on the Kelowna site is within the same range as the 5.6% found by Schneider et al. (2005) and 2.3 – 5.7% reported by Cable et al. (1997b). The absolute control measurement value of 5.0×10^{-10} $m^3/m^2/s$ is slightly lower than that reported by these other two studies (1.1×10^{-9} and 3.3×10^{-8} – 1.8×10^{-7} $m^3/m^2/s$, respectively).

5.1.2 Cover Method Comparison

The initially selected seepage meter cover configuration was suspected of capturing a poor representation of actual groundwater flux when field crews, returning to collect seepage meter measurements at the end of a trial, witnessed the covers rocking back and forth with wave action. It was suspected that the cover movement was mimicking wave forces on an uncovered seepage meter collection bag creating an anomalous influx of water into the bag as well as a larger overall variability within the seepage meter measurements. A cover change was implemented when attempts to stabilize the covers by weighting them down with rocks and "pinning" them to the sediment using three (3) foot lengths of 0.3 cm diameter cylindrical metal through the cover handles were unsuccessful. Parameters (time, sediment, distance from shore, depth to sediment/water interface) were controlled during method comparison trials so the 236% average higher flux measurement in Cover Method 1-type covered seepage meters supported the theory that cover movement was creating anomalous influxes of water to move into the collection bags. The variability (standard deviation) between measurements also decreased by 34% with adoption of Cover Method 2.

A post-audit of Cover Method 1 found that studies successfully utilizing seepage meter covers installed adjacent to the seepage meter at the sediment/water interface selected smaller, rounded covers compared to the 68 L rectangular Rubbermaid bins selected for use at the Kelowna site to allow full groundwater collection bag expansion (Brodie et al., 2009; Rautio and Korkka-Neimi, 2011). These covers would be better able to deflect wave forces and would therefore be less affected by wave action. All cluster measurements were collected using Cover Method 2 covers.

5.1.3 Cluster Measurements

Cluster measurements investigated the potential influence of the depth to the sediment/water interface, the surface sediment type, the distance from shore, and the flux rate on the reproducibility of point measurements. Experiments found the only statistically significant relationship was an increase in intra-cluster variability with an increase in flux rate, a result similar to that observed by Shaw and Prepas (1990a). The wide range of calculated coefficients of variation between the clusters (17.2% – 323.5%) suggests the intra-cluster variability is not caused by changes in the magnitude of the hydraulic gradient but rather from sediment variability along the flow path as water approaches the seepage meter. This argument is supported by work completed by Schulze-Makuch et al. (1999) that found increasing hydraulic conductivity estimates with increasing volumes of the aquifer sampled during pumping tests in heterogeneous sediments. They postulated that K will continue to increase until the sampled volume of the aquifer reaches a representative elementary volume (i.e. a scale where all heterogeneity within the aquifer has been sampled and the heterogeneous aquifer approaches the properties of a homogeneous aquifer). Flux variability will increase with increasing flux rates as the hydraulic gradient is increased through the same heterogeneous material. This view was conservatively applied to the estimate of overall potential variability encountered on the Kelowna site by extending the linear relationship between flux magnitude and variance beyond the upper bounds of the cluster flux magnitude vs. standard deviation graph to include the twenty-one (21) measurements with flux rates up to an order of magnitude higher than the highest cluster value. This included 36% of the individual point measurements which combine to comprise 75% of the total flux variability. The cluster measurements were not temporally scaled prior to statistical analysis to prevent the introduction of "noise" into the data set. Though the clusters were installed in both high and low flow conditions in a range of surface sediment types, the dates and locations selected inadvertently produced flux rates lower than the annual average. A graph of scaled cluster measurements would have covered the entire range of point measurement flux magnitudes but may have under- or over-estimated the influence of parameters on flux variability. Although the impact of small spatial scale sediment heterogeneities on individual point measurements may have introduced up to 4.5×10^5 m^3/yr of variability into the overall flow estimate, this is the cumulative error and does not likely represent the actual range of variability within the total flow calculation.

The lack of a statistical relationship between intra-cluster measurement variability and other tested parameters (distance from shore, depth to sediment/water interface, and surface sediment composition) met with expectations in only some instances. All cluster measurements were installed within close proximity of the shoreline in the topset of deltaic fans so an observable relationship of intra-cluster variability with distance from shore was not expected. The "depth to sediment/water interface" parameter however, was expected to influence the variability of flux measurements as seepage meters in shallower depths receive proportionately more force from wave action and wave action has been shown to increase the variance of seepage meter measurements (Cable et al., 1997b). The seepage meter covers from seepage meter Cover Method 2 must have eliminated this effect by providing adequate wave protection for the groundwater collection bags. The surficial sediment composition was expected to affect the flow variability as smaller substrate sizes would likely have a smaller representative elementary volume and therefore could be expected to have a smaller flux variability over a similar sample size. This was not observed however indicating the spatial distribution of flux rates is likely not primarily driven by the sediment heterogeneity observed at the sediment/water interface but rather by the impacts of regional sediment heterogeneity. Schneider et al. (2005) observed a lack of correlation between flux rate and surface sediment type (silts and clay to cobbles and boulders) over 25 sample locations which suggests larger regional flow paths were also the primary drivers of flux rate distribution in their study environments.

5.1.4 Storm Effects on Individual Point Measurements

The majority of seepage meter measurements attempted during storms were not included in the final record as the measurements were typically lost in periods of high wind activity. Storms may have triggered seiche events but the 153 minute estimated seiche interval (Equation 1) was only 11% of the minimum seepage meter trial length, allowing integration of any hydraulic head gradient changes over the period of deployment.

5.2 Groundwater Flow Estimation

5.2.1 Expansion on methods

5.2.1.1 Temporal scaling

Long-term station measurements were not collected daily so daily flux rates between sampling times were calculated assuming a linear relationship between two adjacent measured flux rates within a long-term record. This method may overestimate or underestimate daily flow rates in portions of the long-term record with a low number of measured flux data points. Visual inspection of the long-term records suggests winter sampling gaps (Knox, February 2012; Maude-Roxby, February 2013; and Lakeshore, January and February 2012 and January 2013) were adequately described by the small number of flux measurements as flow in these months is expected to be minimal. However, the Lakeshore station under-sampling in March - May

2012 likely underestimated flow during this time period, therefore lowering the overall average flux rate and lowering each daily multiplier for this station. Point measurements scaled by the Lakeshore station comprise 72% of total study flow so a sensitivity analysis was completed to investigate the potential impact of this underestimation. A second set of daily multipliers for the Lakeshore long-term station was created by artificially inflating daily values for March - May 2012 to mimic the shape and magnitude of fluxes observed during the spring of 2013. This test indicates the total flow estimation within the study area may have been as high as 4.47×10^5 m^3/yr (26% higher than reported) if actual flux rates were as high as predicted during this period.

Ideally, point measurements would be assigned to long-term stations with flows that were regulated by similar upgradient controls. This could be investigated through a geochemical investigation or repeated measurements at each point measurement location for comparison with the two adjacent long-term flow records. Neither method was practical for this study so long-term station assignments were dictated by absolute distance between stations (Figure 5.1). Surface sediment type in the lakebed and shoreline shape (from plan view) indicate ideal long-term station assignments may have varied from linearly assigned stations for three point measurements collected in September 2011 in boundary areas: one between Knox and Maude-Roxby (“Sails”) and two between Maude-Roxby and Lakeshore (“Rotary left” and “Rotary right”). A sensitivity analysis to investigate the impacts of station reassignment found there were no changes to the overall flow calculation value with the alternate temporal multipliers applied to these points.

Creating daily multipliers ($mult_n$, Equation 5) using the average flux rate for the entire sampling period (24 months) integrates inter-annual flow variability in the annual average flow estimation. Increases in flux rates in any portion of the long-term record will increase the average flux rate and therefore the daily multipliers. Similarly, decreases in flux rate will decrease the daily multipliers. Due to interruptions in the long-term record it was impossible to quantify inter-annual variation for the entire record (September 2011 – August 2012 versus September 2012 – August 2013) within reasonable error. Inter-annual comparisons for this study used a direct comparison of average flux rates over discrete periods with good sampling at all three long-term stations to avoid noise from missing or averaged long-term station data.

5.2.1.2 Spatial flux integration and scaling

Flux within the nearshore area was well described by numerous manually installed nearshore point measurements. However, logistical constraints affected the collection of perpendicular transects (articulating the change in flux with distance out from the shoreline) in two ways:

1) By limiting the number of perpendicular transects; and
2) By limiting the number of point measurements in each transect.

The use of limited resources to obtain repeat transects in high and low flow conditions was prioritized over the collection of transects in additional locations due to the large temporal flow variability expected within the study area. Variability between individual nearshore point measurements led to averaging over depositionally comparable sections which underwent similar physical, chemical and biological processes during formation (Reading, 2004). These sections should have relatively similar hydraulic conductivity with the collection of representative elementary volume sized samples (University of Saskatchewan, 2015). The change in flux with distance from shore was directly investigated within five (5) of the ten (10) shoreline sections of the study area (Figure 3.3d). The remaining five (5) sections were assigned the spatial scaling multiplier of the geologically/structurally closest directly investigated section based on observable similarities (ie. shoreline profile, shape, surficial sediment type, etc.). A sensitivity analysis was completed to investigate the impacts of the somewhat subjective application of calculated spatial scaling factors (Section 3.3.2) to other study sections. Only a 2% increase (7.8 x 10^3 m^3/yr) to the overall flow calculation was observed when an average spatial scaling factor derived from all ten (10) transects was applied to all sections.

The individual perpendicular transects were limited to three points due to equipment availability constraints. All three points were installed below wave base as this area was not previously investigated by the collection of numerous nearshore point measurements. Moving from the shoreline, the first point, q_2, was installed in the first encountered section of sediment that did not show visible patterns created by wave action. The last point, q_4, maximized the length of the transect by being placed at the maximum depth allowed by the equipment. In all transects except for Collett, this point was at the visible edge of the fan topset and was followed quickly by a precipitous drop to the deeper portion of the lake. The middle measurement, q_3, attempted to split the difference between the first and last points. To relate the transect values to nearshore flux rates, a substitute nearshore point, q_1, was selected for each of the perpendicular transects (Appendix D). Using these nearshore measurements, the area integrated for the perpendicular transects approximated shore to L_{ND}, as visualized or visually extrapolated on the transect flux graphs (Figure 5.2). This generally approximated the visible edge of the deltaic fan in high flow conditions, beyond which there would be an accumulation of low hydraulic conductivity modern lacustrine sediments. Annual flow was presumed to average approximately zero beyond L_{ND}. This assumption is supported by the findings of Boyle (1994) and Rosenberry and Pitlick (2009). Comparisons completed by Boyle (1994) found seepage fluxes in the deeper portions of a lake were one to two orders of magnitude lower than nearshore fluxes. His study lake was geologically similarly to Okanagan Lake, situated in fluvial and glacio-fluvial unconsolidated sediments suspected to be overlying a glacial till aquifer confined by glaciolacustrine silts and clays. The current lakebed in the deeper portions of Okanagan Lake is comprised of up to 60 m of interbedded silts and fine sands (Eyles et al. 1990). Rosenberry and Pitlick (2009) found only 1 mm of silt at the sediment/water interface was needed to restrict seepage.

The distance of L_{ND} from shore varied significantly between high flow and low flow transects at some locations. Mission Creek mouth and Collett transects identified L_{ND} within the spatial extent of the transects in low flow conditions. Measurements past L_{ND} were not included in the transect flow calculation as the intent of this project was to estimate the amount of discharge from the Kelowna aquifers to Okanagan Lake and not to investigate the overall flux within the lake itself.

5.2.1.3 Point measurements collected within the Okanagan Mountain Park section

Large sections of the shoreline within the southern portion of the study area were found to be bedrock (Precambrian Monashee gneiss) covered with an insufficient amount of overlying sediment to install seepage meters within the nearshore area (Figure 5.3). Approximately half (6/14) of the nearshore point measurements collected in this area could be considered "convenience" sampling; targeting locations with higher than average surficial sediments. These locations were typically at the outflow of small streams so the collected flux measurements may not be representative of average discharge conditions within this portion of the study area. This may have impacted the overall flow calculation as the Okanagan Mountain Park section is responsible for roughly 35% of total groundwater discharge to Okanagan Lake. Elimination of the six (6) convenience sampling locations found these measurements had almost no impact on the overall flow estimate with an observed decrease of only 0.3% (3.55×10^5 m^3/yr compared to 3.56×10^5 m^3/yr).

5.2.1.4 Correction factor

The numerous seepage meter correction factors applied in literature range between 1.05 (Rosenberry, 2005) and 1.82 (Murdoch and Kelly, 2003); depending on bag type and tubing diameter. A correction factor of 1.05 was selected for the Kelowna discharge study as the bag type (thin walled, 4L wine bag) and tubing diameter (12.7mm internal diameter) were similar to equipment used by Rosenberry (2005). Correction factors affect all measurements so the selected 1.05 was applied to the overall groundwater flow estimate of 3.56×10^5 m^3/yr to produce a friction loss corrected estimate of 3.74×10^5 m^3/yr.

5.2.2 Results Interpretation

The average groundwater flux rate of 1.4×10^{-8} $m^3/m^2/s$ falls within the range of flux measurements collected within the literature in unconsolidated sediment lacustrine environments and is lower than measurements collected in fractured rock basins or marine environments (Attanayake and Waller, 1988; Shaw and Prepas, 1990a/b; Boyle, 1994; Cable et al., 1997a; Cherkauer and Carlson 1997; Schneider et al., 2005), (Table 5.1). Comparison of total flows between study sites is not appropriate due to the variability of spatial scales, controls on flow, and stratigraphy found between individual sites.

5.2.2.1 Temporal investigations

An intra-annual groundwater flux rate change of multiple orders of magnitude has been observed in other study areas and was not unexpected within the Kelowna study area because of the snow melt driven recharge regime (Ala-aho et al., 2013; Sebestyen and Schneider, 2001; Smerdon et al., 2005). The variation in flux rates between subsequent measurements taken at long-term stations was greater than expected by method related error (Figure 5.4). Even with the elimination of site variability by repeating measurements at the same point in space, observed changes between subsequent measurements were still up to 1 x 10^{-8} $m^3/m^2/s$ over one day. These rapid fluctuations in discharge suggest that groundwater flux within the study area is very sensitive to upgradient controls as was found by Boyle (1994), Cherkauer and Carlson (1997), Sebestysen and Schneider (2001), and Alo-aho et al. (2013). Flux measurements between adjacent or all long-term stations often created similarly shaped time versus discharge graphs though there were differences in magnitude and timing (Figure 5.5). Statistically significant matches of time versus discharge graph shape have been found between stations at other study locations (Cherkauer and Carlson, 1997; Ala-aho et al., 2013).

Seepage meter measurements scaled by Knox, Maude-Roxby and Lakeshore long-term stations contributed 7%, 21%, and 72% of the total study area flow, respectively. Normalizing these values by shoreline length revealed highest flow per unit of shoreline was found in the Maude-Roxby area (8.4 x 10^{-5} m^3/s per metre), followed closely by Lakeshore (7.6 x 10^{-5} m^3/s per metre), and distantly by Knox (1.86 x 10^{-5} m^3/s per metre). Examination of the surficial geology in the area (Figure 2.13) shows Maude-Roxby is centrally located within the glacio-fluvial valley to receive water from the largest contributing area while flows to the Knox long-term station are somewhat obstructed by bedrock outcrops. The Lakeshore long-term station likely receives water from Mission Creek and upland areas which receive more precipitation than valley bottoms (Figure 2.7).

The Kelowna study showed large inter-annual variation, with study year two discharge from the Kelowna aquifers to Okanagan Lake equaling only 70% of year one flows (a 30% decrease). This amount of inter-annual change has been observed at other sites with Boyle (1994), Cable et al. (1997a) and Krillin et al. (2010) finding 20%, 11%, and 41% change between subsequent years, respectively. The selection of small, well observed portions of the long-term station records for inter-annual comparison found the magnitude, and even direction of change, to be variable between the long-term station records (Table 4.7). These results indicate flux measurements at individual stations are strongly influenced by independent upgradient controls as was found by Boyle (1994), Schneider et al. (2005), and Ala-aho et al. (2013).

5.2.2.2 Spatial investigations

Spatial scaling factors calculated from transects perpendicular to the shoreline (Appendix D) revealed that the percentage of flow captured by the nearshore point measurement average is approximately 50% of total flow in all transects with the exception of those located on the Mission Creek fan (Appendix D). Mission Creek fan multipliers are 40% lower, indicating nearshore measurements contribute more volume to the integrated transect. This is likely due to the presence of higher K materials brought down from contributing areas by Mission Creek's significant surface water flows (Munter and Anderson, 1981).

Two of the six transects were also likely influenced by fluvial activity during high flow conditions. Mission Creek mouth and Mill Creek transects were observed to have a reversal from the expected discharge pattern by exhibiting an increase in flux with distance from shore over the first two points ($q_1 < q_2$). Impacts of higher creek stage on regional flow patterns have not been investigated and require further work.

5.2.2.3 Supportive investigations

Gradient method analyses and MODFLOW modelling both highlighted data gaps and conceptual uncertainty surrounding groundwater flow estimates from the Kelowna aquifers to Okanagan Lake. The poor agreement found between site scale gradient calculations (Figure 3.1; Table 4.8) and related long-term station data is likely a function of trial length and logistical issues with the mini-piezometer installation method. The instantaneous mini-piezometer measurements may compare poorly with integrated flux rates collected by seepage meters deployed for a minimum of twenty-four (24) hours due to the natural responsiveness of groundwater flux rates to upgradient controls. Wave artifact was also observed in mini-piezometers in some instances indicating the installation method created a hydraulic connection between surface water and depths within the sediment in at least some cases.

