

Hydrogeochemistry of the Kelowna Aquifer System

By

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Abstract

Water availability and quality are issues of concern in the Okanagan due to its arid climate. Groundwater is being used to meet ever increasing demand, however increasing groundwater abstraction requires a detailed characterization of the area's groundwater hydrology in order to sustainably pump groundwater. The physical hydrogeology of the Kelowna aquifer system has been characterized and work on that front is ongoing. Its chemical hydrogeology remains virtually unknown.

The groundwater flow system consists of fractured bedrock aquifers at higher elevations on valley sides and deeper in the valley floor, along with unconsolidated sediments in the valley floor. These unconsolidated sediments comprise a lower confined aquifer, locally an upper confined aquifer and an overlying unconfined aquifer.

A database of water quality analyses for a variety of wells in the Kelowna area was developed. Geochemical modelling was performed using PHREEQC to determine additional hydrogeochemical parameters, followed by further analysis in AquaChem and ArcGIS.

The measurement of relatively high chloride concentrations from wells in the unconfined aquifer demonstrates that urban recharge is an important recharge contributor. A trend in confined aquifer samples towards higher sodium + potassium concentrations is caused by ion exchange of calcium for sodium while a similar trend towards higher magnesium concentrations is accounted for by dedolomitization. The lack of lateral concentration gradients from upland recharge areas towards Okanagan Lake suggests that vertical mixing between aquifers is minimal. A gradient of decreasing major cation and anion concentrations along a transect from Rutland towards Mission Creek is interpreted to be the result of induced recharge to the aquifer from Mission Creek.

This study has indicated the need for greater availability of hydrogeochemical data in the Kelowna aquifer system to enable validation of results and further analysis.

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for Papa, wish you were here

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1) Introduction

Groundwater quantity and quality are both topics of great importance in the Okanagan Basin due to its arid climate and reliance on groundwater for domestic, agricultural and commercial use. Almost all surface water resources have already been allocated (Neilson-Welch and Allen 2007) and increasing population pressures exerted upon the Kelowna water supply mean that hydrogeological assessment is of even greater importance in light of the need for increasing groundwater abstraction.

Extensive work has been performed in the North Okanagan near Vernon and Armstrong as well as in the South Okanagan near Oliver and Osoyoos, yet the hydrogeology of the Central Okanagan remains less well understood despite being the population centre of the valley (Neilson-Welch and Allen 2007). The physical hydrogeology of the Kelowna aquifer system has been characterized in consulting and governmental reports, however a synthesis of the chemical hydrogeology does not exist at all. As early as 1981, Lowen and Letvak (1981) recommended “a groundwater chemistry study ... for the lower Mission Creek area and in particular the Rutland aquifer.” Summit Environmental Consultants Ltd. (2005) stated that “significant uncertainties exist with respect to ... evaluation of water quality”. A thorough analysis and synthesis of the hydrogeochemistry of the Kelowna aquifer system is thus proposed. This will enhance current water quality assessments, enable determination of subsurface geochemical processes, allow for confirmation and expansion upon existing physical models and yield new insights into the Kelowna aquifer system.

Before proceeding it is important to note the caveat that the data underlying this research are the only publicly accessible hydrogeochemical data in the area. It is known

that there are significantly more wells completed within the Kelowna aquifer system than in this dataset, but these have either not been geochemically sampled or the well owners have declined to make this data public. Thus, the dataset used in this study represents a sample of the Kelowna aquifer system hydrogeochemistry and may not be able to determine all trends present in the subsurface.

2.1) Study Area

The Okanagan Basin is located in south-central British Columbia, and its southern extent just crosses the Canada-U.S. border into Washington State (Figure 1). It is a north-south oriented valley with a series of valley bottom lakes connected by aquifers and rivers. Mountainous highlands on either side of the valley drain into these lakes and rivers, with the Thompson Plateau to the west and the Okanagan Highland to the east.

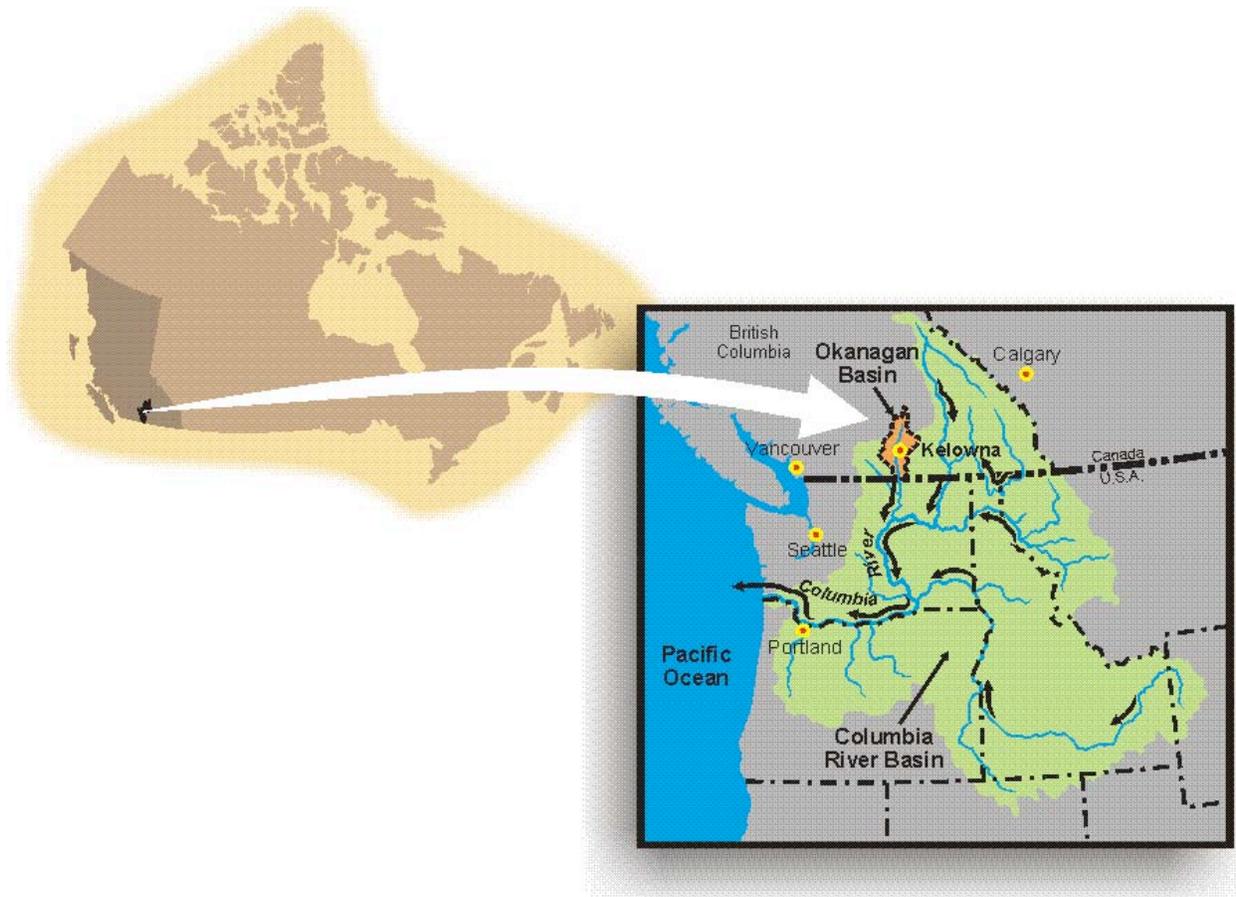


Figure 1. Okanagan Basin location (figure from Paradis et al. 2010)

This study focuses on the Kelowna aquifer system, which is wholly contained within the Okanagan basin. The Kelowna aquifer system underlies much of the Kelowna area, from Rambler Creek at its southern extent to Ellison Lake at its northern extent (Summit Environmental Consultants LTD. 2004). It is bounded to the east by a groundwater divide in the Okanagan Highland and to the west by Okanagan Lake (Figure 2).

2.2) Bedrock Geology

The basement rock present in the Kelowna area is the Precambrian Monashee Gneiss, overlain by the Paleozoic metasedimentary rocks of the Harper Valley Formation (Roed and Greenough 2004). In the Mesozoic, these rocks were subsequently intruded by the granitic Okanagan Batholith and rocks of the Nelson Plutonic Group (Roed and Greenough 2004). Eocene volcanism in the Kelowna area created the dacites and breccia of the Marron, Marama and Kettle River Formations (Roed and Greenough 2004).