Difficulties relating the magnitude of large scale horizontal flux rate estimates (Figure 3.2; Table 4.9) to long-term station flux rates are likely primarily due to the use of estimated horizontal hydraulic conductivity values. Results suggest the estimates of average regional hydraulic conductivity are too high or discharge to Okanagan Lake is limited by a poorly understood low K sediment heterogeneity near the shoreline. The variable elevation of Okanagan Lake also likely causes slight changes in the saturated thickness (b) of the unconfined aquifer, and therefore changes to transmissivity (T = Kb). However, if the aquifer is not homogenous, saturating additional aquifer material may add higher K or lower K material to the saturated aquifer thickness, and therefore potentially change the average hydraulic conductivity of the near shore discharge zone during the year. Measurement locations one and two (Figure 3.2) were immediately upgradient of the Maude-Roxby long –term station but the use of a constant horizontal hydraulic conductivity estimate created a calculated discharge that was a poor match with the observed flux rate.

The wide range of variability in the percentage of flow captured within the nearshore area (26 – 100%) predicted by the sensitivity analysis of the 2-D cross sectional MODFLOW model (Table 4.10), indicates there is a need for further work. This could include improving the estimates of hydraulic conductivity within the confining layer, the confined layer, and the layer of modern lacustrine sediments along the lakebed below wave base. Holding hydraulic conductivity values in the model constant in the unconfined aquifer (10^{-4} m/s) and the confined aquifer (10^{-2} m/s) while adjusting K in the confining layer from 10^{-5} m/s to 10^{-9} m/s resulted in a 54% increase in the percentage of flow captured within the nearshore area. A similar comparison adjusting the K of the confined aquifer from 10^{-2} m/s to 10^{-5} m/s (unconfined = 10^{-4} m/s; confining layer = 10^{-5}

m/s) resulted in a 26% and 100% capture of total flow within the nearshore zone, respectively. The spatial distribution and layer depth of the low hydraulic conductivity sediments along the lakebed also need to be further investigated as they play a crucial role in appropriately describing flow within this system (Table 4.10). Use of accurate hydraulic conductivity data and field data in a more comprehensive 3-D groundwater model would provide an opportunity to better understand the hydrogeological environment including: flux rates across the sediment/water interface, water movement between hydraulically connected aquifers, and responsiveness changes to water budget parameters such as recharge and anthropogenic extractions.

5.2.3 Regional context

5.2.3.1 Water-balance

A full regional water-balance is out of the scope of this project but precipitation volumes, potential evapotranspiration rates, Mission Creek discharge, and confined aquifer potentiometric head were examined as potential influences on groundwater discharge within the study area. Study year comparisons were completed for each of the parameters to suggest possible causes of the observed inter-annual variation in groundwater discharge.

Examination of precipitation volumes and evapotranspiration (ET) rates would ideally include data from higher elevation areas within the watershed as these areas contribute significantly more to groundwater recharge and surface water runoff (Figure 2.7). Unfortunately, there were no higher elevation climate stations operating in this watershed during the study period (Environment Canada, 2015). Valley potential evapotranspiration rates in Study Year 1 (September 1, 2011 and August 31, 2012) were 95% of Study Year 2 (September 1, 2012 and August 30, 2013) values (Farmwest, 2015; Appendix E). Actual evapotranspiration (AET) rates over land are not widely available within the Okanagan (Summit Environmental Consultants Ltd., 2009). Therefore, the relationship between valley bottom AET rates and higher elevation AET rates, including the subsequent impacts on groundwater recharge, are not clearly understood. Valley bottom precipitation in Study Year 1 and Study Year 2 was 300 mm and 331 mm, respectively. Changes in upgradient valley precipitation did not correspond well with the magnitude of groundwater flux observed within the study area (Figure 5.5) though precipitation events matched well with the stage level in Mission Creek (Figure 5.6). Melting of winter snow smoothed the rising limb of the hydrograph while the receding limb dropped quickly without direct rain inputs. Assuming comparable inter-annual changes to precipitation between the study years occurred in higher elevation areas, an increase in Mission Creek total annual discharge volume was expected, but not observed, in year two due to the ten percent increase in precipitation. Instead, Mission Creek discharged 1.5 x 10^7 m^3 less water, equivalent to a 6% decrease from year one values or a 14% departure from values predicted by precipitation data. Mission Creek stage also poorly predicted the flux rate found at the Lakeshore long-term station indicating Mission Creek flows are not likely the primary driver of groundwater flux along the alluvial fan at some distance from the creek mouth (Figure 5.7).

Potentiometric head in MoE confined Aquifer 464 (the Rutland aquifer) is monitored by Provincial Observation Well 236. During Study Year 1 and Study Year 2, the annual averages were 373.700 masl and 373.655 masl, respectively (Figure 5.8). This 0.045 m decrease fits within the trend observed in the 34 year long term record which shows a drop of approximately 5.5 m in potentiometric head between 1979 and 2013 (Figure 5.9). Annual periods of irrigation driven high water demand are also visible as low points on the graph. A comparison of the high demand periods revealed the potentiometric surface within Aquifer 464 was 0.34 m lower in Study Year 2 (373.34 masl) than in Year 1 (373.68 masl). This 0.34 m decrease was not likely reflective of the potentiometric surface level across the entire 69 km^2 aquifer but would certainly have an impact on downgradient portions of the aquifer. It is likely indicative of higher pumping demand during the summer period of Study Year 2. The closest long-term station was observed to have an 84% decrease in flow during this period.

5.2.3.2 Potential influences on groundwater discharge

There are a host of upgradient controls that could possibly influence the rate of groundwater discharge from the Kelowna aquifers to Okanagan Lake (Section 2.1.1.3). The 30% decrease in flow between Study Year 1 and Study Year 2 would be most easily explained by a decrease in recharge (↓ precipitation or ↑ evapotranspiration) or an increase to anthropogenic groundwater extraction in the area. As valley bottom precipitation volumes and evapotranspiration rates predict a slight increase in recharge between Study Year 1 and Study Year 2 (10% ↑ precipitation; 5% ↑ evapotranspiration), pumping was investigated as a potential contributor to the observed flow change at the Kelowna shoreline. The summer of 2012 was closely compared to the summer of 2013 because of the notable difference in groundwater discharge rates and the decrease in confined aquifer potentiometric surface levels between the two time periods.

In 2003, the combined pumping from Aquifer 463 and 464 by major water purveyors was 3.3×10^6 m^3 (van der Gulik et al., 2010). These purveyors represented three out of the five major domestic supply sources within the Kelowna area. Additional water removed by private wells was not metered in 2003 but was estimated at 2.3×10^7 m^3 across the entire Okanagan Valley (van der Gulik et al., 2010). As three of the five major domestic water purveyors within the Kelowna area utilize groundwater for at least part of their production, it is likely that the 22% population increase observed between 2001 and 2011 has led to an increase in overall groundwater use within the Kelowna area (City of Kelowna, 2014). This population growth is not expected to stop in the near future with City of Kelowna's Official Community Plan projecting a 1.51% increase in population per year until 2030 (City of Kelowna, 2013).

Groundwater extraction volumes were provided by one water purveyor for comparison with groundwater fluxes observed during the study period (Table 5.2). The reported 70% increase in groundwater consumption between 2003 and 2012 is likely representative of domestic groundwater extraction trends within the Kelowna area. Application of this increase to the usage of all water purveyors estimated in 2003 leads to an estimate of 2012 extraction rates that may be as high as 5.6×10^6 m^3.

Within the study period, this purveyor reported an 8% increase in extraction between May – August 2012 (1.47×10^6 m^3) and May – August 2013 (1.59×10^6 m^3). Staff were unable to explain the 1.2×10^5 m^3 increase in usage (Per. Comm., 2013). Environment Canada's Kelowna weather station recorded no notable temperature differences and a 13% increase in rainfall between the two time periods (Environment Canada, 2014a).

Current annual pumping rates in the Kelowna area are estimated at an order of magnitude larger than the amount of water discharging from the Kelowna aquifers to Okanagan Lake (Figure 5.10). Small changes in these pumping rates may therefore lead to large percentage changes in water flowing to Okanagan Lake. Changes in the volume of pumping upgradient of the shoreline has likely contributed to the observed 1.2 x 10^5 m^3 decrease in groundwater discharge between Study Year 1 (4.13 x 10^5 m^3) and Study Year 2 (2.90 x 10^5 m^3). Additionally, the known pumping increase over time may account for a large portion of the discrepancy between the rate of groundwater discharge to Okanagan Lake observed during this 2011- 2013 study and the earlier water-balance estimation created by Summit Environmental Consultants Ltd. (2009) to support the OBWB Supply and Demand Project Phase 2 modelling.

5.3 Factors Affecting Future Conditions

This 2011-2013 study has found that the flow of groundwater from the Kelowna aquifers to Okanagan Lake represents a small proportion of the overall water-balance within the Kelowna area, and is small in comparison to known groundwater pumping. The 5.5 m decrease in Aquifer 464 over the last 34 years indicates the extractions from this aquifer are likely already exceeding its natural rate of recharge. Future increases in groundwater extraction rates are expected due to projected population increases in the area. Increased groundwater extraction could impact surface water availability through two mechanisms: interrupting groundwater flow naturally moving downgradient towards surface water bodies, causing a reduction in groundwater discharge observed along the shoreline or creek bed; and, direct recharge of groundwater by surface water, induced by groundwater extractions in hydraulically connected wells.

Known linkages between groundwater and surface water also impact our view of domestic groundwater availability. Groundwater resources material released by the U.S. Geological Survey demonstrates the hydraulic connection between large production wells and adjacent surface water bodies and indicates large percentages of pumped water likely actually originate at surface (Barlow and Leake, 2012). This research implies “fully recorded” creeks in the Kelowna area may be providing part of the water pumped by adjacent wells. These creeks provide water to current surface water license holders, maintain minimum levels required for ecosystem health, and recharge groundwater systems during periods of high surface water flows. Over extraction from groundwater storage could change groundwater flow directions, create induced recharge and potentially decrease flows in surface water during low surface water flow periods. Fluctuations in stage level in Mission Creek hydrometric measurements adjacent to high production wells are likely partially influenced by a hydraulic connection between groundwater and surface water (Figure 5.11). The complexity of the sub-daily to annual scale oscillations observed in Mission Creek stage measurements over the study period suggest further study is required to separate the impacts of groundwater extraction from other anthropogenic and natural influences on stage level. An undergraduate research project which used geochemical mixing models implemented in PHREEQC to investigate potential groundwater flow directions provides further evidence of the connection between groundwater and surface water (Harrington, 2013). Harrington (2013) concluded drawdown in the confined aquifer was leading to leakage from the unconfined aquifer and was inducing recharge from Mission Creek in some locations. Future population driven increases to groundwater extraction within the regional watershed/groundwatershed will likely lead to greater induced recharge from surface water. Increasing groundwater extraction upgradient of the shoreline will also likely continue to decrease the rate of discharge from the Kelowna aquifers to Okanagan Lake. Additional research is required to establish the sustainable rate of groundwater extraction in the Kelowna area.

Climate change is also expected to influence groundwater systems within the study area. Application of Global Climate Models (GCMs) to the Kelowna area predict a decrease in snow, an increase in winter rains, and an increase in “flashier” storm events (Polar Geoscience, 2012). These conditions, especially a reduction in groundwater recharge contributions from snow melt, may affect the groundwater availability within the Kelowna area.

Groundwater extraction within British Columbia is not currently regulated with the exception of major projects, which are currently defined as ≥75 L/s (B.C. Environmental Assessment Office, 2014). The current system does not require groundwater users to consider needs of other hydraulically connected water users or the environment, or address the concept of “sustainable” extraction. Large changes are expected within the groundwater regulatory environment in the near future due to the passing of the *Water Sustainability Act* (WSA) in 2014 which includes various provisions on groundwater use. Expected to come into force in January 2016, the WSA will provide the provincial government with ability to regulate groundwater extraction, include the consideration of water in land use decisions, regulate water use during times of water scarcity, and protect natural environments including maintaining environmental flow needs in creeks and rivers (Province of British Columbia, 2014). While the supportive regulations have not been released, the application of area management plans may be required to regulate groundwater in locations of current or potential water conflict, such as the Okanagan basin.

Estimates of groundwater discharge from the Kelowna aquifers to Okanagan Lake provide important information for an examination of water budgets within the Kelowna area. These values may be used in models to investigate the potential impacts of groundwater extraction rates increases, climate change, or water management strategies.

CHAPTER 5: FIGURES AND TABLES

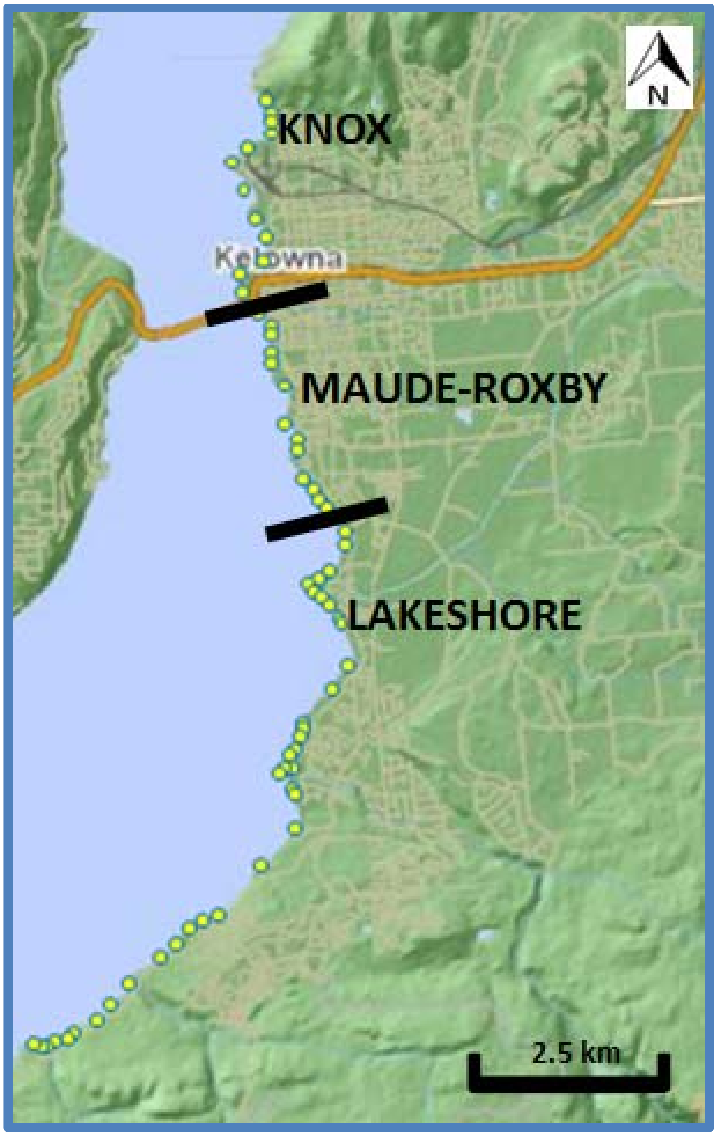


Figure 5.1 Point measurement assignments to long-term stations for the calculation of temporal scaling factors (DataBC, 2013)

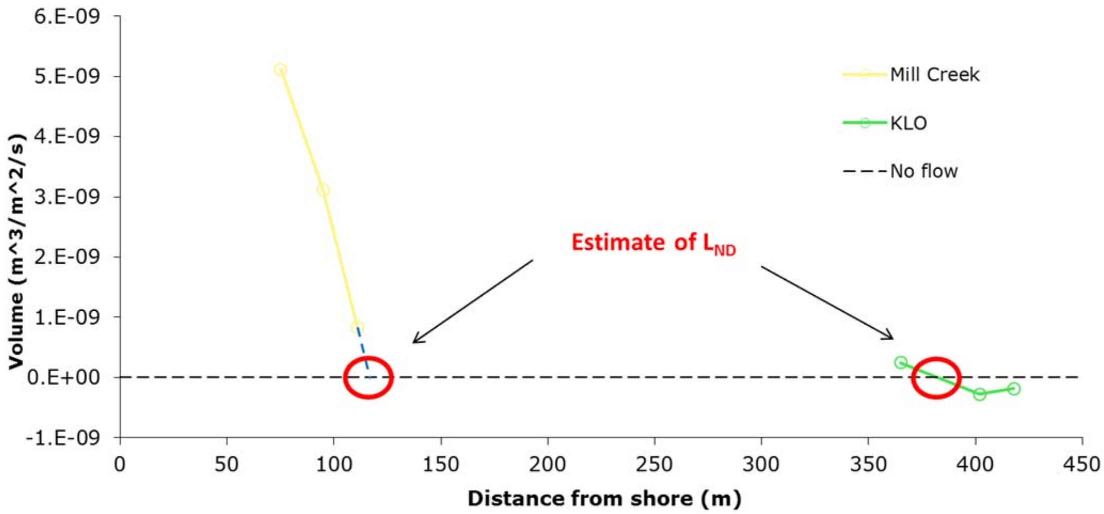


Figure 5.2 Estimation of an L_{ND} value using extrapolation (Mill Creek) and direct interpretation (KLO) transect flux values

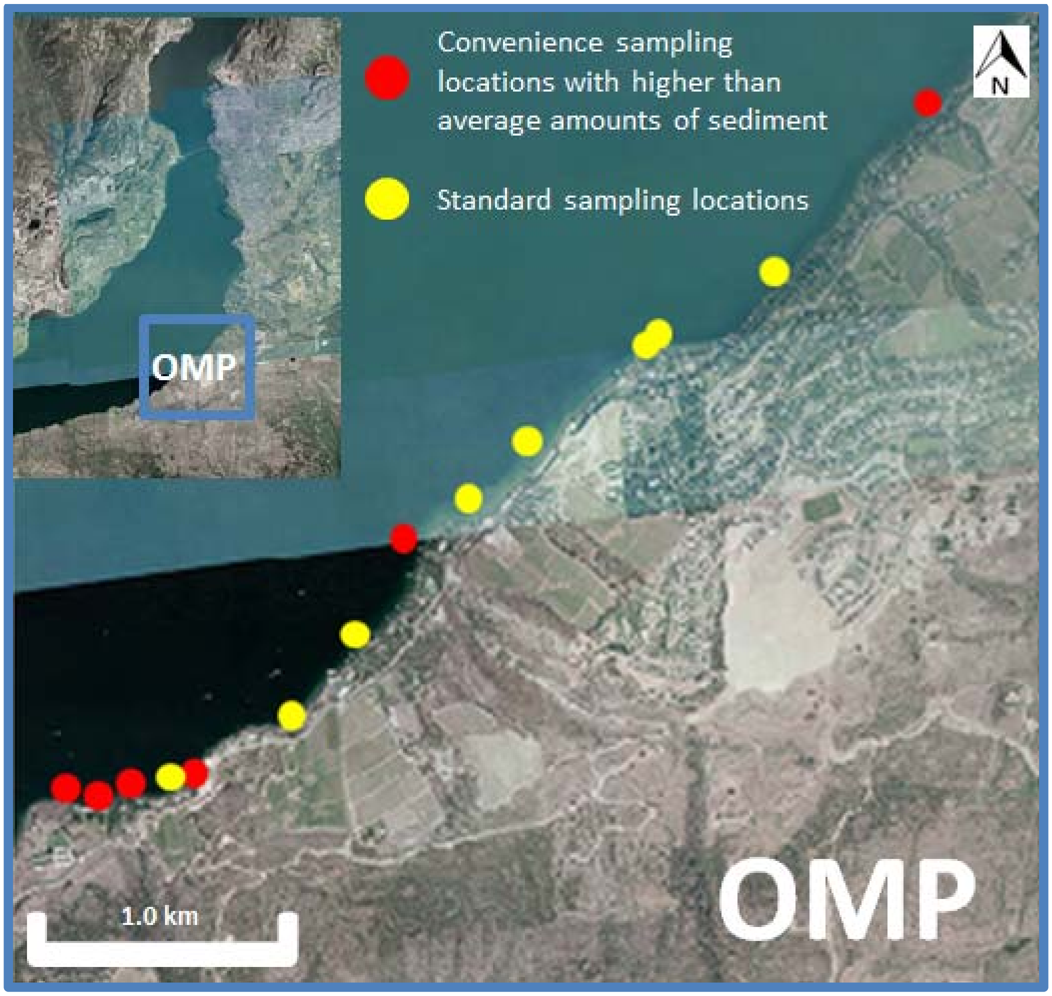


Figure 5.3 Study area along Lakeshore Drive South identified within the groundwater discharge study as the Okanagan Mountain Park (OMP) discharge area due to its close proximity to the BC Park (DataBC, 2013)

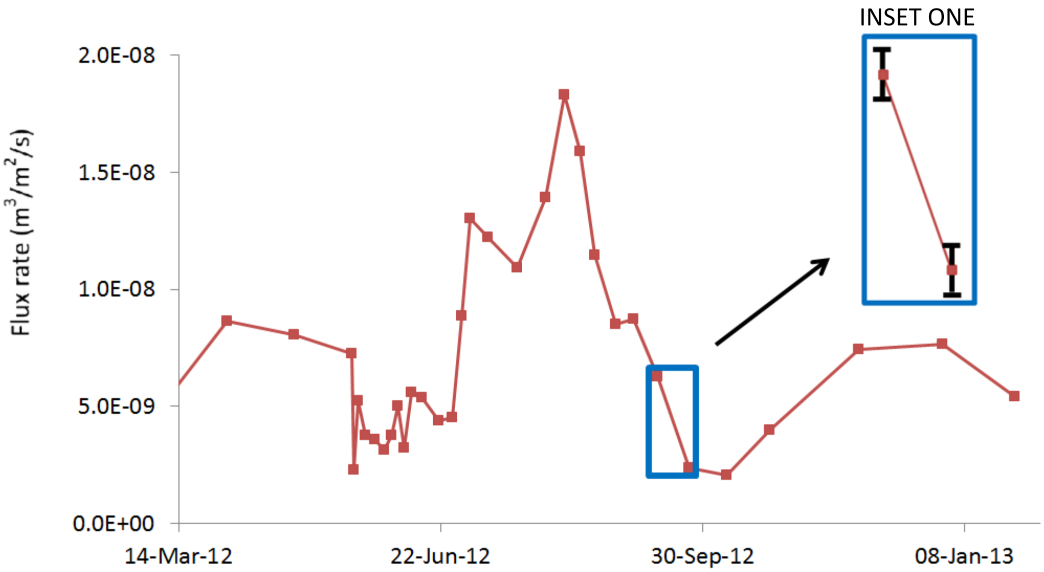


Figure 5.4 Maude-Roxby long-term station flux rates for a portion of the study period. Error bars on "Inset One" values represent method related error.

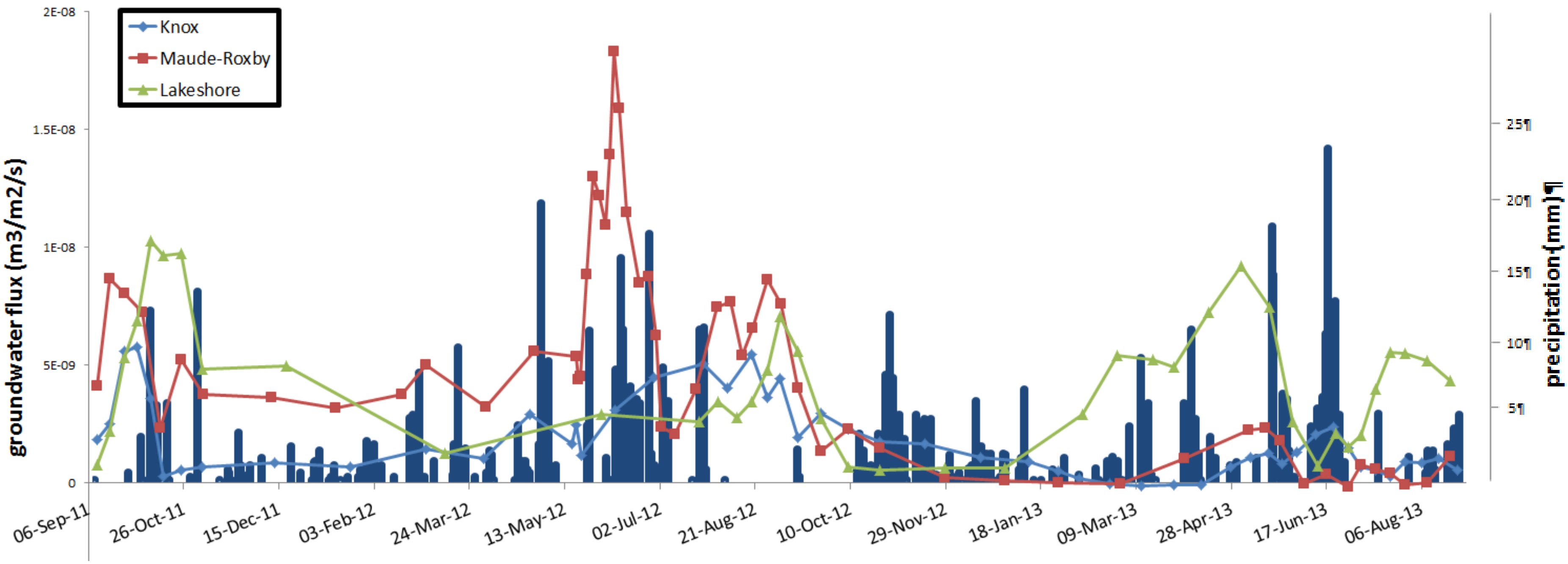


Figure 5.5 Long-term station flux rates compared to valley bottom precipitation events collected at Environment Canada weather station (Climate ID 1123939)

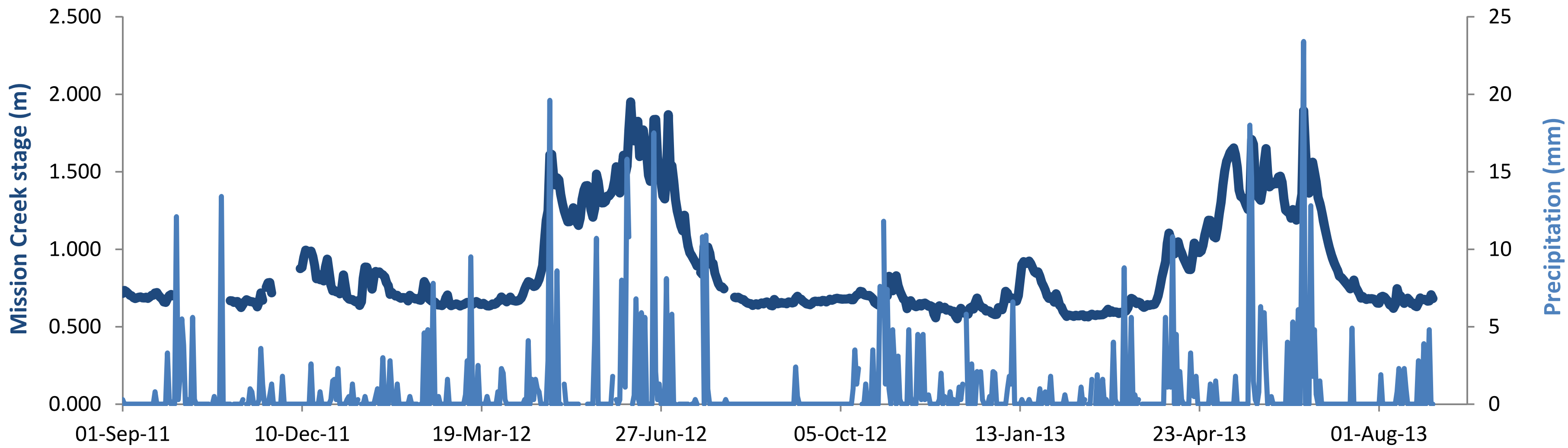


Figure 5.6 Valley bottom precipitation events collected at Environment Canada weather station, Climate ID 1123939 (in light blue) compared to Mission Creek stage measured at Environment Canada hydrometric station 08NM116 (in dark blue)

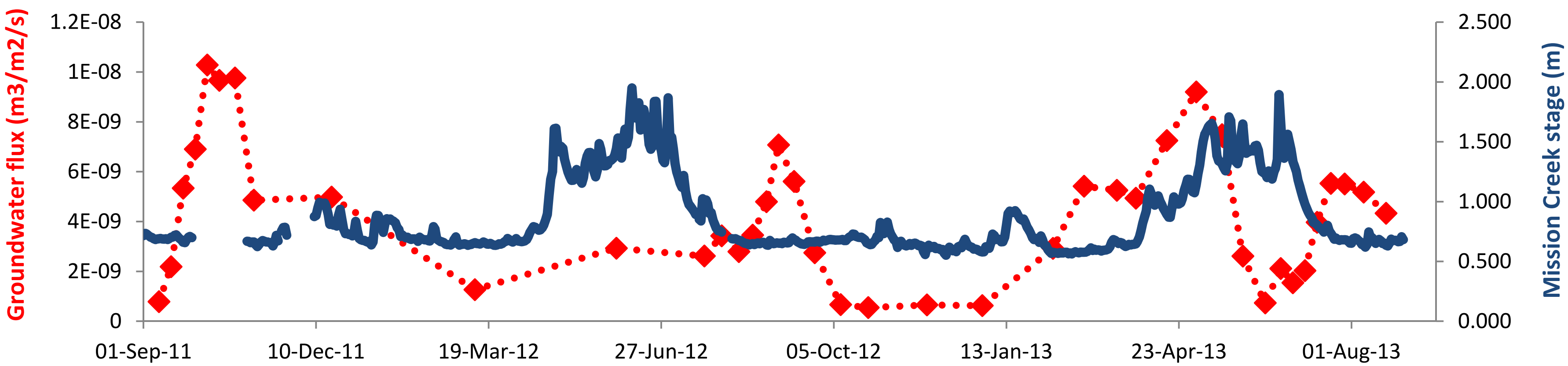


Figure 5.7 Lakeshore long-term station flux rates (in red) compared to Mission Creek stage measured at Environment Canada hydrometric station 08NM116 (in blue)

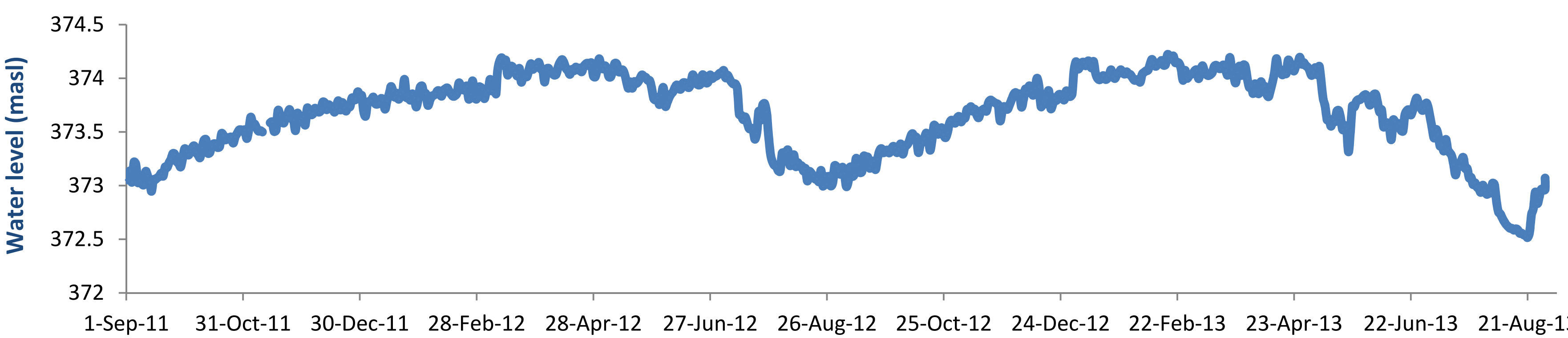


Figure 5.8 Potentiometric surface level in B.C. Ministry of Environment Aquifer 464 between September 2011 and August 2013 measured in Observation Well 236

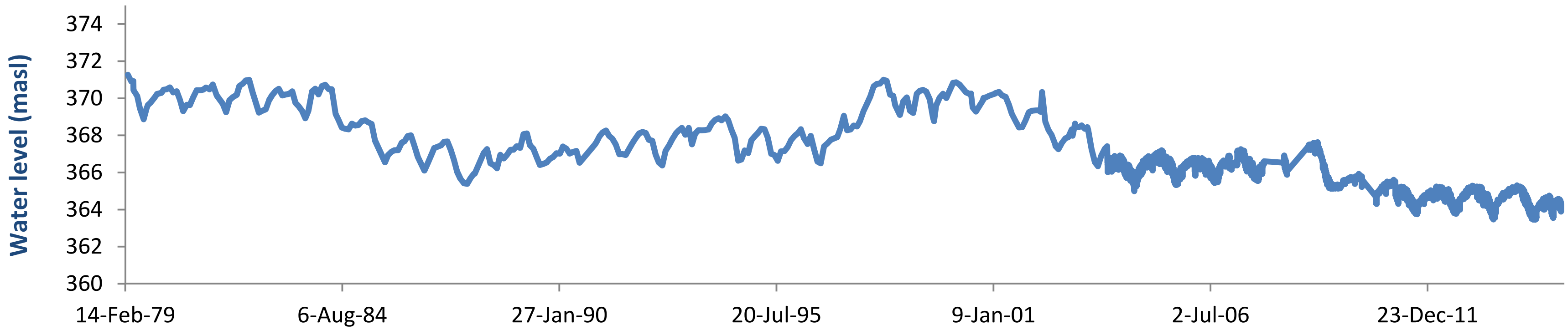


Figure 5.9 Potentiometric surface level in B.C. Ministry of Environment Aquifer 464 between 1979 and 2013

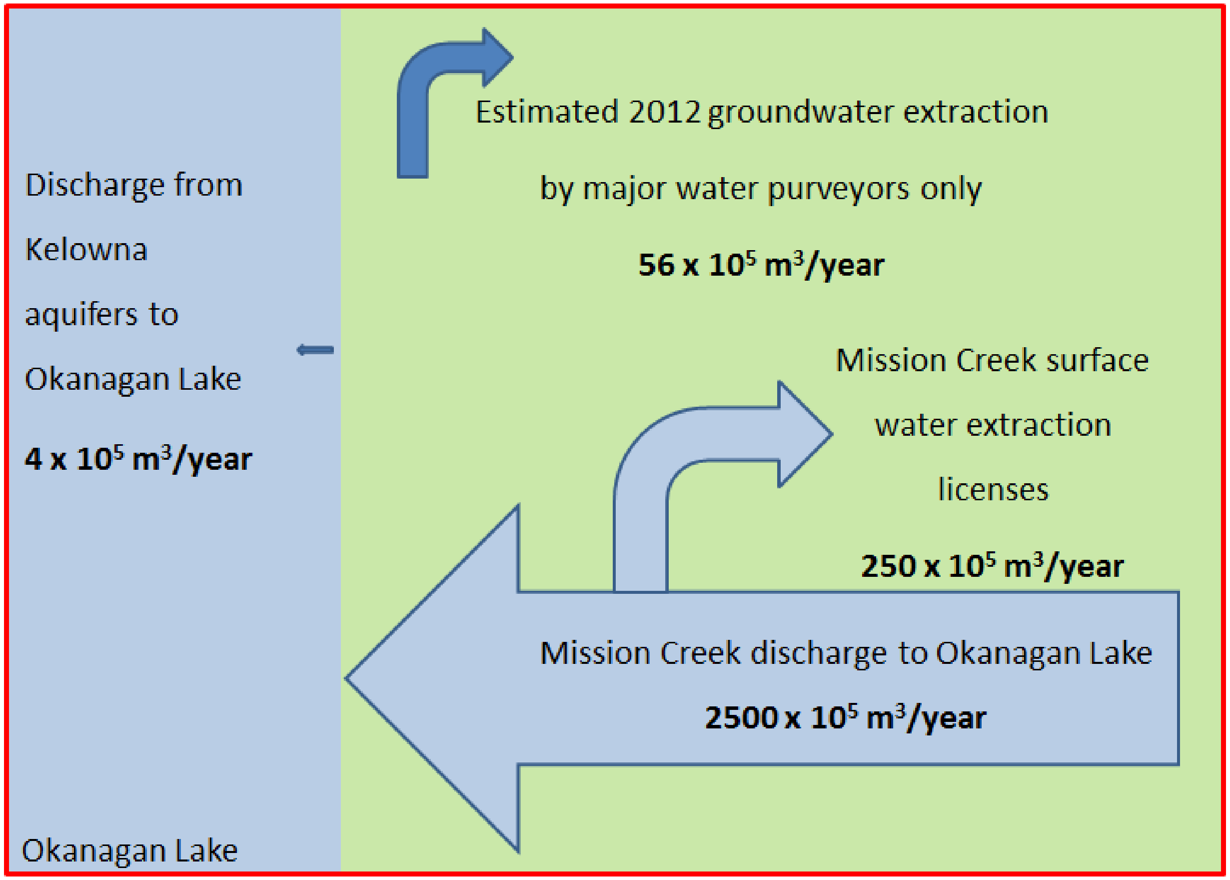


Figure 5.10 Regional significance of the Kelowna groundwater discharge study results