Subsequent erosion of these volcanic rocks laid down the sediments that have since been lithified into the White Lake Formation, composed of conglomerate, sandstone and siltstone (Roed and Greenough 2004). Basaltic volcanism stretching from the Miocene to the Pleistocene represents the youngest rocks in the area (Roed and Greenough 2004).

2.3) Quaternary Geology

The oldest exposed and understood sediments in the Kelowna area are the >60ka Westwold sediments (Figure 2), consisting of fluvial sands overlain by a thin layer of finer sediments deposited in the interglacial period prior to the Okanagan Centre Glaciation (Fulton and Smith 1978). Notably the Westwold sediments contained some marl, providing a significant source of carbonates to the system. The overlying Okanagan Centre Drift (Figure 2) was deposited during its namesake glacial period and is composed of proglacial lake and outwash sediments preceding the till and followed by outwash sediments (Fulton and Smith 1978).

The interglacial period between the Okanagan Centre and Fraser glaciations saw the deposition of the fluvial regime Bessette Sediments (Figure 2). They are composed of interbedded silts, sands and gravels, sometimes overlain by a thin layer of laminated silts (Fulton and Smith 1978). A test hole (Figure 3) drilled by the Geological Survey of Canada (GSC) roughly 1km southeast of Mission Creek's outlet to Okanagan Lake extended to the top portion of the Bessette Sediments (Paradis et al. 2010).

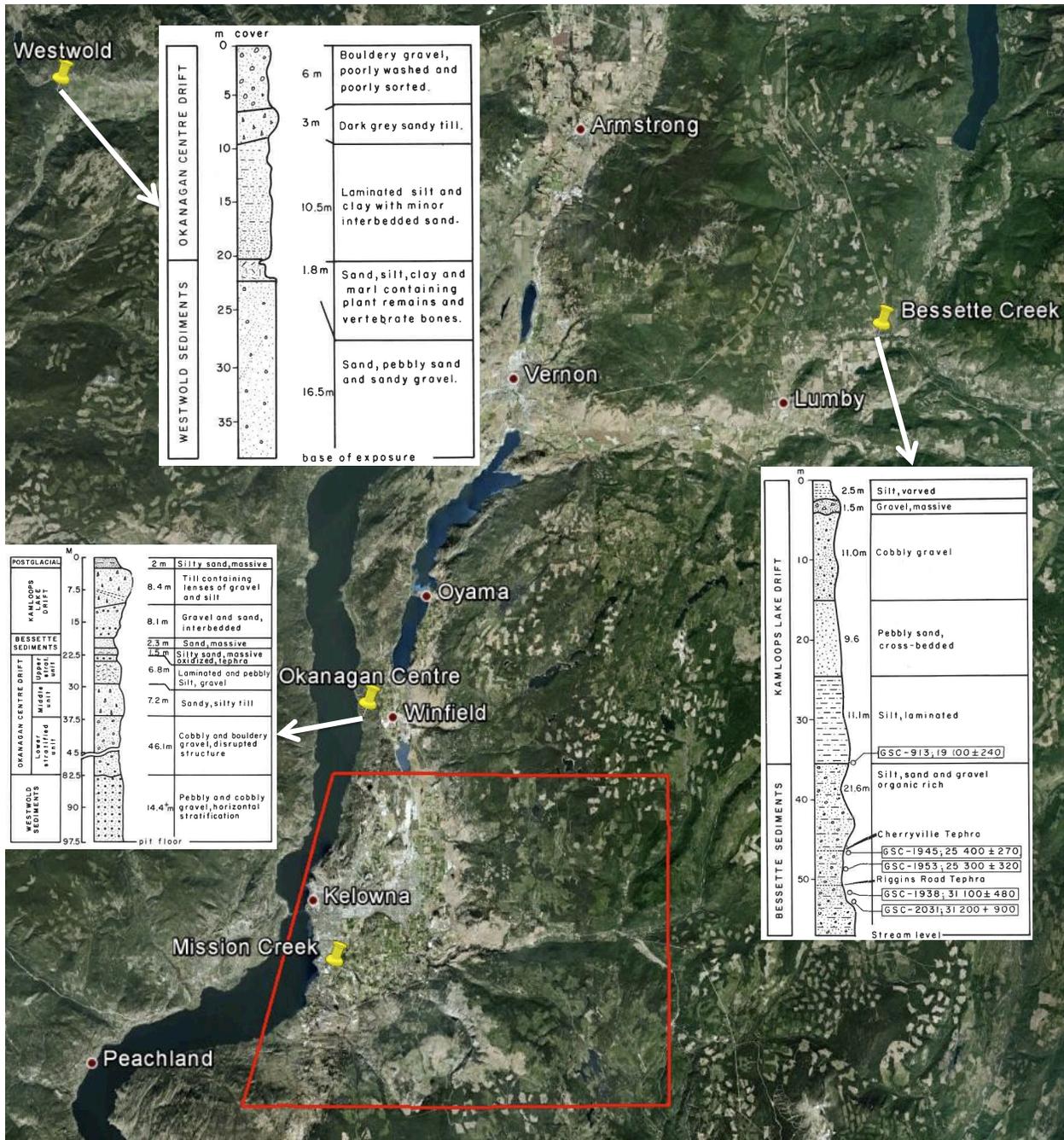


Figure 2. Locations of south-central British Columbia type sections; study area is outlined in red (figure modified from Fulton and Smith 1978, Google Earth)

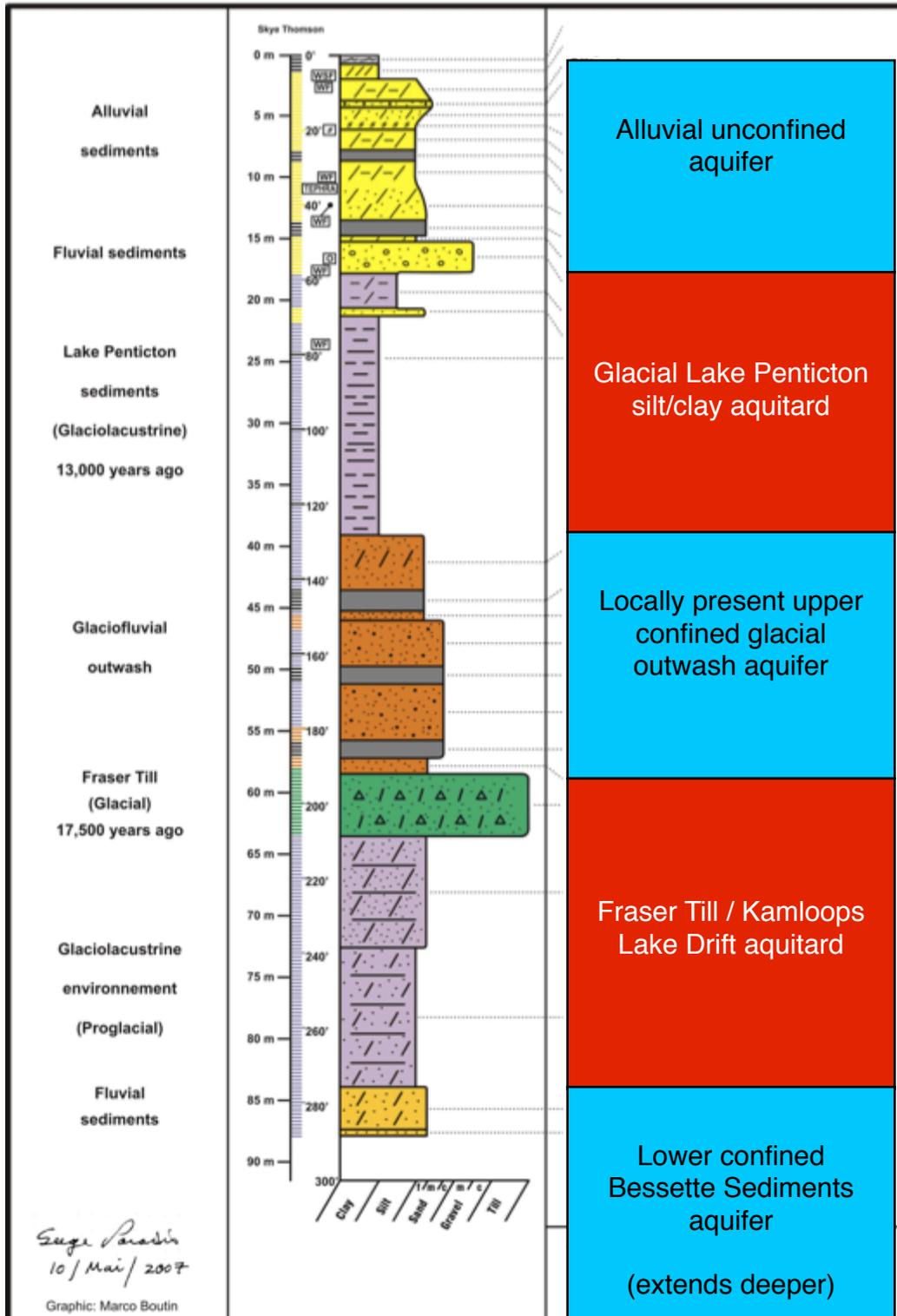


Figure 3. Litholog of the GSC's Mission Creek test hole with hydrostratigraphic interpretation; see Figure 2 for test hole location (figure modified from Paradis et al. 2010).