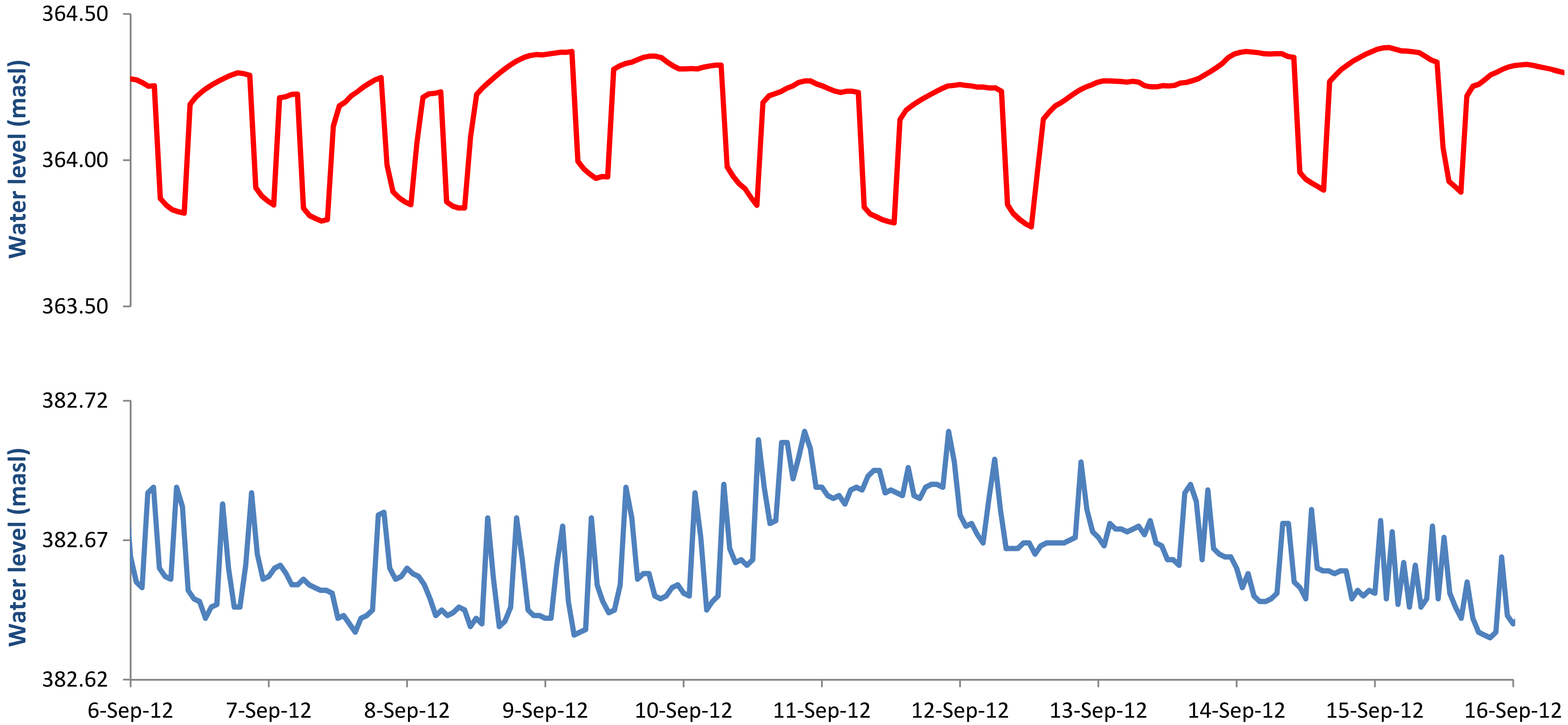


Figure 5.11 Mission Creek stage (in blue; measured at Environment Canada hydrometric station 08NM116) adjacent to a large groundwater extraction point compared to potentiometric surface water levels in B.C. Ministry of Environment Aquifer 464 (in red; measured in Observation Well 236)

Table 5.1 Selected studies reporting rates of groundwater flux to a lake

Reference	Primary Methods	Reported Flux Rates ($m^3/m^2/s$)	Study Area Description
Ala-aho et al., 2013	Chemical tracers, physical methods	$-9.5 – 5.7 \times 10^{-7}$	Esker system
Attanayake and Waller, 1988	Chemical tracers, physical methods	$1.5 – 7.8 \times 10^{-7}$	Fractured rock basin
Boyle, 1994	Physical methods	nearshore = $1.2 \times 10^{-9} – 1.36 \times 10^{-7}$ deep = $-8.1 \times 10^{-11} – 2.54 \times 10^{-10}$	Confined and unconfined unconsolidated aquifers
Isiorho et al., 1996	Electrical resistivity, gradient calculations	$2.3 \times 10^{-10} – 1.4 \times 10^{-5}$	Layered unconsolidated aquifers 4,000,000 km^2 drainage basin
Kidmose et al., 2011	Isotopes, physical methods, modelling	Up to 9.1×10^{-7}	Confined and unconfined aquifers Numerous methods used for comparison
Rautio and Korkka-Niemi, 2011	Thermal, physical, chemical methods	$4.7 \times 10^{-7} – 4.8 \times 10^{-5}$	Esker system

Table 5.1 Selected studies reporting rates of groundwater flux to a lake (continued)

Reference	Primary Methods	Reported Flux Rates ($m^3/m^2/s$)	Comments
Schneider et al., 2005	Physical methods	$1.1 \times 10^{-9} – 2.2 \times 10^{-7}$	Sedimentary bedrock covered by glacial till in some areas
Sebestyen and Schneider, 2001	Physical methods	$-1.7 \times 10^{-7} – 1.7 \times 10^{-7}$	Glacial till over bedrock
Shaw and Prepas, 1990a	Modelling, physical methods	$1.6 \times 10^{-8} – 5.1 \times 10^{-8}$	Glacial till interbedded with alluvial sand and gravel lenses
Shaw and Prepas, 1990b	Physical methods	$3 \times 10^{-10} – 2 \times 10^{-7}$	Glacial till over sedimentary bedrock
Taniguchi and Fukuo, 1996	Physical methods	Approx. $5 \times 10^{-8} – 2.2 \times 10^{-7}$	Unconsolidated sand and gravel
Woessner and Sullivan, 1984	Physical methods	Approx. $9 \times 10^{-9} – 1.4 \times 10^{-6}$	Unconsolidated materials over sedimentary bedrock

Table 5.2 Groundwater extraction volumes from one Kelowna area water purveyor

Year	Month	Daily Averages (x 1000 US Gallons)	Monthly (US Gallons)	Monthly (m^3)
2011	Sept	2517	7.55E+07	2.86E+05
	Oct	986	3.06E+07	1.16E+05
	Nov	1249	3.75E+07	1.42E+05
	Dec	1196	3.71E+07	1.40E+05
2012	Jan	1326	4.11E+07	1.56E+05
	Feb	1354	3.79E+07	1.43E+05
	Mar	1370	4.25E+07	1.61E+05
	Apr	1593	4.78E+07	1.81E+05
	May	2542	7.88E+07	2.98E+05
	Jun	2313	6.94E+07	2.63E+05
	Jul	3556	1.10E+08	4.17E+05
	Aug	4207	1.30E+08	4.94E+05
Study Year 1 Total			7.39E+08	2.80E+06
	Sept	3121	9.36E+07	3.54E+05
	Oct	1852	5.74E+07	2.17E+05
	Nov	1361	4.08E+07	1.55E+05
	Dec	1341	4.16E+07	1.57E+05
2013	Jan	1530	4.74E+07	1.80E+05
	Feb	1695	4.75E+07	1.80E+05
	Mar	1493	4.63E+07	1.75E+05
	Apr	1594	4.78E+07	1.81E+05
	May	2669	8.28E+07	3.13E+05
	Jun	2703	8.11E+07	3.07E+05
	Jul	4465	1.38E+08	5.24E+05
	Aug	3816	1.18E+08	4.48E+05
Study Year 2 Total			8.43E+08	3.19E+06
Study Year 2 Total / Study Year 1 Total (%)				114%

CHAPTER 6: CONCLUSIONS

6.1 Major Findings

Projected population increases and potential climate change effects have led to concerns about future water availability in the Kelowna area. The estimate of annual groundwater discharge from the Kelowna aquifers to Okanagan Lake, based on field measurements collected between September 2011 and August 2013, is approximately one percent of the groundwater discharge estimate from the Phase 2 Okanagan Water Supply and Demand Project groundwater study (Golder Associates and Summit Environmental Consultants Ltd., 2009). Measurements repeated weekly at the same locations showed an annual change in flux in up to two to three orders of magnitude (10^{-11} to $10^{-9}/10^{-8}$ $m^3/m^2/s$); with peak groundwater flows observed during surface water high flow periods. Simplified cross sectional modelling work indicates that the measured flows represent between 26 to 100% of the total discharge from the Kelowna aquifers to Okanagan Lake. The annual groundwater discharge of 3.7×10^5 m^3 is likely less than 7% of the volume being extracted from upgradient aquifers by pumping in 2012. Within the two year study period, increased pumping rates from year one to year two may have accounted for part of an 84% decrease in flows observed at one long-term station as well as contributed to a 14% decrease from expected flows in Mission Creek and a 0.34 m decrease in the potentiometric surface within the confined Rutland aquifer.

Long-term potentiometric monitoring indicates groundwater pumping rates have likely exceeded recharge in some Kelowna aquifers for the past 34 years. Other studies using modelling and geochemistry have suggested groundwater pumping is inducing recharge from adjacent fluvial water bodies in some areas. Future climate change driven decreases to groundwater recharge may further reduce groundwater availability required to support minimum environmental flow needs in surface water during high irrigation demand periods in the late summer months.

6.2 Recommendations:

Challenges encountered during the physical measurement and quantification of groundwater fluxes to Okanagan Lake led to the following methodological recommendations to future researchers investigating similar problems:

1) Make additional efforts to describe the underlying geology influencing discharge within the study area;
2) Use a continuous flux monitoring seepage meter for long term station data such as the device developed by Fritz et al. (2009) or Taniguchi and Fukuo (1996) to create a more complete record of temporal variations;
3) The collection of numerous point measurements is very time and labour intensive. This effort may be reduced by using the average of a “high flow” and a “low flow” nearshore measurement to roughly estimate 50% of annual flow contained in a one (1) metre strip stretching from the shoreline to L_{ND}[3]; and
4) There is significant natural variability between individual point measurements because the sampling size is smaller than the representative elementary volume. Clusters of three point measurements should replace individual measurements where possible.

The overall findings of this study led to the following recommendations for future work on water resources in the Kelowna area:

1) Further work to characterize the hydrogeological environment within the Kelowna area, including efforts to refine hydraulic conductivity values for major geologic units and clarify dominant flow paths from the confined aquifer to Okanagan Lake;
2) Investigation into gains and losses along the entire length of major fluvial systems including a description of the impacts of adjacent pumping;
3) Further quantification of water budget parameters including groundwater extractions by all users within the Kelowna aquifers;

[3] This concept does not hold true near large fluvial outflows.

4) Completion of a coupled groundwater/surface water interactions model for the Kelowna area utilizing information described in the above recommendations; and
5) Investigation into sustainable extraction rates within the Kelowna area.

Water management within the Kelowna area is complicated by a historical lack of groundwater regulation, an anticipated increasing pressure on the limited resource by water users with competing interests, and a general lack of hydrogeological information. Currently available evidence indicates it is likely that groundwater use in the Kelowna area already exceeds the natural recharge rate.

The low discharge from the Kelowna aquifers suggests that all water users should advocate for water managers and urban planners to establish cautious groundwater extraction rates in the Kelowna area to ensure the groundwater system can continue to support both human and environmental water needs. In the future, the establishment of an area based management plan, with input from all stakeholders, may be the key to protecting the interests of all water users.

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APPENDICES

Appendix A: Seepage Meter Construction and Use

This appendix provide details on the construction of the Lee-type seepage meters used on the Kelowna groundwater discharge project, installation method adjustments used to accommodate site-specific sediments (Table A-1), and the results from the collection bag cover comparison trails (Table A-2).

A modern Lee-type seepage meter contains three main components: the main drum, a vent line to allow for the removal of any accumulated air or gas during the settling period, and a bag line to connect the collection bag to the drum while preventing water losses or additions during installation and removal. A cover is also required to protect the seepage meter collection bag from potential human or environmental interference.

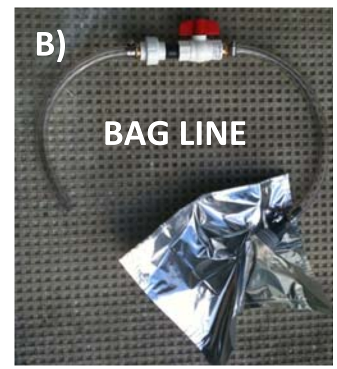


Figure A-1 A Lee-type seepage meter including the: A) vent line; and B) bag line

A complete vent line is comprised of a: ¾” internally threaded bulkhead attached to the drum, ¾” threaded male adapter with barb, screw clamp, $^{5}/_{8}$” ID tubing, screw clamp, ¾” threaded male adapter with barb, ¾” cap, flotation attached with zip tie. From the drum to the collection bag, the bag line is comprised of a: ¾” internally threaded bulkhead, ¾” threaded male adapter with barb, screw clamp, $^{5}/_{8}$” ID tubing, ¾” union fitting, ¾” threaded adapter, ¾” ball valve, ¾” threaded male adapter with barb, screw clamp, $^{5}/_{8}$” ID tubing, screw clamp, ½” threaded male adapter with barb, friction fitting with ½” internal threading, and 4 L, double walled wine bag.

Installation of the seepage meters into different sediment types was found to require variation in the standard installation methodology (Table A-1).

Table A-1: Sediment-dependent adjustments to seepage meter installation techniques

Dominant sediment type	Adjustments	Comments
Fines (silt/clay)	The depth of seepage meter insertion into the sediment was measured prior to the start of the trial. The depth was re-measured at the end of the trial to ensure the seepage meter had not further settled into the sediment.	Only required in one location. The seepage meter was not observed to have settled after the initial 24 hour settling period. If further settling had been observed, the seepage meter would have been left in place and the trail restarted.
Sands	Standard installation.	
Very coarse (cobbles)	The uppermost cobbles were removed to allow for a seal along the sediment/water interface. Perimeter check was completed to ensure the seepage meter was completely inserted into the sediment.	Several trials were lost or provided unrealistic results due to seepage meter rocking with wave action because of the creation of sediment-caused “pivot points”. After the initial trials, seepage meters were buried deeper into the sediment and weighted down with additional cobbles to decrease movement.

A seepage meter cover comparison trial was completed to describe the impacts of a cover method change which was implemented during the 2012 summer field season (Section 3.2.4). The raw data from this comparison trial is presented in Table A-2.

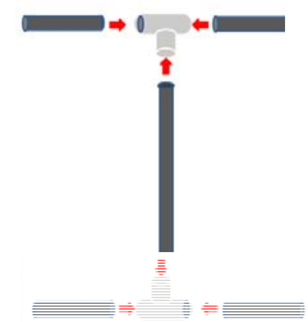
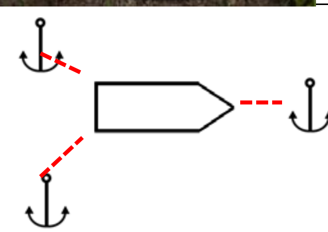
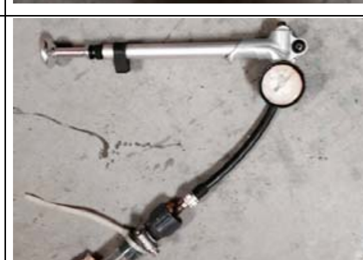
Table A-2: Cover method comparison trial data

Location	Install date	Time	Volume (L)		Flux ($m^3/m^2/s$)	
		(seconds)	Method 1	Method 2	Method 1	Method 2
Knox	2013-07-28	254940	0.120	0.234	1.77E-09	3.45E-09
			0.539	0.238	7.95E-09	3.51E-09
West Ave	2013-08-03	332520	2.377	0.145	2.69E-08	1.64E-09
			1.630	0.180	1.84E-08	2.03E-09
Maude-Roxby	2013-08-10	344160	0.151	0.054	1.65E-09	5.90E-10
			0.209	0.075	2.28E-09	8.19E-10
KLO	2013-08-20	437100	-0.074	0	-6.36E-10	0.00E+00
			0.250	0.062	2.15E-09	5.33E-10
Mill Creek N	2013-08-30	518160	0.852	0.272	6.18E-09	1.97E-09
			0.456	0.155	3.31E-09	1.12E-09
Mill Creek S	2013-08-30	518160	0.827	-	6.00E-09	-
			0.134	0.154	9.72E-10	1.12E-09
Gyro	2013-09-11	538980	0.236	0.256	1.65E-09	1.79E-09

Appendix B: Boat Deployment of Seepage Meters

Use of seepage meters below wave base, in depths of water between 1.1 m and 3.5 m, required adjustments to the standard seepage meter construction and installation techniques (Table B-1).