Next in the stratigraphic sequence is the Fraser till (also known locally as the Kamloops Lake Drift), a diamicton deposited during the Fraser glaciation (Figure 3). It consists of a gravel and sand matrix in areas underlain by granitic rocks (Paradis et al. 2010). The matrix becomes more clayey in areas underlain by Tertiary bedrock. This till is discontinuous in higher elevation areas and on hilltops.

The Fraser till is overlain by glaciofluvial sediments (Figure 3) associated with meltwater from the Fraser glaciation. These stratified sediments commonly occur as terraces in the upper parts of the Mission Creek valley and as ice contact complexes at the base of the foothills south of Kelowna (Paradis et al. 2010).

The next unit in the stratigraphic sequence is composed of glaciolacustrine silts and clays (Figure 3) with littoral sands, deltaic sands and gravels, and localized dropstones (Paradis et al. 2010). This unit was deposited by the proglacial Glacial Lake Penticton and thus exists only below 441m in elevation. Proglacial lakes Daves, Clark and Mission Creek were all short lived and thus did not deposit any stillwater sediments, although they are recognizable by series of delta complexes from their various stages.

Following glacial retreat, the so-called older alluvium deposits (Figure 3) were formed by extensive sedimentation by the, at the time, much larger Mission, Hydraulic and KLO creeks (Paradis et al. 2010). They consist of 0.5-15m of sands, gravelly sands, gravels and organics. Subsequently, a very active period of erosion by Mission, Hydraulic, KLO, Bellevue and Priest Creeks reworked this older alluvium, forming the alluvial fan on which most of Kelowna lies.

The overlying modern alluvium deposits (Figure 3) consist of silts, sands, gravelly sands, gravels and organics from 0.5-3m in thickness (Paradis et al. 2010). However,

they exist only locally alongside modern creeks and are likely only significant to the hydrogeology along Mission Creek.

2.4) Hydrostratigraphy

The underlying bedrock of the region is faulted and fractured, representing aquifer material with sufficient groundwater flow to allow pumping (Lawson 1968, Voekler and Allen 2012). Some wells have been completed in bedrock at higher elevations along valley sides where it outcrops. Bedrock aquifers in the region have been mapped to a small degree as BC Ministry of Environment (MOE) aquifers 470, 472 and 473 in the Glenmore, Ellison and Joe Rich areas respectively.

Little is known of the hydrostratigraphy of the sedimentary materials below the Bessette sediments and there are no groundwater samples available from them thus they are not considered in this study.

The Bessette sediments, deposited during the interglacial period between the Okanagan Centre and Fraser glaciations, represent the lower confined aquifer in the study area, bounded by the Okanagan Centre Drift aquitard below it and by the Fraser Till aquitard above it (Figure 3). Most large yield production wells are screened within this hydrostratigraphic unit. This lower confined aquifer is the best mapped of those in the Kelowna aquifer system, as BC MOE aquifers 463 and 464 which cover most of the Kelowna valley floor.

In some locations below 441m elevation, an upper confined aquifer locally exists as the post-Fraser glaciofluvial outwash is bounded by the Fraser Till aquitard below it and the Glacial Lake Penticton silts aquitard above it (Figure 3). The upper confined

aquifer has not been as well mapped, only appearing as BC MOE aquifer 469 in Glenmore.

The overlying older and modern alluvium units comprise the surficial unconfined aquifer (Figure 3). In some higher elevation locations where the post-Fraser glaciofluvial outwash exists and was not confined by Glacial Lake Penticton silts, this outwash also comprises part of the unconfined aquifer. Domestic supply, stormwater disposal drywells and other low yield wells are commonly completed within this hydrostratigraphic unit. Once again, government aquifer mapping is rather poor for the unconfined aquifer which exists as BC MOE aquifers 462 and 467 in Mission and Rutland respectively.

2.5) Physical Hydrogeology

Limited aquifer mapping has been done in the Kelowna area by the GSC, shown in Figure 4 (Smerdon and Allen 2009). Thus, while the entire area commonly contains aquifer material in either the form of unconsolidated sediments or fractured bedrock, aquifers have not been mapped for the entire area. However, GSC aquifers 463 and 464 (Figure 4) represent the bulk of the unconsolidated sediment portion of the Kelowna aquifer system. The GSC barely considers the layering of the aquifer system though, and often only maps in a single aquifer when there are multiple layers present.

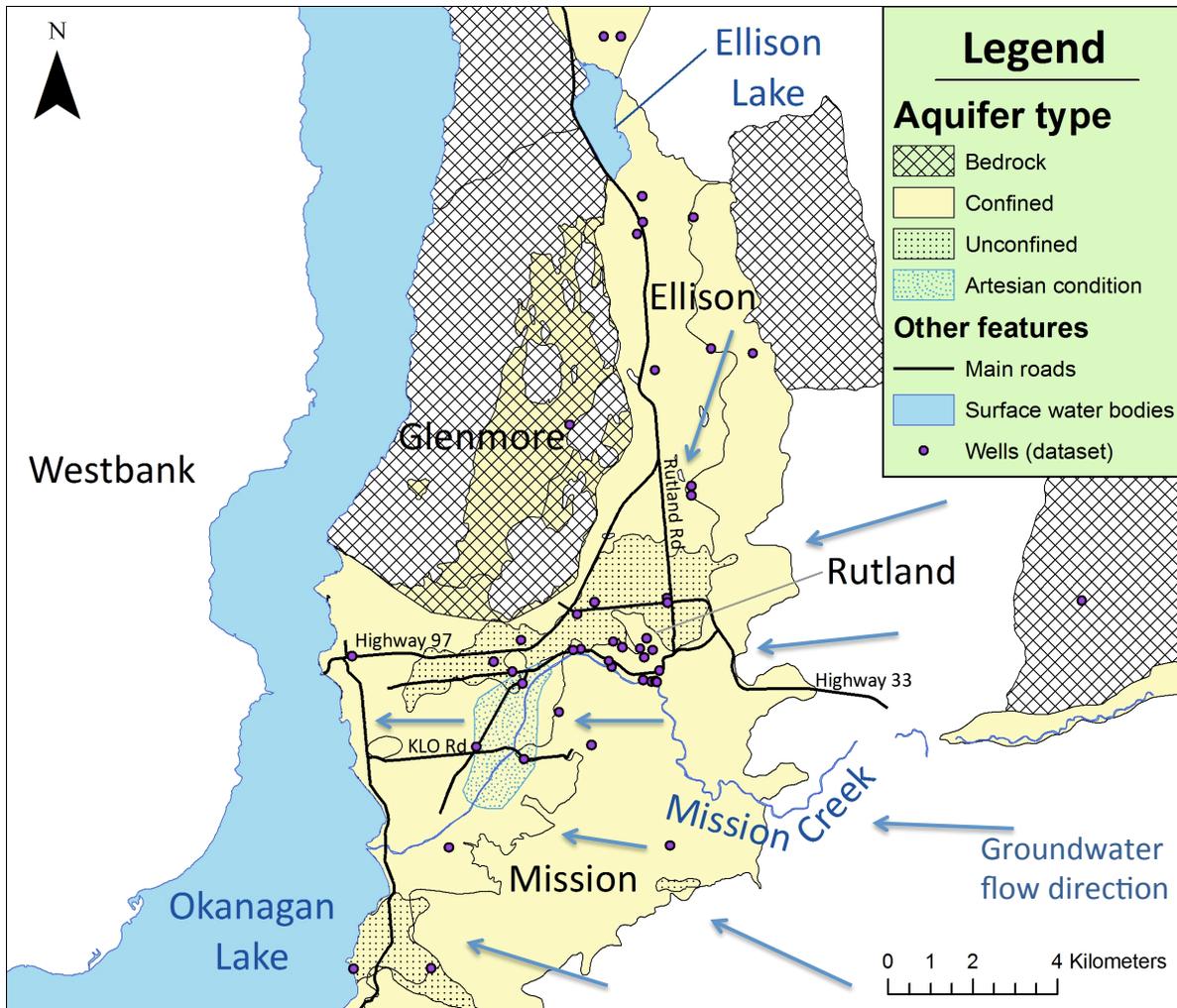


Figure 4. Plan view of the Kelowna aquifer system with well locations, GSC delineated aquifers and general groundwater flow trends estimated from modeling by Smerdon and Allen (2009)

In reality, the Kelowna aquifer system is a much more complex layered system as displayed by the hydrostratigraphic interpretation in Figure 3. The cross-section in Figure 5 shows the more general geometry of the aquifer system. Bedrock aquifers are present as the Marama Formation and the White Lake Formation are faulted and fractured. The lower confined aquifer is represented by the Interglacial Gravel in Figure 5. Note that the locally present upper confined aquifer was not encountered in this

cross-section. The unconfined aquifer is shown as “Fluvial deltaic silt, sand, gravel, organic”.

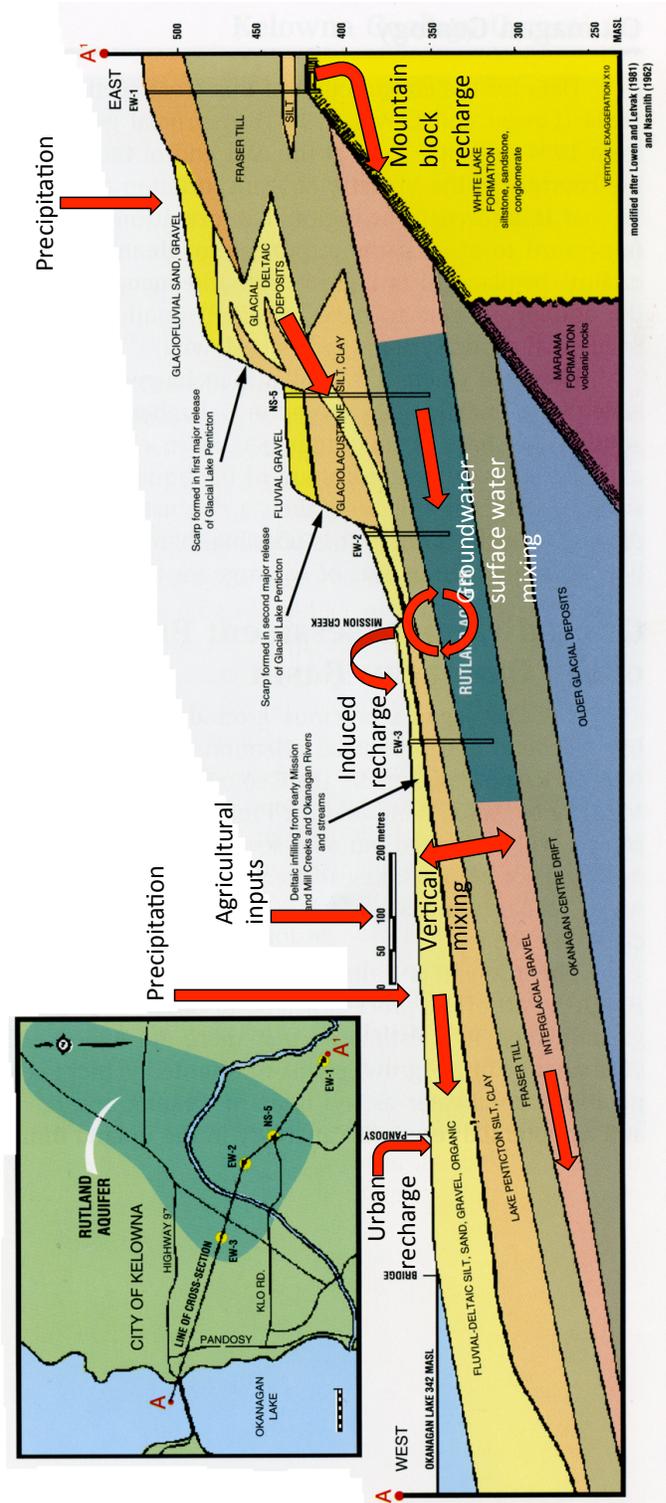


Figure 5. Cross-section of the Kelowna aquifer system with anticipated processes (figure modified from Roed and Greenough 2004).

As visible in Figure 5, a number of physical processes are expected within the Kelowna aquifer system. Naturally, precipitation will directly recharge the unconfined aquifer. It is also likely that urban recharge and agricultural recharge will enter the unconfined aquifer as the study area contains agricultural activity and urban development. Mountain block recharge has been shown to be a significant recharge source to the confined aquifer (Smerdon et al. 2009, Smerdon and Allen 2009).

2.6) Groundwater Modeling

Smerdon and Allen (2009) created a physical model for their Mission Creek watershed modeling area (Figure 6), comprising most of the Kelowna aquifer system. This modeling was performed with minimal vertical subdivision of the unconsolidated sediments into hydrostratigraphic units and unit thickness and extent were only roughly defined. Thus, this modeling is only sufficient to provide general regional groundwater flow trends.

As visible in Figure 6, groundwater flow is generally from eastern upland recharge areas towards the discharge area at Okanagan Lake to the west. However, Smerdon and Allen (2009) note that the root mean square error in hydraulic head is 68.1m. This means that while the model is appropriate for characterizing larger scale groundwater flow, it is likely insufficient for local scale applications.

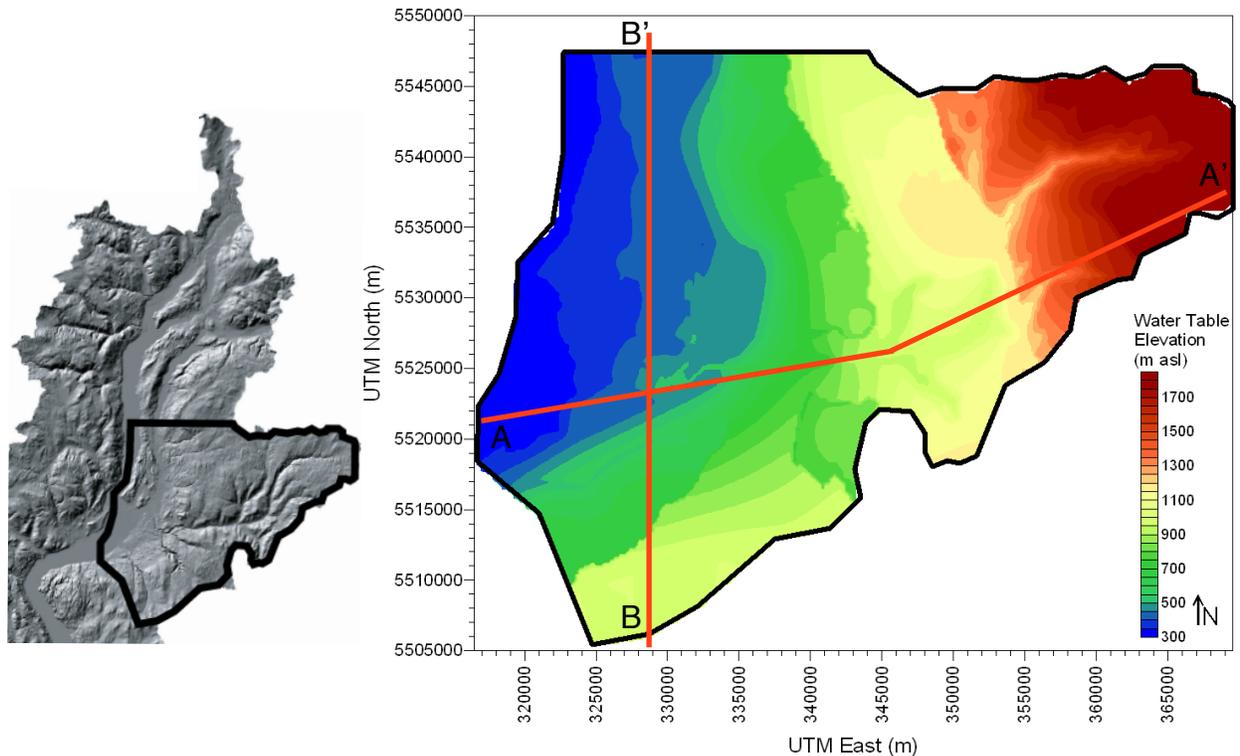


Figure 6. Modeled hydraulic head distribution for the Mission Creek watershed modeling area as shown in context of the Okanagan Basin, with cross-section transects used in Figure 7 (figure modified from Smerdon and Allen 2009)

From this modeling work, cross-sections (Figure 7) were also developed to display the vertical and horizontal components of groundwater flow in the subsurface. Cross-section A-A' shows subhorizontal flow in bedrock, with downward flow where Mission Creek exits its river valley into its fan, and with flow moving upwards near discharge at Okanagan Lake. This demonstrates potential for vertical mixing from the confined aquifer into the unconfined aquifer. Furthermore, an examination of the location of artesian wells in the area (Ministry of Environment 2013a) shows a concentration of these alongside Mission Creek near the west side of its prominent

horseshoe bend (Figure 4). This also indicates the possibility for upwards vertical mixing from the confined aquifer to the unconfined aquifer.