Table B-1: Construction and installation adjustments to seepage meters to facilitate use below wave base

Issue	Resolution	Figures
Maintaining contact with the seepage meter while at depth	Construct a “T” bar allowing for continuous contact with the seepage meter during deployment and removal	
Applying even, twisting motion (clockwise and counter-clockwise) and downward pressure to ensure adequate positioning of the seepage meter below the water/sediment interface	Have metal loops welded to the upper edge of the seepage meter to provide contact points for the “T” bar	
Prevent the boat from drifting during seepage meter installation (leverage)	Secure the boat against movement by utilizing three boat anchors installed in three opposing directions	
Closing and opening the ball valve from the water surface	New shut off valve designed to operate using a packer (balloon)	
Prevent the deflation of the packer in colder temperature water	Replace air within the packer with lake water	

These modifications allowed the deployment and operation of seepage meters from the surface of the water; preventing the need for researcher submersion into cold water or the use of S.C.U.B.A. equipment and allowing for the use of a standardized installation technique across the range of depths (below).

B-1 General Procedure for Seepage Meter Use in Deeper Water

The following procedure was used for deeper water installations (1.1 m – 3.5 m):

- The boat was secured from movement using anchors deployed in three opposing directions;
- The collection bag was preloaded with 1 L of lake water;
- The seepage meter shut off valve (packer) was inflated using lake water and the vent line was opened;
- The seepage meter was lowered and installed into the sediment using a “T” shaped extendable bar;
- A minimum of 24 hours later, the vent line was capped and the packer was deflated to start the trial;
- Upon completion of the trial, the packer was re-inflated to trap water in the collection bag;
- The seepage meter was removed using the “T-bar”; and
- The contents of the collection bag were measured using a graduated cylinder and the volume recorded for use in flux calculations.

B-2 Seepage Meter Adjustment Testing

The collection of an accurate groundwater flux volume is critical to the calculation of a representative trial flux rate. The key challenge in the adaption of the Lee-type seepage meter for deeper water deployment was the prevention of movement of water between the seepage meter and the collection bag during seepage meter deployment, stabilization, and removal. While this is easily achieved in near-shore measurements using a hand-tightened ball valve, ensuring a remotely activated version of the hand-tightened ball valve provided the same water-tight closure required two levels of testing:

1) Time trials - testing the ability of the packer to stay inflated and prevent movement between the seepage meter and the collection bag under pressure and over twice the time length of an average trial; and
2) Method comparison trials – directly assessing seepage meters outfitted with deep water deployment setups versus standard nearshore seepage meters in a near-shore environment (Table B-2).

Table B-2: Comparison of a standard Lee-type seepage meter setup with an adjusted seepage meter for deployment at depths of 1.1 m to 3.5 m tested in a near-shore environment

Location name	Configuration	Total trial time (s)	Volume (mL)	Volume (m^3)	Flux ($m^3/m^2/s$)
Gyro 1	nearshore	772260	91	9.10E-05	4.43E-10
Gyro 1	deep	772260	179	1.79E-04	8.71E-10
Gyro 1	nearshore	772260	200	2.00E-04	9.73E-10
Gyro 1	deep	772260	60	6.00E-05	2.92E-10
Gyro 2	deep	773160	90	9.00E-05	4.38E-10
Gyro 2	nearshore	773160	409	4.09E-04	1.99E-09
Gyro 2	deep	773160	102	1.02E-04	4.96E-10
Gyro 2	nearshore	773160	730	7.30E-04	3.55E-09

Appendix C: Seepage Meter Data

Table C-1: Point measurements used in the final flux calculations in the Kelowna groundwater discharge study

Location Coordinates UTM Zone 11 U	Location Name	Install date	Distance from shore (m)	Corrected[1] and measured flux ($m^3/m^2/s$)	Temporal multiplier[2]	Temporally scaled flux ($m^3/m^2/s$)
320907 E 5531037 N	Knox tree	2011-09-05	3	*2.70E-09*	0.41	1.11E-09
320880 E 5530773 N	Sutherland Park	2012-08-12	12	1.49E-09	0.36	5.35E-10
320349 E 5530528 N	Manhattan Beach	2011-09-07	9	*1.69E-10*	0.52	8.77E-11
320179 E 5530403 N	Manhattan Point	2011-09-07	9	*4.20E-10*	0.52	2.18E-10
320327 E 5530121 N	btwn Rotary/Man. Pt	2011-10-08	63	*2.80E-09*	0.47	1.31E-09
320441 E 5529933 N	Grand right	2011-09-07	9	*3.64E-09*	0.52	1.89E-09
320485 E 5529806 N	Half moon bay	2013-04-22	14	5.70E-10	3.86	2.20E-09
320466 E 5529778 N	Grand left	2011-09-07	11	*7.84E-10*	0.52	4.08E-10
320420 E 5528977 N	Sails	2011-09-07	16	*2.20E-08*	0.52	1.14E-08
320509 E 5527955 N	Burne	2012-08-11	9	2.34E-09	0.41	9.61E-10
320526 E 5527880 N	Cadder L	2011-09-07	11	*2.11E-09*	1.03	2.17E-09
320531 E 5527883 N	Cadder R	2012-08-09	10	*1.41E-08*	0.41	5.79E-09
320473 E 5527673 N	Royal	2011-09-08	22	*3.55E-09*	0.93	3.30E-09
320465 E 5527575 N	Strathcona	2011-09-08	19	*3.55E-09*	0.93	3.30E-09
320661 E 5526375 N	btwn West and Meikle	2011-10-09	26	*4.08E-09*	0.70	2.86E-09
320648 E 5526170 N	Meikle	2011-09-15	11	*1.96E-09*	0.43	8.43E-10
320670 E 5525794 N	Watt	2011-09-30	20	*5.12E-09*	0.41	2.10E-09
320806 E 5525551 N	Gyro R	2011-09-21	23	*5.59E-09*	0.38	2.12E-09
320955 E 5525312 N	Gyro L	2011-09-21	35	*2.44E-08*	0.38	9.29E-09
321148 E 5524938 N	Rotary R	2011-09-30	39	*1.24E-09*	0.53	6.58E-10
321177 E 5524760 N	Rotary L	2011-09-30	32	*1.03E-09*	0.53	5.46E-10
320821 E 5524356 N	Mission Cr R mouth	2012-08-12	10	1.37E-08	1.24	1.70E-08
320631 E 5524245 N	Truswell 1	2012-08-05	43	*1.95E-08*	1.12	2.19E-08

Table C-1: Point measurements used in the final flux calculations in the Kelowna groundwater discharge study (continued)

Location Coordinates UTM Zone 11 U	Location Name	Install date	Distance from shore (m)	Corrected[1] and measured flux ($m^3/m^2/s$)	Temporal multiplier[2]	Temporally scaled flux ($m^3/m^2/s$)
320520 E 5524176 N	Truswell 2	2012-08-05	135	*3.63E-09*	1.12	4.07E-09
320624 E 5524130 N	Truswell 3	2012-08-05	42	*1.01E-07*	1.12	1.13E-07
320730 E 5524019 N	Mission fan	2012-08-03	8	*1.10E-08*	1.08	1.19E-08
320808 E 5523901 N	Bluebird North	2012-08-03	7	*1.55E-08*	1.08	1.67E-08
320947 E 5522962 N	Hobson 1	2011-09-21	10	*6.67E-09*	0.89	5.93E-09
320961 E 5522953 N	Hobson 2	2012-08-07	10	*9.71E-09*	1.17	1.14E-08
320707 E 5522718 N	btwn Hobson & Sarsons	2011-10-10	20	*2.89E-08*	0.35	1.01E-08
320236 E 5522347 N	Sarsons 1	2012-07-17	5	*1.36E-08*	1.34	1.82E-08
320225 E 5522280 N	Sarsons 2	2011-09-22	19	*1.11E-09*	0.80	8.91E-10
320235 E 5522142 N	Sarsons 3	2012-07-17	16	*4.19E-08*	1.34	5.62E-08
320110 E 5521922 N	Eldorado 1	2012-08-07	17	*3.36E-09*	1.17	3.93E-09
320092 E 5521922 N	Eldorado 2	2011-09-21	21	*4.50E-09*	0.89	4.01E-09
320036 E 5521831 N	Eldorado 3	2012-08-03	9	*4.75E-08*	1.08	5.13E-08
319952 E 5521630 N	Bellevue gated beach	2011-10-09	17	*4.89E-09*	0.35	1.71E-09
319870 E 5521624 N	Bellevue 1	2012-08-03	21	*4.70E-09*	1.08	5.08E-09
319836 E 5521534 N	Bellevue 2	2012-08-03	1	*2.36E-09*	1.08	2.55E-09
319956 E 5521339 N	Collett 1	2012-08-07	4	*2.13E-09*	1.17	2.49E-09
319951 E 5521336 N	Collett 2	2011-09-23	8	*9.80E-10*	0.73	7.15E-10
319957 E 5521205 N	Farris 1	2011-10-05	20	*3.60E-09*	0.40	1.44E-09
319984 E 5521173 N	Farris 2	2012-08-07	7	*2.13E-09*	1.17	2.49E-09
319997 E 5520837 N	Lakeshore bend	2011-10-10	14	*3.35E-09*	0.35	1.17E-09
319560 E 5520399 N	Boat	2012-08-12	9	8.93E-09	1.24	1.11E-08
318790 E 5519720 N	N. of Cedar Creek	2012-07-28	2	*5.29E-10*	1.14	6.03E-10
318370 E 5519535 N	Braeloch 1	2011-10-05	12	*1.81E-09*	0.40	7.22E-10

Table C-1: Point measurements used in the final flux calculations in the Kelowna groundwater discharge study (continued)

Location Coordinates UTM Zone 11 U	Location Name	Install date	Distance from shore (m)	Corrected[1] and measured flux ($m^3/m^2/s$)	Temporal multiplier[2]	Temporally scaled flux ($m^3/m^2/s$)
318334 E 5519591 N	Braeloch 2	2012-08-07	10	*5.00E-08*	1.17	5.85E-08
317783 E 5519191 N	Cedar Creek 1	2012-07-18	5	*2.48E-08*	1.34	3.33E-08
317576 E 5519035 N	Cedar Creek 2	2012-07-12	9	*1.27E-09*	1.33	1.69E-09
317286 E 5518885 N	1 - S of Cedar Creek	2012-07-28	4	*1.67E-08*	1.14	1.91E-08
316928 E 5518498 N	2 - S of Cedar Creek	2012-07-28	9	*2.15E-09*	1.14	2.45E-09
316646 E 5518301 N	R of pump house	2012-07-28	1	*9.16E-09*	1.14	1.04E-08
316255 E 5518104 N	Swans	2012-07-28	1	*2.80E-08*	1.14	3.19E-08
316153 E 5518086 N	Bertram 0	2012-07-18	10	*4.96E-09*	1.34	6.65E-09
316054 E 5518102 N	Bertram L	2011-10-05	13	*6.43E-09*	0.40	2.57E-09
315958 E 5518093 N	Bertram 3	2012-07-16	10	*1.95E-08*	1.34	2.61E-08
315796 E 5518103 N	Bertram R	2011-10-05	13	*9.46E-09*	0.40	3.78E-09

[1] All measurements collected prior to August 11, 2012 were downscaled by 226% to correct for the use of seepage meter bag cover method 1 (Section 3.2.4).

[2] Temporal multipliers were calculated using the method outlined in Section 3.3. Example calculations are provided in Appendix D.

Table C-2: Long-term station data: Knox station

Trial start (YYYY-MM-DD)	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Method adjusted flux[1] ($m^3/m^2/s$)
2011-09-03	85800	275	1.20E-08	*5.11E-09*
2011-09-10	86760	40	1.73E-09	*7.34E-10*
2011-09-18	91620	-20	-8.21E-10	*-3.48E-10*
2011-09-24	100908	450	1.68E-08	*7.10E-09*
2011-10-02	87060	550	2.37E-08	*1.01E-08*
2011-10-08	90479	10	4.15E-10	*1.76E-10*
2011-10-16	96480	30	1.17E-09	*4.95E-10*
2011-10-22	94799	10	3.97E-10	*1.68E-10*
2011-11-05	96480	60	2.34E-09	*9.91E-10*
2011-11-18	90000	50	2.09E-09	*8.85E-10*
2012-02-14	84301	40	1.78E-09	*7.56E-10*
2012-03-03	88139	20	8.53E-10	*3.61E-10*
2012-03-15	88200	180	7.67E-09	*3.25E-09*
2012-05-15	85860	-30	-1.31E-09	*-5.57E-10*
2012-05-16	86040	330	1.44E-08	*6.11E-09*
2012-05-20	85860	-30	-1.31E-09	*-5.57E-10*
2012-05-21	86100	100	4.37E-09	*1.85E-09*
2012-05-24	86100	120	5.24E-09	*2.22E-09*
2012-07-13	85500	280	1.23E-08	*5.22E-09*
2012-07-21	95880	360	1.41E-08	*5.98E-09*
2012-08-10	72060	180	9.39E-09	*3.98E-09*
2012-08-20	89340	50	2.10E-09	2.10E-09
2012-08-27	76980	210	1.03E-08	1.03E-08
2012-09-04	90300	-35	-1.46E-09	-1.46E-09
2012-09-10	75840	90	4.46E-09	4.46E-09
2012-09-23	192780	145	2.83E-09	2.83E-09
2012-10-10	174660	72	1.55E-09	1.55E-09
2012-10-24	347880	236	2.55E-09	2.55E-09
2012-11-12	254520	80	1.18E-09	1.18E-09
2012-12-19	90600	30	1.24E-09	1.24E-09
2013-01-20	607380	140	8.66E-10	8.66E-10
2013-01-27	602580	103	6.43E-10	6.43E-10
2013-02-03	1724700	-4	-8.72E-12	-8.72E-12
2013-02-23	1898040	-9	-1.78E-11	-1.78E-11
2013-03-16	616200	-9	-5.49E-11	-5.49E-11
2013-03-24	1981500	-124	-2.35E-10	-2.35E-10
2013-04-16	507420	10	7.41E-11	7.41E-11
2013-04-27	330840	-9	-1.02E-10	-1.02E-10
2013-05-10	177840	101	2.13E-09	2.13E-09

Table C-2: Long-term station data: Knox station (continued)

Trial start (YYYY-MM-DD)	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Method adjusted flux[1] ($m^3/m^2/s$)
2013-05-18	520080	172	1.24E-09	1.24E-09
2013-05-25	264000	25	3.56E-10	3.56E-10
2013-05-31	440280	94	8.03E-10	8.03E-10
2013-06-11	330180	245	2.79E-09	2.79E-09
2013-06-23	166200	118	2.67E-09	2.67E-09
2013-06-28	342480	159	1.75E-09	1.75E-09
2013-07-05	2869140	81	1.06E-10	1.06E-10
2013-07-13	435720	30	2.59E-10	2.59E-10
2013-07-20	337200	117	1.30E-09	1.30E-09
2013-07-28	258600	-50	-7.27E-10	-7.27E-10
2013-08-04	430200	243	2.12E-09	2.12E-09
2013-08-15	429060	131	1.15E-09	1.15E-09
2013-08-24	428340	-18	-1.58E-10	-1.58E-10
2013-09-02	250680	48	7.20E-10	7.20E-10

[1] All measurements collected prior to August 11, 2012 were downscaled by 226% to correct for the use of seepage meter bag cover method 1 (Section 3.2.4).

Table C-3: Long-term station data: Maude-Roxby station

Trial start (YYYY-MM-DD)	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Method adjusted flux[1] ($m^3/m^2/s$)
2011-09-10	97620	220	8.47E-09	*3.59E-09*
2011-09-18	92040	410	1.67E-08	*7.10E-09*
2011-09-24	99120	950	3.60E-08	*1.53E-08*
2011-10-02	88980	100	4.22E-09	*1.79E-09*
2011-10-16	96060	280	1.10E-08	*4.64E-09*
2011-10-22	94020	30	1.20E-09	*5.08E-10*
2011-11-05	99840	660	2.48E-08	*1.05E-08*
2012-02-14	83220	480	2.17E-08	*9.19E-09*
2012-03-03	87540	110	4.72E-09	*2.00E-09*
2012-03-15	87480	210	9.02E-09	*3.82E-09*
2012-05-18	86040	210	9.17E-09	*3.89E-09*
2012-05-19	85920	490	2.14E-08	*9.08E-09*
2012-05-20	86040	170	7.43E-09	*3.15E-09*
2012-05-21	85500	50	2.20E-09	*9.31E-10*
2012-05-23	86040	510	2.23E-08	*9.44E-09*
2012-05-29	82800	840	3.81E-08	*1.62E-08*
2012-06-01	93540	790	3.17E-08	*1.35E-08*
2012-06-02	82020	360	1.65E-08	*6.99E-09*
2012-06-07	104220	810	2.92E-08	*1.24E-08*
2012-06-08	83100	1170	5.29E-08	*2.24E-08*
2012-06-09	83160	1050	4.75E-08	*2.01E-08*
2012-06-15	84240	270	1.20E-08	*5.11E-09*
2012-06-20	95460	550	2.17E-08	*9.18E-09*
2012-06-29	90600	640	2.66E-08	*1.13E-08*
2012-06-30	77040	280	1.37E-08	*5.79E-09*
2012-07-01	81120	90	4.17E-09	*1.77E-09*
2012-07-08	90720	-20	-8.29E-10	*-3.51E-10*
2012-07-21	93480	280	1.13E-08	*4.77E-09*
2012-08-03	80520	380	1.77E-08	*7.52E-09*
2012-08-10	73680	465	2.37E-08	*1.01E-08*
2012-08-11	93300	320	1.29E-08	*5.46E-09*
2012-08-21	76800	15	7.34E-10	7.34E-10
2012-08-27	92100	330	1.35E-08	1.35E-08
2012-09-04	90180	280	1.17E-08	1.17E-08
2012-09-11	98640	-60	-2.29E-09	-2.29E-09
2012-09-23	191100	137	2.69E-09	2.69E-09
2012-10-10	174960	170	3.65E-09	3.65E-09

Table C-3: Long-term station data: Maude-Roxby station (continued)

Trial start (YYYY-MM-DD)	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Method adjusted flux[1] ($m^3/m^2/s$)
2012-10-24	348300	50	5.40E-10	5.40E-10
2012-11-12	251820	20	2.99E-10	2.99E-10
2013-01-20	606360	-25	-1.55E-10	-1.55E-10
2013-01-27	604440	30	1.87E-10	1.87E-10
2013-02-03	1724220	-21	-4.58E-11	-4.58E-11
2013-04-29	258480	-15	-2.18E-10	-2.18E-10
2013-05-07	249900	227	3.41E-09	3.41E-09
2013-05-15	243720	233	3.59E-09	3.59E-09
2013-05-25	265680	-2	-2.83E-11	-2.83E-11
2013-05-31	441000	209	1.78E-09	1.78E-09
2013-06-22	241740	-118	-1.83E-09	-1.83E-09
2013-06-28	332640	105	1.19E-09	1.19E-09
2013-07-05	272580	10	1.38E-10	1.38E-10
2013-07-13	341940	95	1.04E-09	1.04E-09
2013-07-20	351840	54	5.77E-10	5.77E-10
2013-07-28	265320	-25	-3.54E-10	-3.54E-10
2013-08-04	433860	-52	-4.51E-10	-4.51E-10
2013-08-24	431520	101	8.80E-10	8.80E-10
2013-09-02	253080	198	2.94E-09	2.94E-09

[1] All measurements collected prior to August 11, 2012 were downscaled by 226% to correct for the use of seepage meter bag cover method 1 (Section 3.2.4).