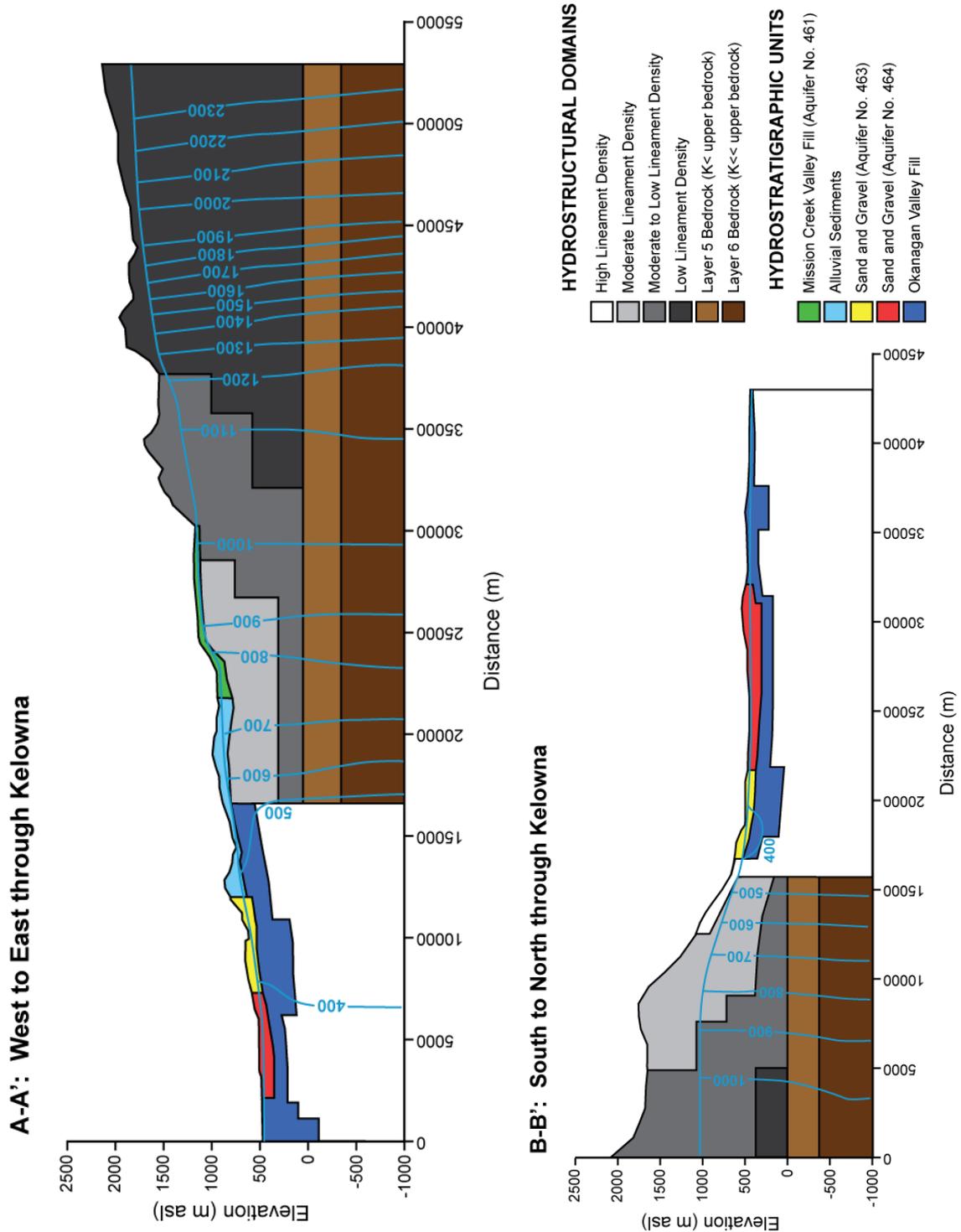


Figure 7. Cross sections with modeled hydraulic head contours (figure from Smerdon and Allen 2009)

Cross-section B-B' in Figure 7 shows subhorizontal flow in bedrock, with flow converging into Mission Creek. This suggests that groundwater - surface water interaction is occurring between the creek and aquifer. Lowen and Letvak (1981) also identified that groundwater - surface water interaction was taking place along Mission Creek. Generally, it is a gaining stream near discharge at Okanagan Lake, while it can be either a gaining or losing stream upstream depending on conditions at the time of measurement (Lowen and Letvak 1981).

Finally, pumping is the major physical anthropogenic process in the Kelowna aquifer system, with the majority coming from Rutland Waterworks District's (RWD) and Glenmore-Ellison Irrigation District's (GEID) well fields (Smerdon and Allen 2009). Basic reverse particle tracking was performed by Smerdon and Allen (2009) in an attempt to determine the capture zones of the RWD and South East Kelowna Irrigation District (SEKID)'s pumping well fields (Figure 8). This analysis determined that these were both drawing groundwater from the area where Mission Creek transitions from a river valley into its fan. Specifically, RWD's pumping well field is located adjacent to Mission Creek and given the low hydraulic gradients in the area and the results of reverse particle tracking (Figure 8), it is probable that pumping in Rutland and Mission is inducing recharge from the creek into the aquifer. However, Smerdon and Allen (2009) cautioned that given the error in the model, smaller scale analyses such as this would be inconclusive.

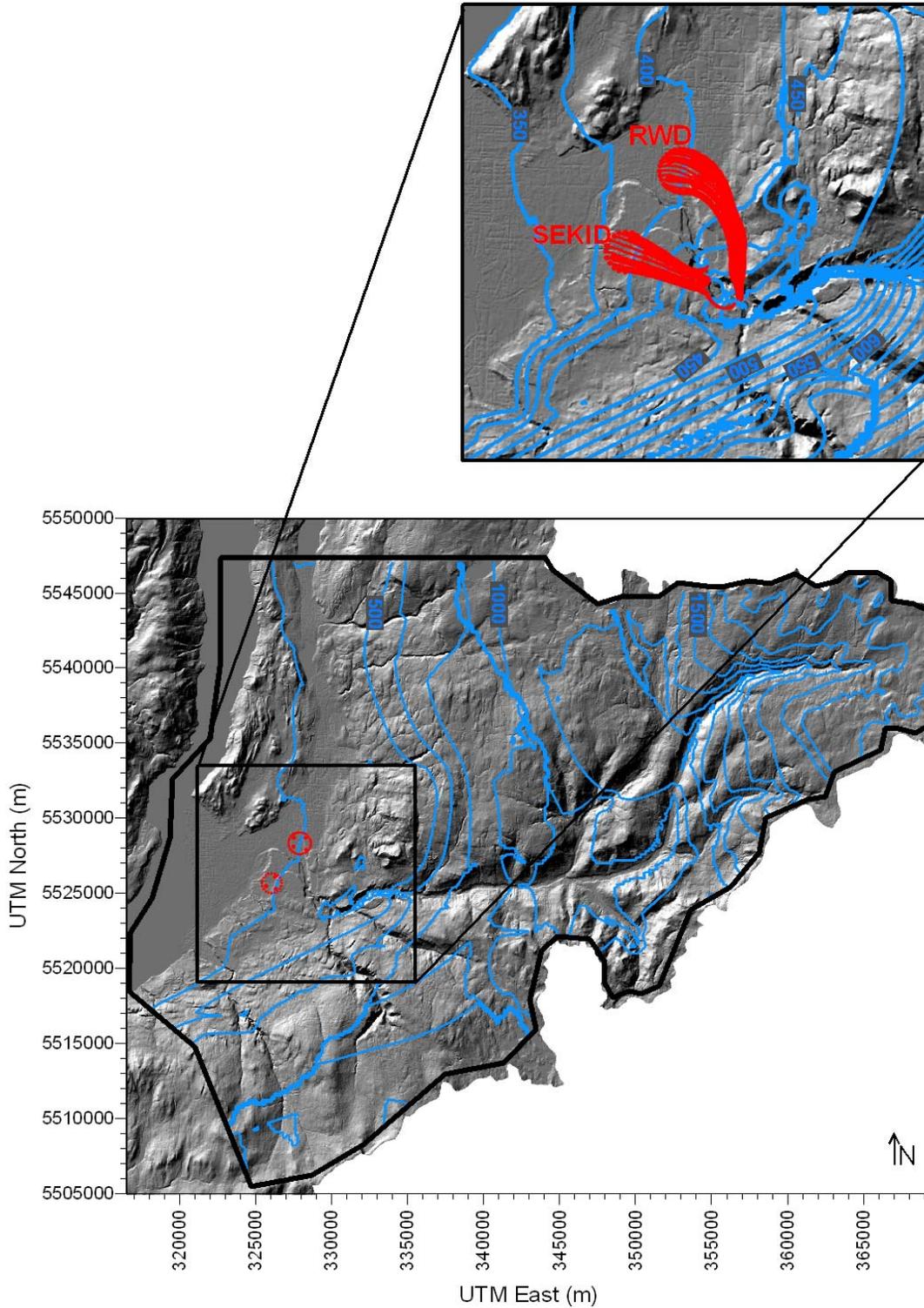


Figure 8. One year reverse particle tracking delineating RWD and SEKID pumping well field capture zones (figure from Smerdon and Allen 2009)

2.7) Hydrogeochemical Processes

In the unconfined, confined, and bedrock aquifers, it is anticipated that hydrogeochemistry will evolve towards higher total dissolved solids (TDS) downgradient and with increasing depth as groundwater has more time to dissolve minerals in the aquifer material (Freeze and Cherry 1979). However, unlike confined and bedrock aquifers, unconfined aquifers receive significant direct recharge inputs influencing hydrogeochemistry (Figure 9). Precipitation, urban recharge and agricultural recharge typically are all important processes in unconfined aquifers. Precipitation is a dilute input that does not change greatly in chemical composition over time at one location, although it does respond to anthropogenic gas additions to the atmosphere (Freeze and Cherry 1979).

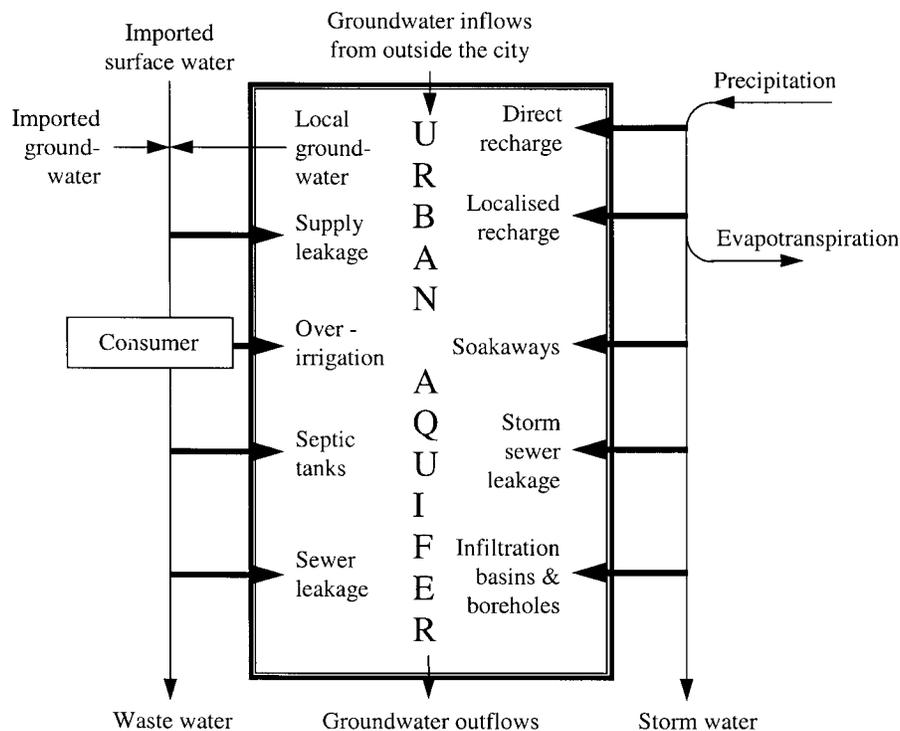


Figure 9. Urban and agricultural recharge processes (figure from Barrett et al. 1999)

On the other hand, urban recharge commonly contains elevated levels of chloride, sulfate, nitrate, ammonium, boron, phosphate, chlorofluorocarbons, trihalomethanes, faecal organics, detergent organics and chlorinated solvents (Barrett et al. 1999). In this dataset, analyses are only available for chloride and sulphate. Chloride is a common indicator of urban recharge as it enters the subsurface as dissolved road salt (NaCl), septic tank leakage, sewage and industrial waste (Eisen and Anderson 1979, Hamilton and Helsel 1995, Perera et al. 2013). Similarly, high sulphate concentrations can result from human and industrial waste (Eisen and Anderson 1979).

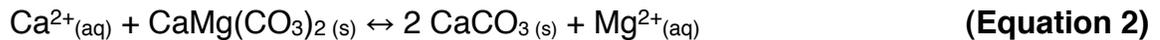
The primary component of an agricultural recharge signature is elevated nitrate from dissolved inorganic fertilizers and manure (Hamilton and Helsel 1995). High potassium and chloride from potash or elevated calcium and magnesium from liming are also other potential identifiers of agricultural recharge (Hamilton and Helsel 1995). Urban and agricultural recharge can easily infiltrate the soil profile down to the unconfined aquifer as there are no aquitards slowing its flow.

In confined aquifers, ion exchange reactions are important controls on hydrogeochemistry (Domenico and Schwartz 1997). In general, these reactions consist of the exchange of sorbed species for dissolved species. Divalent ions will be preferentially sorbed compared to monovalent ions, and within each the species with smaller hydrated ionic radii will be preferentially sorbed compared to larger hydrated ionic radii (Freeze and Cherry 1979). The sequence of adsorption affinity for common cations is $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$. The most important ion exchange reaction is the interaction of freshwater and saltwater, presented here as freshwater intruding more saline water (Appelo and Postma 2005):



This reaction sorbs calcium to the aquifer material while it dissolves sodium into the groundwater. Over time, ion exchange reactions will reach equilibrium, thus a change in hydrogeochemistry must be caused by some change in the flow system.

While ion exchange commonly relates calcium and sodium in an aquifer, dedolomitization is one of the controlling reactions in the relationship between calcium and magnesium. The following reaction relates the equilibrium between calcite and dolomite in an aquifer (Appelo and Postma 2005):



An excess of either dissolved calcium or magnesium will drive the equilibrium reaction one way or another.

Groundwater - surface water interactions can also significantly impact hydrogeochemistry proximal to surface water bodies, although such relationships can be complex and difficult to characterize. While classical literature has approached this as a matter of mixing between the two waters, Grasby et al. (1999) indicate that ion exchange reactions between the two are often the actual cause of hydrogeochemical evolution of these waters. Commonly higher TDS groundwater interacts with commonly lower TDS surface water by ion exchange reactions, changing the chemistry of both waters (Grasby et al. 1999).

3) Methods

Groundwater geochemistry data was collected from a variety of government, consulting and water purveyor sources (Table 1). Government and consulting reports were obtained from the Ministry of Environment's (2013b) EcoCat document archive.