Table C-4: Long-term station data: Lakeshore station

Trial start (YYYY-MM-DD)	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Method adjusted flux[1] ($m^3/m^2/s$)
2011-09-10	95520	-180	-7.08E-09	*-3.00E-09*
2011-09-18	92460	300	1.22E-08	*5.17E-09*
2011-09-24	97800	270	1.04E-08	*4.40E-09*
2011-10-02	86400	350	1.52E-08	*6.45E-09*
2011-10-08	88800	550	2.33E-08	*9.87E-09*
2011-10-16	95400	870	3.43E-08	*1.45E-08*
2011-10-22	93420	270	1.09E-08	*4.60E-09*
2011-11-05	95820	610	2.39E-08	*1.01E-08*
2011-11-18	89400	-10	-4.20E-10	*-1.78E-10*
2012-03-03	86520	280	1.22E-08	*1.22E-08*
2012-07-12	82140	140	6.41E-09	*2.71E-09*
2012-07-21	91080	180	7.43E-09	*3.15E-09*
2012-08-03	80100	100	4.69E-09	*1.99E-09*
2012-08-11	97440	315	1.22E-08	*5.15E-09*
2012-08-20	90120	70	2.92E-09	1.24E-09
2012-08-27	89820	95	3.98E-09	3.98E-09
2012-09-04	90120	220	9.18E-09	9.18E-09
2012-09-10	76860	165	8.07E-09	8.07E-09
2012-09-23	188160	-21	-4.20E-10	-4.20E-10
2012-10-10	175260	28	6.01E-10	6.01E-10
2012-10-24	346680	168	1.82E-09	1.82E-09
2012-11-12	255600	-53	-7.79E-10	-7.79E-10
2013-01-20	606840	149	9.23E-10	9.23E-10
2013-01-27	601260	278	1.74E-09	1.74E-09
2013-03-14	160140	260	6.10E-09	6.10E-09
2013-03-16	620700	1387	8.40E-09	8.40E-09
2013-04-16	510480	698	5.14E-09	5.14E-09
2013-05-09	82560	337	1.53E-08	1.53E-08
2013-05-14	338700	641	7.11E-09	7.11E-09
2013-05-31	442320	-9	-7.65E-11	-7.65E-13
2013-06-15	607860	116	7.17E-10	7.17E-10
2013-06-22	240540	95	1.48E-09	1.48E-09
2013-06-28	338400	373	4.14E-09	4.14E-09
2013-07-05	2332800	614	9.89E-10	-9.89E-10
2013-07-13	339480	265	2.93E-09	2.93E-09
2013-07-20	358680	950	9.96E-09	9.96E-09
2013-07-28	268860	265	3.70E-09	3.70E-09
2013-08-04	427260	325	2.86E-09	2.86E-09

Table C-4: Long-term station data: Lakeshore station (continued)

Trial start (YYYY-MM-DD)	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Method adjusted flux[1] ($m^3/m^2/s$)
2013-08-24	425160	1015	8.97E-09	8.97E-09
2013-09-02	255300	79	1.16E-09	1.16E-09

[1] All measurements collected prior to August 11, 2012 were downscaled by 226% to correct for the use of seepage meter bag cover method 1 (Section 3.2.4).

Table C-5: Cluster measurement data

Location Coordinates UTM Zone 11 U	Location Name	Install date	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Depth (m)	Distance from shore (m)
320886 E 5531052 N	Poplar Point	2013-04-29	259320	70	1.01E-09	0.48	31.6
		2013-04-29	259320	352	5.10E-09	0.48	31.6
		2013-04-29	259320	88	1.28E-09	0.48	31.6
		2013-07-20	333540	650	7.33E-09	0.93	31.1
		2013-07-20	333540	208	2.34E-09	0.97	31.1
		2013-07-20	333540	136	1.53E-09	0.97	31.1
320887 E 5530771 N	Knox	2013-01-29	965820	511	1.99E-09	0.49	10.0
		2013-01-29	965820	380	1.48E-09	0.49	10.0
		2013-01-29	965820	72	2.80E-10	0.49	10.0
		2013-06-05	402480	132	1.23E-09	1.02	8.8
		2013-06-05	402480	102	9.53E-10	1.04	8.8
		2013-06-05	402480	144	1.34E-09	1.02	8.8
320485 E 5529806 N	Half Moon Bay	2013-04-22	452520	156	1.30E-09	0.82	13.9
		2013-04-22	452520	30	2.49E-10	0.82	13.9
		2013-04-22	452520	20	1.66E-10	0.82	13.9
320153 E 5528298 N	Mill Creek	2012-11-20	457080	32	2.63E-10	0.81	29.5
		2012-11-20	457080	63	5.18E-10	0.81	29.5
		2012-11-20	457080	-38	-3.13E-10	0.81	29.5
		2013-06-15	272520	89	1.23E-09	0.91	10.8
		2013-06-15	272520	357	4.92E-09	0.93	10.8
		2013-06-15	272520	211	2.91E-09	1.01	10.8
320543 E 5527094 N	Maude-Roxby	2013-07-05	270000	320	4.46E-09	1.05	31.1
		2013-07-05	270000	10	1.39E-10	1.05	31.1
		2013-07-05	270000	153	2.13E-09	1.05	31.1

Table C-5: Cluster measurement data (continued)

Location Coordinates UTM Zone 11 U	Location Name	Install date	Time (seconds)	Volume (mL)	Flux ($m^3/m^2/s$)	Depth (m)	Distance from shore (m)
320111 E 5525665 N	KLO	2013-01-29	958200	-28	-1.10E-10	0.58	34.0
		2013-01-29	958200	-80	-3.14E-10	0.58	34.0
		2013-01-29	958200	298	1.17E-09	0.58	34.0
		2013-07-13	338040	220	2.45E-09	1.10	23.8
		2013-07-13	338040	163	1.81E-09	1.10	23.8
		2013-07-13	338040	234	2.60E-09	1.10	23.8
320912 E 5525361 N	Gyro Beach	2012-11-10	431220	82	7.15E-10	0.68	38.5
		2012-11-10	431220	329	2.87E-09	0.68	38.5
		2012-11-10	431220	68	5.93E-10	0.68	38.5
		2013-06-28	332400	598	6.76E-09	1.39	44.4
		2013-06-28	332400	112	1.27E-09	1.39	44.4
		2013-06-28	332400	710	8.03E-09	1.39	44.4
320938 E 5523547 N	Mission Creek	2012-10-10	345180	689	7.50E-09	0.80	15.0
		2012-10-10	345180	406	4.42E-09	0.80	15.0
		2012-10-10	345180	-22	-2.40E-10	0.80	15.0
		2013-06-22	240540	86	1.34E-09	1.11	11.8
		2013-06-22	240540	217	3.39E-09	1.19	11.8
		2013-06-22	240540	72	1.13E-09	1.16	11.8

Appendix D: Overall Flow Calculation

This appendix further expands on the calculations outlined in Section 3.3 and provides additional supporting information.

Table D-1: General procedure for the overall flow calculation

Step	Description	Example Location
Step 1	Collect long-term station data (Appendix C) and generate daily temporal scaling factors ($mult_n$) for each station using linear interpolation and Equation 5 (Section 3.3.1)	Table D-2
Step 2	Apply station specific $mult_n$ values to temporally scale individual point measurements (Appendix C) to become representative of average flux across the two year study period	Table C-1
Step 3	Select nearshore point measurements to relate to perpendicular transects	Table D-3
Step 4	Integrate perpendicular transect data (Figure 3.5) and create spatial scaling factors (Section 3.3.2)	Table D-4
Step 5	Calculate flow for each of the ten discharge areas (Figure 3.4) using the average of temporally scaled nearshore measurements and spatial scaling factors	Table D-5
Step 6	Sum the discharges calculated within each discharge area to obtain the study area total flow	Table D-6
Step 7	Apply an appropriate correction rate to account for internal friction within the seepage meters (Section 5.2.1.4)	Table D-6

NOTE: This procedure was repeated using alternate values for the Lakeshore long-term station as part of a sensitivity analysis (Section 5.2.1.1). This procedure was repeated during the inter-annual variation investigation by creating $mult_n$ values representative of average flux across each study year period (Step 2).

Table D-2: Example calculations for the linear interpolation of long-term station data from discrete measurements to daily estimates and generation of temporal scaling factors

Date	Collected and linearly interpolated points (x 10^{-9} $m^3/m^2/s$)	Temporal Scaling Factor Calculations	Temporal Scaling Factors
September 10, 2011[1]	**4.0**	$mult_{Sept\ 10,\ 2011} = q_{LT\ avg} / q_{LT\ Sept\ 10,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 4.0 \times 10^{-9}\ m^3/m^2/s$	0.50
September 11, 2011[2]	4.2	$mult_{Sept\ 11,\ 2011} = q_{LT\ avg} / q_{LT\ Sept\ 11,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 4.2 \times 10^{-9}\ m^3/m^2/s$	0.48
September 12, 2011[2]	4.4	$mult_{Sept\ 12,\ 2011} = q_{LT\ avg} / q_{LT\ Sept\ 12,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 4.4 \times 10^{-9}\ m^3/m^2/s$	0.45
September 13, 2011[2]	4.6	$mult_{Sept\ 13,\ 2011} = q_{LT\ avg} / q_{LT\ Sept\ 13,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 4.6 \times 10^{-9}\ m^3/m^2/s$	0.43
September 14, 2011[2]	4.8	$mult_{Sept\ 14,\ 2011} = q_{LT\ avg} / q_{LT\ Sept\ 14,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 4.8 \times 10^{-9}\ m^3/m^2/s$	0.42
September 15, 2011[2]	5.0	$mult_{Sept\ 15,\ 2011} = q_{LT\ avg} / q_{LT\ Sept\ 15,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 5.0 \times 10^{-9}\ m^3/m^2/s$	0.40
September 16, 2011[2]	5.2	$mult_{Sept\ 16,\ 2011} = q_{LT\ avg} / q_{LT\ Sept16,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 5.2 \times 10^{-9})\ m^3/m^2/s$	0.38
September 17, 2011[1]	**5.4**	$mult_{Sept\ 17,\ 2011} = q_{LT\ avg} / q_{LT\ Sept\ 17,\ 2011} = 2.0 \times 10^{-9}\ m^3/m^2/s\ /\ 5.4 \times 10^{-9}\ m^3/m^2/s$	0.37

[1] Direct measurement indicated in bold

[2] Linearly interpolated indicated in italics

Table D-3: Nearshore point measurements selected to relate to perpendicular transects

Transect[1]	Closest long-term station[1]	Closest Point Measurement[2]	No. of Points	Date	Flux Rate ($m^3/m^2/s$)
Manhattan	Knox	Knox cluster	3	05-Jul-13	1.22E-09
Mill	M/R	Mill Creek cluster	3	20-Nov-12	1.56E-10
KLO	M/R	KLO cluster	3	13-Jul-13	2.29E-09
Mission Creek mouth	Lakeshore	Truswell	2	05-Aug-12	6.01E-08
Mission Creek fan	Lakeshore	Lakeshore cluster	3	22-Jun-13	1.95E-09
Collett	Lakeshore	Collett	1	07-Aug-12	2.13E-09

[1] Location of transects and long-term stations found in Figure 3.3

[2] Guidance for the selection of nearshore points:

- Select and temporally scale the closest point in space to the perpendicular transect.
- Exclude all points collected using Cover Method 1.
- Preferentially select clusters, if available.
- Exclude points collected during a period of extremely low long-term station flux rates or a period with minimal long-term station data.

Table D-4: Example calculations for integration of perpendicular transects and creation of spatial scaling factors using the method outlined in Section 3.3.2 and Figure 3.5

Discharge area	Name[1]	Date	Temporally scaled flux ($m^3/m^2/s$)	Distance from shore (m)	Area (m x 1 m of shoreline)	Integrated transect[2] (m^3/s)	Flow captured in Q_1 (m^3/s)	% of Q_{total} captured in Q_1	Multiplier
Manhattan	$Nearshore_{low}$	2013/07/05	1.22E-09	9	58	1.58E-07	7.10E-08	45.0%	2.224
	$q_{1,low}$	2012/10/03	1.44E-09	107	57.5				
	$q_{2,low}$	2012/10/03	-2.94E-11	124	22.5				
	$q_{3,low}$	2012/10/03	1.76E-10	152	28				
	$Nearshore_{high}$	2013/07/05	1.22E-09	9	58	1.41E-07	7.10E-08	50.4%	1.984
	$q_{1,high}$	2013/06/14	6.91E-10	107	57.5				
	$q_{2,high}$	2013/06/14	7.27E-10	124	22.5				
	$q_{3,high}$	2013/06/14	4.92E-10	152	28				
	$Nearshore_{avg}$		1.22E-09	9	58	1.49E-07	7.10E-08	47.7%	**2.098**

[1] "low" and "high" subscripts describe low flow and high flow conditions, respectively. q_1 = the point closest to shore in the transect
[2] Using the method outlined in Figure 3.5

Table D-5: Example discharge area flow calculation

Discharge area	q_{avg}[1] ($m^3/m^2/s$)	Q_1 area[2] (m^2)	Q_1 Flow[3] (m^3/s)	Discharge area flow[4] (m^3/s)
Manhattan	5.40×10^{-10}	51272	2.77×10^{-5}	5.81×10^{-5}

[1] Arithmetic average of temporally scaled point measurements collected across the discharge area

[2] Total shoreline length of the Manhattan discharge area (884 m) multiplied by the length of Q_1 in the Manhattan perpendicular transect (58 m)

[3] q_{avg} multiplied by the Q_1 area

[4] Q_1 flow multiplied by the spatial scaling factor for the discharge area

Table D-6: Overall flow calculation results

Discharge area	Spatial scaling factor	Discharge area flow (m^3/s)
Knox	1.760	3.79×10^{-4}
Manhattan	2.098	5.81×10^{-5}
Grand/City Park	1.760	3.36×10^{-4}
Mill	2.219	6.52×10^{-4}
KLO	1.962	1.30×10^{-3}
Gyro	2.219	3.83×10^{-4}
Mission Creek	1.161	1.97×10^{-3}
Bellevue/Hobson	1.989	1.66×10^{-3}
Collett	1.760	5.96×10^{-4}
OMP	1.760	3.94×10^{-3}
Study Area[1]		1.13×10^{-2}

[1] Total discharge within the study area converts to 3.56×10^5 m_3/year (3.74×10^5 m_3/year after the application of the 1.05 correction factor)

Appendix E: Supportive Data

Table E-1: Sources for data supporting the discussion of potential influences on the Kelowna discharge study flow estimates

Data type	Location Identifier	Data Provider	Web link
Precipitation	Kelowna Climate Station ID: 1123939	Environment Canada	http://climate.weather.gc.ca/climateData/hourlydata_e.html?timeframe=1&Prov=BC&StationID=48369&hlyRange=2009-08-27%7C2015-05-03&Year=2013&Month=8&Day=31&cmdB1=Go
Groundwater levels	Provincial Observation Well 236	B.C. Ministry of Environment	http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/index.html?ID=236
Lake elevation	Okanagan Lake at Kelowna Hydrometric Station ID: 08NM083	Environment Canada	https://wateroffice.ec.gc.ca/report/report_e.html?type=realTime&stn=08NM083
Creek stage/flow	Mission Creek at East Kelowna Hydrometric Station ID: 08NM116	Environment Canada	https://wateroffice.ec.gc.ca/report/report_e.html?type=realTime&stn=08NM116
Evapotranspiration	1. Kelowna Airport 2. Glenmore 3. Belgo	Farmwest	http://farmwest.com/climate/et

Appendix F: Bathymetry and Geology Data Supporting MODFLOW Transect Development

This appendix provides data that supports the development of the MODFLOW model presented in Section 3.4. The lake portion of the MODFLOW transect was informed by bathymetric map contours translated into MODFLOW grid positions (Table F-1). The MODFLOW grid positions in the geological portion of the MODFLOW transect were informed by multiple referenced papers and reports (Table F-2). The z-axis represents depth (masl) in the model while the x-axis represents length (distance along the transect in metres). The (x = 0, z = 0) position in the model grid is the upper left hand corner and represents 500 masl, 2 km west of the shoreline. The maximum extent of the grid (x = 194, z = 150) found at the lower right corner, represents 200 masl, at the transect intersection with Gallagher's Canyon (Figure 2.6).