Source	Details
BC Ministry of Environment Environmental Monitoring System (Skye Thomson pers. comm. 2013)	14 wells, some with multiple analyses
Glenmore-Ellison Improvement District (2012)	1 well, sampled five times, GEID area
AGRA (1998)	6 wells sampled once
Lowen (1979)	12 wells sampled once, Mission Creek area
Pacific Hydrogeology Consultants (1980)	2 wells sampled once, Rutland area
Kala Groundwater Consulting (1994)	1 well sampled once, Rutland area
Kala Groundwater Consulting (2001)	2 wells sampled once, GEID area
Kala Groundwater Consulting (1989)	1 well sampled once, GEID area
Kala Groundwater Consulting (2003)	1 well sampled once, Sunset Ranch area
Golder Associates (2003)	1 well sampled once, Rutland area
EBA Engineering Consultants (1997)	14 wells sampled once, all unconfined
Johnson (1994)	14 wells, sampled between one and four times each, Mill Creek area
Swain (1990)	Mission Creek surface water, sampled eighteen to twenty-one times depending on parameter

Table 1. Summary of data sources of hydrogeochemical analyses

Initial selection of BC MOE Environmental Monitoring System (EMS) sites was done by exporting data from the BC Water Resources Atlas (Ministry of Environment 2013a) into ArcGIS then selecting appropriate wells within the study area. EMS identifiers were then used to download water chemistry data from the EMS database. Geochemical analyses of water samples from reports were digitized into an Excel spreadsheet and merged with data obtained from the EMS system. All geochemical analyses were then imported into an Aquachem 5.1 (Schlumberger Water Services) database created specifically for this project. Some graphing of results was done in Aquachem, while the rest was done with Microsoft Excel 2010.

Geochemical speciation, mixing, exchange and 1D transport modeling was accomplished with the computer code PHREEQC Version 3 (Parkhurst and Appelo 2013), using PHREEQC-I as a GUI. The standard PHREEQC.dat database was used. Groundwater temperature was assumed to be 8.1°C for all calculations as this was the average groundwater temperature measured.

Sometimes, concentrations of chemical species were reported as total concentration as opposed to dissolved concentration. For the purposes of this research, only dissolved concentrations were used in order to maintain consistency. Also, actual bicarbonate ion concentrations were rarely reported. Using sample pH, alkalinity values were converted to bicarbonate values assuming that all alkalinity exists as bicarbonate. This assumption is reasonable given that nearly all the samples have a pH between 7 and 9, where >95% of alkalinity exists as bicarbonate (Fetter 2000). Density corrections were not made as all samples were relatively fresh and had relatively low TDS.

Well depth, location and elevation as well as aquifer material were obtained from well logs and maps provided in the reports or obtained through the BC MOE's WELLS database (Ministry of Environment 2013c). Artesian condition information was obtained through the BC Water Resources Atlas (Ministry of Environment 2013a). Where exact coordinates were not provided street intersections or location descriptors were used along with Google Earth to approximate location. It is also cautioned that well depth may not always be exactly accurate as sometimes the depth is reported as the bottom of the borehole, which often contains a packer or sump while the screened interval is slightly above.

Spatial analysis of groundwater geochemistry within different hydrostratigraphic units was performed in ArcGIS 9.3 (ESRI 2008). Further spatial data was obtained from GeoGratis (Natural Resources Canada 2013) and the GSC's Open File 6146 (Paradis 2009).

4) Results

As visible in Tables 2, 3, and 4, Kelowna groundwater is generally fresh, slightly basic and usually within the limits set by the Guidelines for Canadian Drinking Water Quality (Health Canada 2012). Generally, calcium and sodium are the dominant cations. Bicarbonate is the primary anion as nearly all alkalinity in Kelowna groundwater exists as bicarbonate. Groundwater temperature was only measured twice, yielding a mean of 8.1°C. Mean annual temperature is commonly used as a proxy for groundwater temperature, and this measured groundwater temperature is consistent with Kelowna Airport's mean annual temperature of 7.7°C (Environment Canada 2013).

In the unconfined aquifer (Table 2), chloride, nitrate, and to a lesser extent sulphate all have mean concentrations greatly exceeding their median concentrations and both exhibit a very high standard error of the mean and large range. This demonstrates that they are locally very significant to the hydrogeochemistry.

The confined aquifer (Table 3) is more basic than the unconfined aquifer, and it also contains appreciably lower concentrations of all major ions. Specifically, nitrate and chloride are present at significantly higher concentrations in the unconfined aquifer compared to the confined aquifer.

Parameter	Mean	Median	Range	Standard deviation	Number of samples
Alkalinity (mg/L CaCO₃)	239	228	86 - 465	85	18
pH	7.4	7.4	6.13 - 8.84	0.5	53
Specific conductance (µS/cm)	439	460	100 - 1050	252	56

Parameter	Mean	Median	Range	Standard deviation	Number of samples
Ca-dissolved (mg/L)	64.9	70.0	24 - 107	23.9	15
Mg-dissolved (mg/L)	23.1	21.4	6.45 - 51.5	12.8	15
Na-dissolved (mg/L)	52.6	32	6.77 - 343	82.6	15
K-dissolved (mg/L)	4.1	4.0	1.4 - 7	1.9	15
Cl-dissolved (mg/L)	56.2	19.2	1.2 - 317	84.0	18
SO ₄ dissolved (mg/L)	62.6	35.5	11.3 - 358	78.6	18
NO ₃ -dissolved (mg/L)	8.1	3.2	0 - 26.6	8.8	26

Table 2. Summary of Kelowna unconfined aquifer major ion concentrations and selected parameters

Parameter	Mean	Median	Range	Standard deviation	Number of samples
Alkalinity (mg/L CaCO ₃)	203	188	36 - 414	109	50
pH	8.1	8.1	6.5 - 9.4	0.6	51
Specific conductance (µS/cm)	433	340	88 - 1019	287	33
Ca-dissolved (mg/L)	46.0	45.8	3.54 - 99	36.8	45
Mg-dissolved (mg/L)	20.3	15.0	3.32 - 51.2	13.5	43
Na-dissolved (mg/L)	26.0	20.6	4.3 - 69	18.3	49
K-dissolved (mg/L)	2.8	2.6	0.71 - 6.5	1.4	39
Cl-dissolved (mg/L)	6.0	4.4	0 - 28.3	5.4	52
SO ₄ dissolved (mg/L)	45.3	36.0	0 - 143	40.2	51
NO ₃ -dissolved (mg/L)	1.1	0.1	0 - 4.8	1.6	18

Table 3. Summary of Kelowna confined aquifer major ion concentrations and selected parameters

Groundwater from bedrock wells (Table 4) exhibits very low TDS, and ion composition varies greatly depending on bedrock type. Note that the Joe Rich well (69) was sampled immediately after drilling and thus exhibits significantly higher dissolved species concentrations than it should under natural conditions (Skye Thomson pers. comm. 2013).

Parameter	Penticton Creek	Mission Creek	Joe Rich
Alkalinity (mg/L CaCO₃)	21.2	11.3	1010
pH	6.48	6.7	7.89
Specific conductance (µS/cm)	48.7	23	1660
Ca-dissolved (mg/L)	6.21	n/a	92.6
Mg-dissolved (mg/L)	0.473	n/a	136
Na-dissolved (mg/L)	2.15	1.6	56.8
K-dissolved (mg/L)	0.501	0.3	9.2
Cl-dissolved (mg/L)	0.26	0.5	4.1
SO₄ dissolved (mg/L)	3.61	0	28.4
NO₃-dissolved (mg/L)	n/a	0.7	0.0033

Table 4. Major ion concentrations and selected parameters for 3 different observed bedrock groundwater types

Water chemistry was compared to well depth and it was found that there is a distinct lack of the usually anticipated concentration gradients in many parameters with respect to depth. In a system with minimal topography and subhorizontal stratigraphy, deeper groundwater represents older groundwater which is expected to be anoxic and

possess higher TDS (Freeze and Cherry 1979). However, as visible in Figure 5, the Kelowna aquifer system exhibits moderate topographical relief and its geology is both complex and tilted. There are also no gradients in dissolved species concentrations from upland recharge areas towards discharge areas at Okanagan Lake observable in the current dataset for both confined and unconfined aquifers.

Of note is the distribution of nitrate in the Kelowna aquifer system. The only locations for which high nitrate values were observed were two housing developments (wells 4-8 in Figure 10) monitoring groundwater contaminated by leaky septic tanks and sewage treatment plant failure (City of Kelowna 2006, 2010). High nitrate values as would be expected in areas of heavy agricultural use such as Ellison and Mission were not observed. Wells in these areas exist only within the confined aquifer, and thus it is likely that agricultural inputs of nitrate from manure have not yet percolated to such depths.