Table F-1: Spatial translation of Okanagan Lake bathymetric contours into MODFLOW 2-D transect points

Bathymetric contour (ft)[1]	Bathymetric contour (m)	Lakebed elevation (masl)	No. of 2 m cells from top of lake	**Z-axis position in model**	Map width of contour (mm)	Actual width of contour (m)	No. of 50 m cells	**X-axis position in model**
0	0.0	342	0	**79**	0	0	0	**41**
50	15.2	327	8	**87**	6	644	13	**28**
100	30.5	312	15	**94**	2	215	4	**23**
150	45.7	296	23	**102**	2.8	300	6	**17**
200	61.0	281	30	**109**	2.2	236	5	**13**
250	76.2	266	38	**117**	3.1	333	7	**6**
262 [2]	80.0	262	40	**119**	2.8	300	6	**1**

[1] Fish and Wildlife Branch (1966)
[2] estimated from map

Table F-2 Spatial translation of geology into MODFLOW 2-D transect points

Boundaries	X-axis position	Surface elevation (masl)	Elevation of potentiometric surface (masl)	**Elevation of potentiometric surface (z-axis position)**	Top of confining layer (masl)	Top of confining layer (z-axis position)
Shoreline	**41**	342	n/a	n/a	306	**97**
KLO 1 start[1]	**56**	344	n/a	n/a	310	**95**
KLO 2 start[1]	**71**	346	n/a	n/a	316	**92**
KLO 3 start[1]	**97**	352	n/a	n/a	340	**80**
Mission Creek 1	**116**	n/a	356	72	350	**75**
Obs Well 262	**148**	372	n/a	n/a	370	**65**
x = 193	**193**	430	n/a	n/a	430	**35**
Mission Creek 2	**194**	n/a	420	40		

Boundaries	Top of confined layer (masl)	**Top of confined layer (z-axis position)**	Top of no flow boundary (masl)	Top of no flow boundary (z-axis position)	Thickness of confined layer (m)	
Shoreline	260	**120**	n/a			
KLO 1 start[1]	280	**110**	n/a			
KLO 2 start[1]	306	**97**	200	**150**	106	
KLO 3 start[1]	330	**85**	275	**113**	55	
Mission Creek 1	340	**80**	300	**100**	40	
Obs Well 262	366	**67**	330	**85**	36	
x = 193	420	**40**	348	**76**	72	
Mission Creek 2	420	**40**	350	**75**	70	

[1] KLO sections were primarily created with information from GSC seismic reflection work (Pugin and Pullan, 2009). All other sections were influenced by multiple references (Paradis et al., 2010; Roed and Greenough, 2004; Lowen and Letvak, 1981; Nasmith, 1962; DataBC, 2013).

Appendix G: GeoMontreal Conference Paper

This paper was presented at GeoMontreal, the 66th Canadian Geotechnical Conference and the 11th Joint Canadian Geotechnical Society and the International Association of Hydrogeologists (IAH/CNC) Groundwater Conference. This conference took place between September 29 and October 3, 2012 in Montreal, PQ.

Physical meaurements of groundwater contributions to a large lake.

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ABSTRACT
Population increases and climate change are expected to increase water stress in the semi-arid Okanagan Valley in the Interior of British Columbia. This study used seepage meters and Darcy flux calculations to estimate the groundwater discharge between July 2011 and May 2013 along a 17 km section of Okanagan Lake immediately adjacent to the City of Kelowna. The site, which has been identified as a significant contributor of groundwater to the overall lake budget, exhibited strong temporal and inter-annual variation. Groundwater flux rates ranged from 10-11 to 10-8 m3/m2/s over a year and the September – December 2012 period contributed only 25% of the September to December 2011 discharge. The final groundwater discharge measurement at this site will be used to constrain groundwater values in a basin-scale water balance model constructed to inform water use and planning decisions within the Okanagan Valley.

RÉSUMÉ
Nous pouvons nous attendre à l'augmentation du stress sur l'eau dans les régions semi-arides de l'intérieur de la Colombie Britannique, plus précisément dans la Vallée de l'Okanagan, due aux changements climatique et à la croissance démographique. Cette étude utilise des méthodes physiques pour estimer les décharges d'eau souterraine de 2.3 x 106 m3/année sur une section du Lac Okanagan de 17 km, directement adjacente à la Ville de Kelowna, dans le but précis de restreindre les valeurs d'eau souterraine utilisées dans un bassin – à l'échelle ''Mike She'' et sur un modèle d'eau balancée. Ce model sera utilisé par ''Okanagan Basin Water Board (OBWB) pour informer sur l'utilisation et la planification de l'eau dans la vallée. Le site fut particulièrement choisi pour la recherche sur les eaux souterraines puisqu'il est identifié comme étant un contributeur principal d'eau souterraine dans l'ensemble du budget du lac.

1 INTRODUCTION

Future population increases and climate change effects are expected to cause pressure on available freshwater supplies in British Columbia's semi-arid Okanagan Valley. Concerns that water resources within the valley are close to full allocation, combined with the area's relatively low average precipitation, have created a need for accurate and comprehensive water supply and demand information. The Okanagan Basin Water Board (OBWB) is a regional water governance body that has been working on a water supply and demand model to inform water use and planning decisions within the valley (OBWB 2011). Groundwater has been identified as one of the largest contributors of potential error in the model (Summit 2010). In particular, the rate of groundwater discharge to mainstem valley lakes is a key component of the Okanagan Basin regional water balance.

Recent research has highlighted that flow between mountain blocks and valley-fill aquifers in mountainous terrain, such as that around Kelowna (Figure 1), is poorly understood (Wilson and Guan, 2004; Manning and Solomon, 2005; Welch and Allen, 2012). Groundwater discharge from these valley-fill aquifers to adjacent lakes can be modelled or measured directly. Conceptual deficiencies in our understanding of flow between bedrock and valley aquifers leads to uncertainty within groundwater or integrated groundwater-surface water models; though the accuracy of models can be improved through calibration with physical data (Konikow and Bredehoeft, 1992). This study used physical methods to quantify groundwater discharge from the Kelowna aquifers to Okanagan Lake to provide additional calibration of the groundwater component in upgradient models.

1.1 Study Site

Okanagan Lake is a large, deep lake located in south, central British Columbia (Figure 1) with a surface area of 351 km^2 (Summit 2005) and a maximum depth of 232 m (Roed and Greenough 2004).

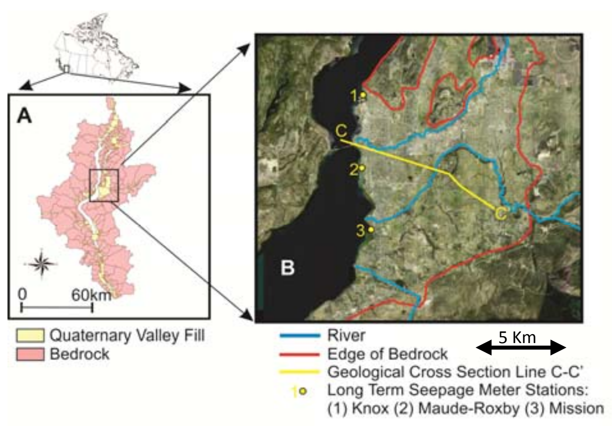

Figure 1. Overview of study location including: (A) location of Okanagan Basin and distribution of Quaternary valley fill sediment within the basin (adapted from Golder 2009). and (B) locations of surficial bedrock, major creeks, and long-term seepage meter stations in the study area.

The study site encompasses the Okanagan Lake eastern shoreline adjacent to the City of Kelowna. It is bounded between the Knox Mountain area to the north (49°54'22.54"N, 119°29'42.01"W) and Lakeshore Road to the south (49°47'12.15"N, 119°33"43.24"W). The topography in the Kelowna area ranges from the 342 metres above sea level (masl) at Okanagan Lake to 2000 masl in the nearby mountains.

Kelowna contains a population of over 100 000 people and covers an approximately 200 km^2 area, 120 km^2 of which is directly on the valley floor. Dominant land uses along the shoreline of the study area include residential and park land with a small amount of industrial area in the north and agricultural area in the south.

1.2 Geology

The Okanagan Valley runs north to south and is comprised of bedrock deeply excised into a "V" shape by glacial activity and filled in with up to 750 m of Pleistocene sediments from a series of glacial, glaciolacustrine and fluvial events (Roed and Greenough 2004). A geologic transect of the Kelowna valley (Figure 2) shows the sequence suggested by Paradis et al (2010) and Lowen and Letvak (1981) which consists of recent fluvial sediments (silt, sands, gravelly sands, gravels and organics) at surface resting on top of glaciolacustrine silts and clays accumulated near the end of the Fraser Glaciation. This glaciolacustrine layer confines lower sediment formations created by a series of older glacial and interglacial events. Recent lake bottom sediments along the study shoreline range from fine silts and clays to coarse cobbles.

1.3 Precipitation

The semi-arid climate provides the City of Kelowna with 380 mm of precipitation annually (Figure 3) with approximately one quarter falling as snow (Environment Canada, 2013a). The distribution of precipitation within the watershed is topographically driven with higher elevation locations receiving over 1000 mm/yr (Golder 2009).

1.4 Hydrology

There are six notable creeks within the Kelowna study area including (from north to south); Brandt's Creek, Mill (Kelowna) Creek, Fascieux Creek, Wilson Creek, Mission Creek and Bellevue Creek, the largest of which (Mission Creek) contributes 2.5 x 10^8 m^3/yr of water (or 28% of the total surface inflow) to Okanagan Lake (Summit 2009). Snowmelt provides 75% of streamflow within the Okanagan basin with 86% of the total stream flow occurring between March and July (Summit, 2009). Water losses from creeks during times of high flow contribute to groundwater recharge while groundwater provides baseflow to creeks during low flow periods of the year.

Sediment contributions from creek drainage basins dictate the hydraulic conductivity at the water/sediment interface over a large portion of the nearshore within the study area. The Bellevue Creek alluvial fan is comprised of coarse cobbles washed clean of fine sediments by nearshore wave activity and shoreline currents. The Mission Creek alluvial fan is comprised of clayey silt overlying sand, cobbles and boulders.

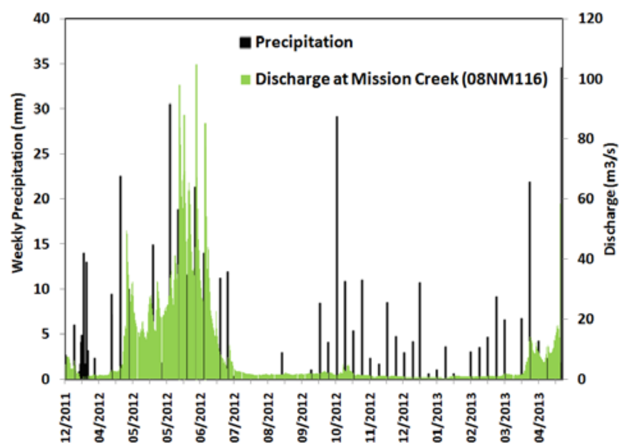

Figure 3. Kelowna precipitation and discharge from Mission Creek, November 2011 – May 2013 (Environment Canada 2013a,b).

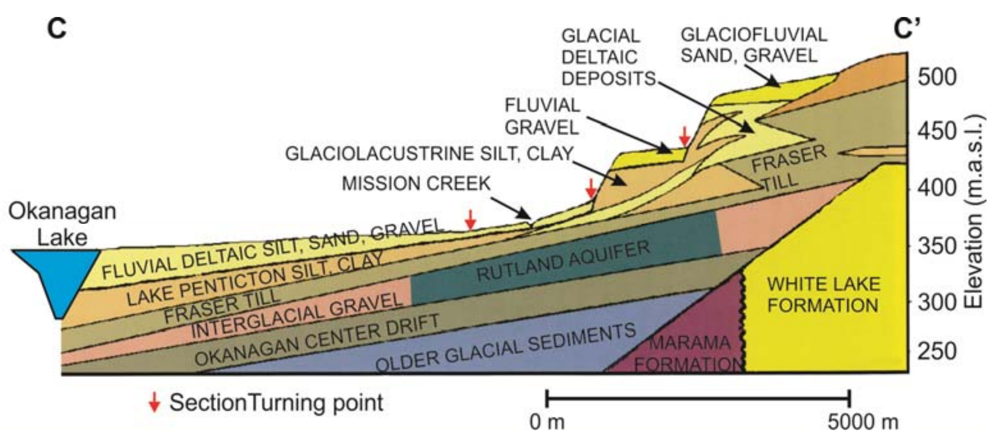

Figure 2. Transect of Kelowna geology marked C – C' on Figure 1 (adapted from Roed and Greenough, 2004).

1.5 Hydrogeology and Groundwater/Surface Water Interactions

The Kelowna area aquifers are comprised of both alluvial valley aquifers and upland bedrock aquifers (Figure 1). The majority of the valley aquifers are within sand and gravel formations (Water Resources Atlas, 2013) confined by fine glaciolacustrine sediments (Lake Penticton silt) and the Fraser Till (Figure 2). Groundwater flow moves towards Okanagan Lake and includes directional components other than the regionally-dominant north to south direction due to topographical influences and physical bedrock barriers (Golder 2009). Recharge to bedrock aquifers may discharge directly to valley aquifers as mountain block recharge or, more significantly, as discharges to surface water within the bedrock portion of stream valleys (Welch and Allen, 2012). The unconfined aquifers are expected to interact with creeks, and receive direct recharge from precipitation, irrigation return and urban infrastructure leaks.

Geologic transects and lake bathymetry indicate the major confined aquifer in the Kelowna area (the Rutland aquifer) likely dips below Okanagan Lake in the majority of the study area. It contributes water to the overlying unconfined aquifer, or directly to Okanagan Lake, by upwards flow (Figure 2). This structure presents two possible routes of groundwater discharge to the lake: discharge within the study area on the eastern side of the lake, or discharge further to the west of the shoreline into the bottom of the lake. Water discharging to the west of the study area must move through the confining layer and low hydraulic conductivity modern lacustrine sediments accumulated at the sediment/water interface that are known to restrict groundwater flow (Rosenberry et al., 2010). The position of the study site in the overall geology ensures it collects water from the unconfined Kelowna aquifers but it remains unproven whether the dominant flow path from the confined aquifer releases in the study area.

Basic groundwater theory predicts that the groundwater flux decreases with distance from shore (Schwartz and Zhang, 2003). This prediction is based on a simplistic model of groundwater flow in a homogeneous system that may not hold true within the study area. Other factors influencing the accuracy of estimations based on physical measurements include patterns of spatial and temporal variability. The temporal variability of precipitation within the mountainous Okanagan Valley and the timing of freshet has been well described (Summit 2009). The "...*seepage in lakes is known to vary directly as a function of precipitation*" (Sebestyen and Schneider, 2001) and therefore some temporal variability of the groundwater flux is expected. Temporal and inter-annual variability of groundwater flow observed in other groundwater systems (Sebestyen and Schneider, 2001; Cable et al., 1997; Shaw and Prepas, 1990b, Schneider et al., 2005) suggests groundwater flow estimations could be greatly impacted if the natural range of variability is not sampled.

1.6 Prior Discharge Estimates

Three numerical studies have been conducted on the Kelowna aquifer system, but limited groundwater data (groundwater heads) was available for calibration. The Okanagan Basin Hydrology Model (OBHM) was generated using MIKE SHE and MIKE 11 modelling platforms to describe the supply side of the overall OBWB supply and demand model. Independent groundwater, irrigation demand, surface water hydrology, lake evaporation, and instream flow studies were undertaken. The groundwater study utilized Darcy's Law calculations to estimate groundwater as 40% of the overall inputs to Okanagan Lake. Both the Golder (2009) and Smerdon and Allen (2009) studies routed the majority of recharge in the mountainous watershed into the valley fill. The surface water hydrology study only calculated groundwater as a residual of their regional water balance model and found it to be 5.7% of the total inflow into Okanagan Lake. Water balance calculations were completed at spatially discrete locations down the Okanagan Valley. Unfortunately, this "nodal" approach precluded a direct calculation of groundwater flow from the Kelowna aquifers. An estimate of groundwater discharge was created by scaling the groundwater group's discharge value to the surface water study's reported relative percentage contribution of groundwater within the overall budget. Other recent work examining groundwater flow through the Kelowna aquifers includes a regional scale groundwater flow model created in Visual MODFLOW (Smerdon and Allen, 2009). Groundwater discharge values for the three studies ranged by two orders of magnitude (Table 1).

Table 1. Summary of estimated discharge to Okanagan Lake from Kelowna aquifers

Study	**Method**	**Discharge (m^3/yr)**
[1]Groundwater	Darcy Flux calculation: regional gradient and transmissivity	32×10^6
[1]Surface Water	Residual of water balance modelling	5×10^6
Smerdon and Allen (2009)	Visual MODFLOW (Base case with pumping)	183×10^6

[1]Phase 2 OBWB Supply and Demand Project (Summit 2010)

While all of these studies are self-described as first estimations of the hydrologic system, the wide range of results is reflective of the authors' use of different simplified conceptual models to describe the interaction between upper watersheds and valley fill aquifers. The range of results suggests the employment of downgradient physical measurements would be very useful to help resolve between the conceptual models of flow and for numerical model calibration.

The goals of this study are:

1) To use physical methods to estimate groundwater discharge from the Kelowna aquifers;

2) To investigate temporal and inter-annual variability of groundwater flow; and
3) To establish whether physical methods are required to verify upgradient modelling attempts.

2 METHODS

Groundwater flow within the study area was estimated using seepage meter measurements and hydraulic gradient information collected between June 2011 and May 2013. The field program will continue until September 2013 with project completion scheduled for April 2014.

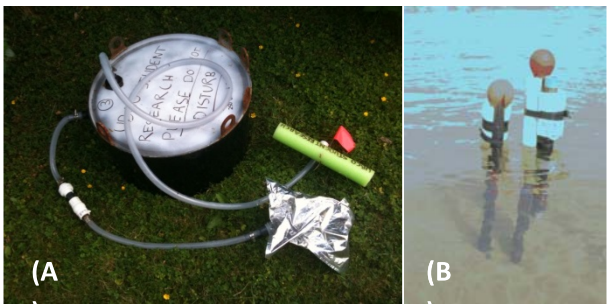

Figure 3: Apparatus used for groundwater discharge estimation: (A) Lee-type seepage meter, (B) piezometer nest used for hydraulic gradient measurement.

Lee-type seepage meters (Lee, 1977) were utilized using modern adjustments suggested by Brodie (2009) and Rosenberry and LaBaugh (2008), (Figure 3). Vent and bag lines were attached by bulkheads to the top and side of a 208L drum section, respectively. The bag line was comprised of tubing connecting: a ball value to start and stop trials, a union for easier bag removal and a thin, four litre, double-walled foil wine bag as a collection bag. The collection bag was pre-loaded with one litre of water to decrease anomalous influxes of water during the initial stages of the trial and was covered to reduce the pressure related impacts of wave action on groundwater collection. Seepage meter trials ran from 24 hours to five days targeting to ensure collection volumes exceeded a minimum collection volume of 50 mL, selected to exceed estimated total measurement errors of +/- 20 mL from volume measurement error and capture bag residuals.

Installation methodology adjustments were used on this project to adapt to the variable sediment types within the study area. Seepage meters are most successful in sandy substrates as they provided a good balance of easy insertion and support for the physical weight of the apparatus. A small percentage of the near-shore study area was comprised of fine sediments; in these locations, seepage meters were inspected to ensure additional settling did not occur during the collection period. Coarser sediment locations (gravelly cobbles) required the removal of surface cobbles to allow the seepage meter to achieve a complete sediment/water interface seal, as found in Rosenberry et al (2012).

Three (3) seepage meters were installed in September 2011 in locations marked on Figure 1. These seepage meters were left in place to track changes in groundwater discharge from September 2011 to May 2013 (Figure 4). These long-term stations were measured every one to two weeks except when prevented by ice impingement, low lake levels or human interference. The access route used to approach the long-term seepage meters was varied to minimize impacts of sediment compression on groundwater flow patterns.

Heterogeneity between seepage meter measurements was investigated by installing seepage meters in clusters or transects parallel to the shoreline in locations with comparable surface sediment, depth to sediment/water interface, and distance to shore. Transects were placed perpendicular to the shoreline at six locations to examine the change in groundwater flux with distance from shore. Sixty-six (66) point measurements were collected with seepage meters to provide information about groundwater flow within the study area.

Darcy's Law (Equation 1) was used to perform gradient calculations at five individual sampling sites.

$$q = K\frac{(h_1 - h_2)}{\Delta l} \qquad [1]$$

Where
q is the Darcy flux ($m^3/m^2/s$), K is hydraulic conductivity (m/s), h = groundwater head (m), and l = distance between h_1 and h_2 (m).

Mini-piezometers (Figure 3) were inserted adjacent to seepage meter installations at many of the sampling sites at depths of 1.0 m and 0.3 m below the sediment/water interface and within the lake to establish the hydraulic gradient. Laboratory falling or constant head tests were used to estimate the vertical hydraulic conductivity of grab-sampled surface sediments.

Control measurements were conducted to determine the range of error associated with seepage meter use. Seepage meters were installed over an impermeable barrier buried into the sediment to block groundwater flow, similar to Cable et al (1997). A standard seepage meter was inserted adjacent to the control meter and was run concurrently.

3 RESULTS

Control measurement trials returned readings higher than adjacent seepage meter installations in all cases. In the absence of site specific control measurements, a literature value was selected as a lower bound for usable measurements. Lee and Cherry (1978) suggest that flux rates lower than 0.01 cm/day (1.1575 x 10^{-9} $m^3/m^2/s$) are too small to be measured accurately. All measurements lower than this value were excluded from the first groundwater flow estimation.

Long-term station rates of discharge were found to change by up to three orders of magnitude over an annual cycle (10^{-11} – 10^{-8} $m^3/m^2/s$) (Figure 4).

Inter-annual variation was observed by comparing the 2011 and 2012 September to December discharge rates (Figure 4). The 2012 fluxes were approximately one quarter of the fluxes observed in 2011 (Table 2).

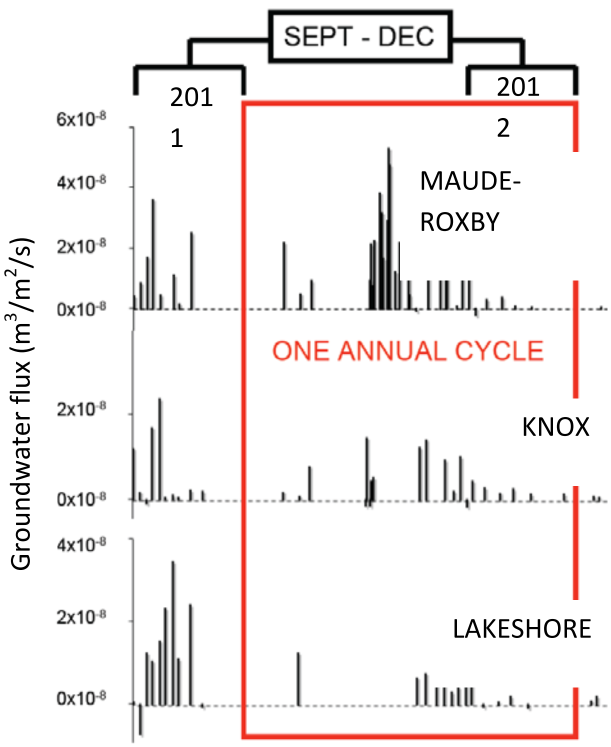

Figure 4: Groundwater discharge measured at long-term stations between September 2011 and March 2013.

Table 2: Long-term station average discharge and inter-annual variation

Average groundwater discharge	Knox ($m^3/m^2/s$)	Maude-Roxby ($m^3/m^2/s$)	Lakeshore ($m^3/m^2/s$)
Sept 2011 – Mar 2013	$4.8x10^{-9}$	$8.2x10^{-9}$	$5.6x10^{-9}$
2011 Sept – Dec[A]	$6.0x10^{-9}$	$1.3x10^{-8}$	$1.2x10^{-8}$
2012 Sept – Dec[B]	$1.8x10^{-9}$	$2.8x10^{-9}$	$3.1x10^{-9}$
Percentage of 2011 flows 2012*	29%	21%	25%

=100 [(A)/(B)]

The long-term station data was used to scale individual point measurements by setting the month with the highest flow at a particular station to 1.0 and assigning a proportional weighting to all other months. Point measurements were assigned to the proportion table of the closest long-term station. This allowed point measurements taken at a specific single time to be scaled to estimate average groundwater flux over a full annual cycle.

Seven (7) cluster measurements were collected during the period of low groundwater flow (November – February) to investigate site-scale heterogeneity (Table 3). An average variability of 113% was calculated over all clusters. The transect data was not included in the final analysis due to difficulties controlling for equal depth, equal distance from shore, and similar surface sediment over larger distances. A one sided analysis of variance (JMP 4, SAS 2002) was performed to examine the data for relationships between variability and flow rate, depth, distance from shore and sediment type. The only significant relationship with variability was found to be flow rate ($P > 0.0002$). A linear graph of flow rate versus variability produces an R^2 value of 0.95. Depth had a weak linear relationship to variance ($R^2 = 0.63$). Sediment type and the distance from the shoreline appeared to play no role in the variability of groundwater flux collected between the seepage meters placed in clusters. Additional measurements will be collected during the months of May and June 2013 to investigate the repeatability of these results during high flow.

Table 3: Spatial heterogeneity investigation parameters and measurements.

Cluster	Water Depth (m)	Distance from shore (m)	Surface Sediment	Average Flux ($m^3/m^2/s$)	Standard Deviation
1	0.48	31.6	Sandy clay	2.5×10^{-9}	2.3×10^{-9}
2	0.80	10.0	Sandy silt*	1.3×10^{-9}	8.8×10^{-10}
3	0.82	13.9	Silty sand	5.7×10^{-10}	6.3×10^{-10}
4	0.68	29.5	Sand	1.6×10^{-10}	4.3×10^{-10}
5	0.81	34.0	Sandy silt	2.5×10^{-10}	8.0×10^{-10}
6	0.58	38.5	Sand	1.4×10^{-9}	1.3×10^{-9}
7	0.49	13.7	Sand	3.9×10^{-9}	3.9×10^{-9}

* organics present

The theoretical decrease in groundwater flow with distance from shore generally held true in low flow conditions; measured fluxes fell below the method detection limit between 60 to 380 m from shore (Figure 5).

The sixty-six (66) point measurements collected between July 2011 and September 2012 returned an average groundwater flux of 2.8×10^{-8} $m^3/m^2/s$. After temporal scaling was completed using long-term station values, the average flux was 2.3×10^{-8} $m^3/m^2/s$.

Site scale hydraulic gradient calculations were unsuccessful during the initial attempts performed between September 2011 and April 2012 during the period of low groundwater flow. Calculations often returned hydraulic gradients counter to the results of the adjacent seepage meters. These methods were attempted prior to our understanding of the magnitude of the temporal variation within the system and will be attempted again in high flow conditions.

A first overall flow calculation assigned an area to each temporally scaled point measurement. The linear shoreline distance was divided by splitting the distance between two point measurements. For a preliminary calculation, the distance from the shoreline was fixed at 200 m. The distance from shore was fixed for the first estimation because of the lack of data from transects perpendicular to the shoreline during high flow. This data will be collected during the 2013 sampling season which should result in an improved estimation of total flow. The 200 m distance was selected based on examination of low flow data, bathymetry and geology within the study area. The first estimation of total flow from Kelowna area aquifers to Okanagan Lake was 2.3×10^6 m^3/yr.

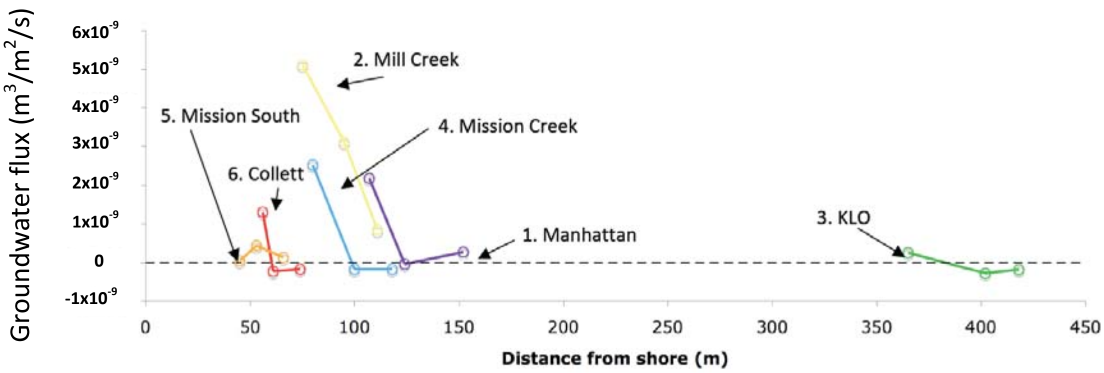

Figure 5: Groundwater flux measured in transects perpendicular to the shoreline

4 DISCUSSION

The control measurements attempted in 2012 were installed in finer sediment than the sand reported in Cable et al. (1997). Lack of sediment "set up" prior to insertion of seepage meters probably allowed wave action in the nearshore installation area to generate a venturi effect, reducing the hydraulic head in the collection bag and allowing for a false increase in groundwater discharge (Libelo and McIntyre 1994). Seepage meters perforated to redirect groundwater flow away from the collection bag, similar to the control meters reported in Schneider et al. (2005), will be utilized during the 2013 sampling season. Examination of the long-term station data (Figure 4) describes a smooth trend at flux values well below Lee and Cherry's (1978) suggested lower bound for accuracy of 0.01 cm/day. This suggests this cut-off value is overly conservative at the Kelowna study site, with accurate measurements possible at lower discharge rates. The long-term groundwater flux record currently includes all measurements in an effort to capture the seasonal trend but will be readjusted after the 2013 control measurements are complete.

Long-term groundwater discharge measurements on this site were found to show temporal variation (Figure 4) as found in other studies (Kirillin et al. 2010; Schneider et al., 2005). Fluxes ranging from 10-11 – 10-8 m3/m2/s were collected over an 18 month period. The relationship between groundwater flux rates and Mission Creek discharge (Environment Canada, 2013b) behaves as expected with groundwater discharge rates increasing after freshet and decreasing over a longer timescale than surface flows. Valley floor precipitation values do not correlate well with groundwater flux rates, and further work would be needed to determine the influence of precipitation based recharge.

Data collected from the study site also shows a large degree of inter-annual variation as has been found in other locations (Cable et al., 1997; Kirillin et al., 2010). The 2012 September to December period is approximately 25% of values collected for the same period in 2011 (Table 2). Cable et al. (1997) found a 50% drop in discharge between two subsequent years on their study site. This was found to correspond with similar changes in the local water table height over the same period. Other sites have found no variation in annual flow (Attanayake and Waller, 1988; Kidmose et al., 2011). As with temporal variation, inter-annual variation does not appear to be linked to precipitation upon first inspection. Precipitation in September to December 2012 was 40% higher than the same period in 2011 (Environment Canada, 2013a). Further work will examine other variables possibly effecting groundwater flow rates such as groundwater extraction.

Site scale spatial variability observed at the Kelowna site has been found in many study locations (Rosenberry and LaBaugh, 2008). The seepage meter cluster measurements found the average of spatial variability to be 113% and to be directly related to changes in flow rate. The variability in the measurements suggests that the seepage meter area does not cover an area representative of the range of sediment types at a given measurement location. Shaw and Prepas (1990a) also identified an increase in the variance of measurements with an increase in flow rate due to heterogeneity in subsurface sediments. Isiorho and Meyer (1999) found the use of smaller seepage meters increased the variability of seepage measurements in field and lab trials. Increasing the size of the seepage meter beyond the 0.6 metre diameter to capture a representative area is not possible due to logistical constraints. The cluster measurement data will be used to describe the range of error in the final groundwater discharge estimation. Sediment size and distance from shore parameters were not found to influence the variability of measurements. Another large lake study, Schneider (2005), completed an analysis on the influence of sediment type on groundwater flow at 25 locations and also found no direct correlation between groundwater flow and sediment type.

Study area scale spatial variability, influenced by a variety of factors, is present in other marine and lake groundwater research (Tanaguchi et al., 2003; Cable et al., 1997; Schneider 2005). Cable et al. (1997) found variability in flow rates across a study area could be explained by examining underlying geology; known springs in karstic terrain produced higher rates of groundwater discharge. Boyle (1994) and Schneider et al. (2005) found a direct link to precipitation in the contributing watershed. In the Kelowna study area, groundwater discharge is also influenced by geology and climate. The Maude-Roxby long-term station consistently returned higher flux rates than the other two long-term stations as it receives flow from a larger upgradient contributing area (Figure 1).

The decrease in groundwater flux with distance from shore predicted by basic groundwater theory was observed along the Kelowna shoreline (Figure 5) and was consistent with observations at other locations (Cable et al, 1997; Attanayake and Waller, 1988; Schneider et al., 2005). Bathymetry and flux rates from transects perpendicular to shore will be used to describe groundwater discharge flux rate changes with distance from shore during high and low flow times of year. Transect flux rates will be scaled temporally similar to the long-term station data set. The initial flow estimate used a fixed distance from shore, and assumed that flux was constant across that distance. In future, fluxes from individual point measurements will be scaled according to distance from shore using representative transects in a manner similar to the temporal scaling to long-term station data.

The results of the three prior groundwater estimation methods employed in the Kelowna area were separated by one to two orders of magnitude (Table 1) because of their differing conceptual models of flow between mountain block and valley aquifer. Direct measurement of groundwater discharge provides an estimate of annual flow one order of magnitude lower than the Groundwater Study (Golder, 2009) and two orders of magnitude lower than the Visual MODFLOW model (Smerdon and Allen, 2009). Direct measurement of groundwater flux at the sediment/water interface in this study presumes the majority of the water moving out of the confined Rutland Aquifer is discharging within the study area. This seems reasonable due to the known dip angle of the formation and the flow path restrictions encountered by water discharging further out into Okanagan Lake. Cross sectional (2-D) MODFLOW simulations will be completed to further investigate the two potential flow paths. If the confining layer is contributing groundwater to the study area as expected, the Groundwater Study and the Visual MODFLOW model greatly overestimated groundwater discharge into Okanagan Lake. This would support the conceptual model of Welch and Allen (2012), which post-dates these studies, in which the majority of recharge to bedrock within mountainous watersheds returns as baseflow prior to the river meeting the valley floor. Physical measurements of groundwater flux within the Kelowna study area can now be used to evaluate or calibrate the three previously completed flow estimates.

5 CONCLUSIONS

1. An initial estimate of groundwater discharge from the Kelowna aquifers to Okanagan Lake is 2.3 x 10^6 m^3/yr.
2. A physical measurement of groundwater flow is needed to evaluate the results of upgradient modelling.
3. Groundwater discharge is seasonally and inter-annually variable in mountainous systems. Invesigations using physical methods need to cover the range of temporal variability in order to accurately describe discharge patterns.

The next steps for this ongoing project include:

- Collection of additional long-term, transect and point measurements of seepage during freshet in 2013 when river stage and lake level are expected to be high;
- The use of MODFLOW modelling software to inform the locations of the 2013 sampling program and investigate flows associated with the confined aquifer;
- Completion of regional scale gradient calculations using monitored well and lake levels as well as hydraulic conductivity measurements from Paradis 2010; and
- Further investigation into the connection between individual upgradient groundwater budget parameters (ie. groundwater pumping rates, precipitation) on groundwater discharge rates along the Kelowna shoreline.

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