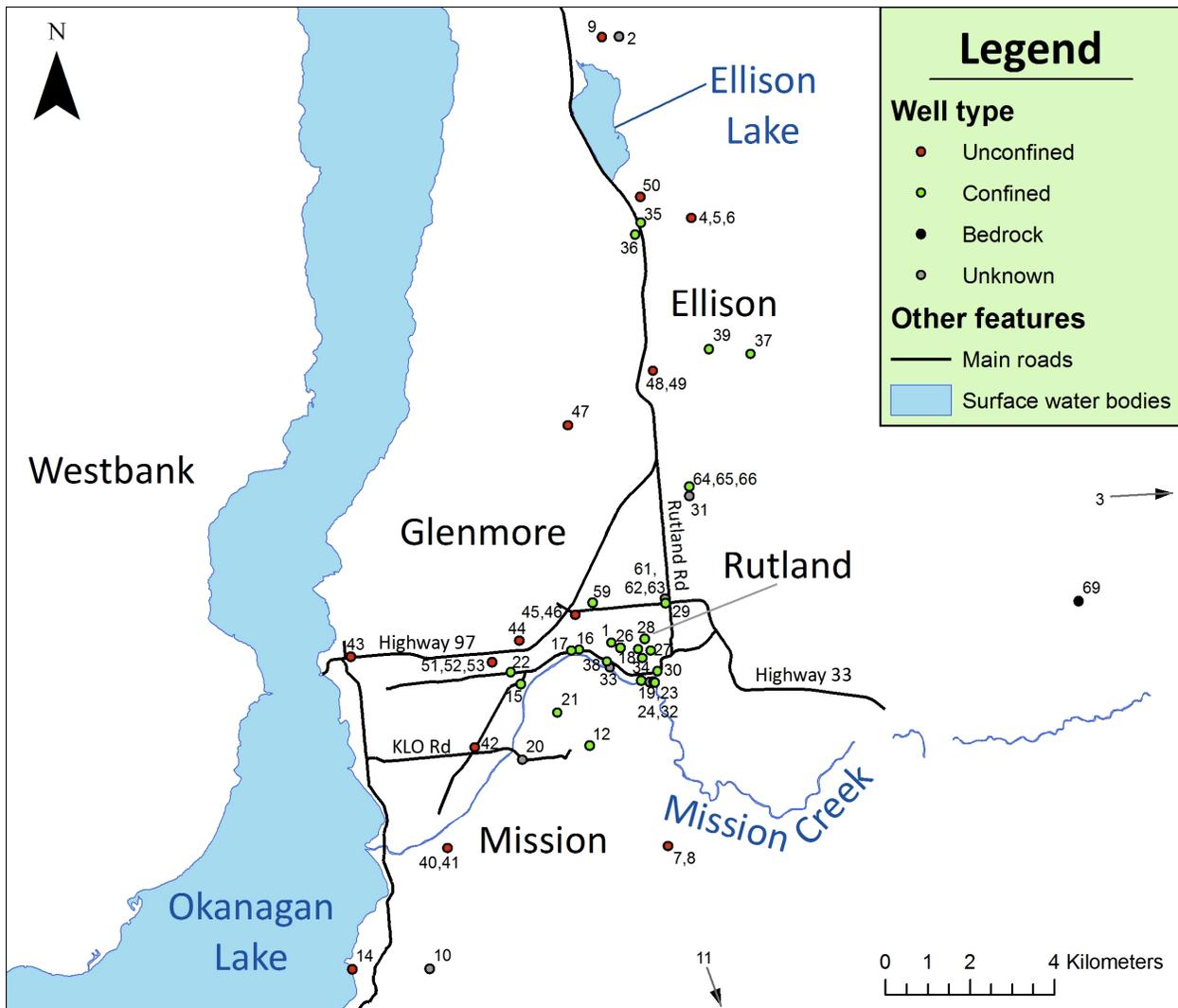


Figure 10. Kelowna aquifer system, with locations of wells in the project dataset and project well numbers for identification; PHREEQC 1D geochemical transport modeling transect is indicated by the red line

As visible in the Piper plot in Figure 11, groundwater is primarily of the calcium-bicarbonate type. Groundwater in the unconfined aquifer displays a distinct trend towards chloride. Samples from the confined aquifer trend away from calcium towards both magnesium and sodium + potassium.

Groundwater from wells completed in bedrock show similar anion compositions, but two very different cation compositions (Figure 11). This indicates that different bedrock types are controlling the geochemistry of these groundwaters. Indeed, an examination of Massey et al. (2005)'s bedrock mapping indicates that the Penticton Creek (well 11 in Figure 10) is completed in Okanagan Batholith granite, the upper Mission Creek (well 3 in Figure 10) is completed in Chilcotin Group volcanics and the Joe Rich (well 69 in Figure 10) is completed in undivided metamorphics of the Shuswap Assemblage.

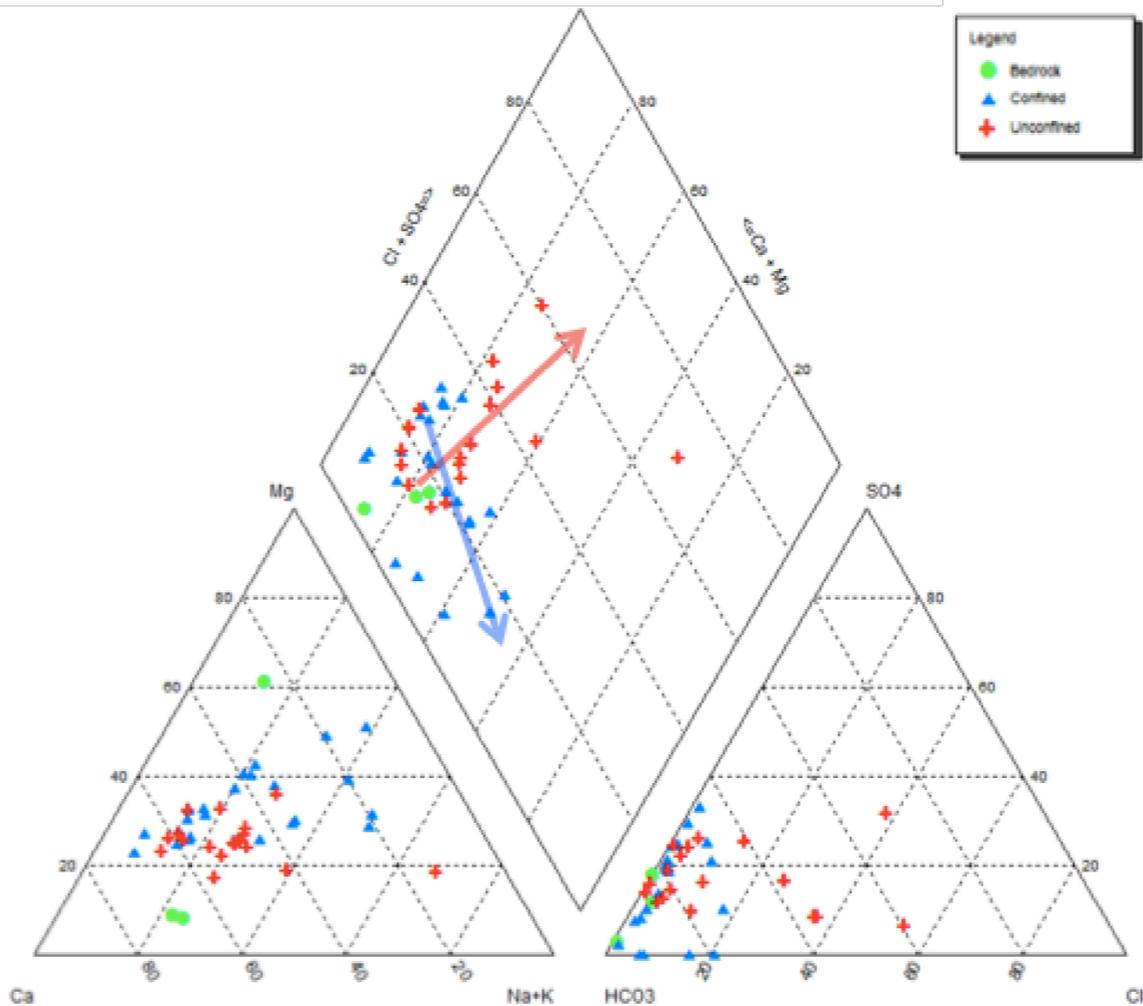


Figure 11. Piper plot of all groundwater geochemical analyses for the Kelowna aquifer system. Trend towards chloride is indicated by the red arrow, while the trend towards magnesium and sodium + potassium is indicated by the blue arrow.

Kelowna area groundwater is generally supersaturated with respect to calcite and dolomite (Figure 12). It is somewhat undersaturated with respect to gypsum, and is heavily undersaturated with respect to halite. Saturation indices are higher for calcite than dolomite at low TDS, while the opposite is true at high TDS.

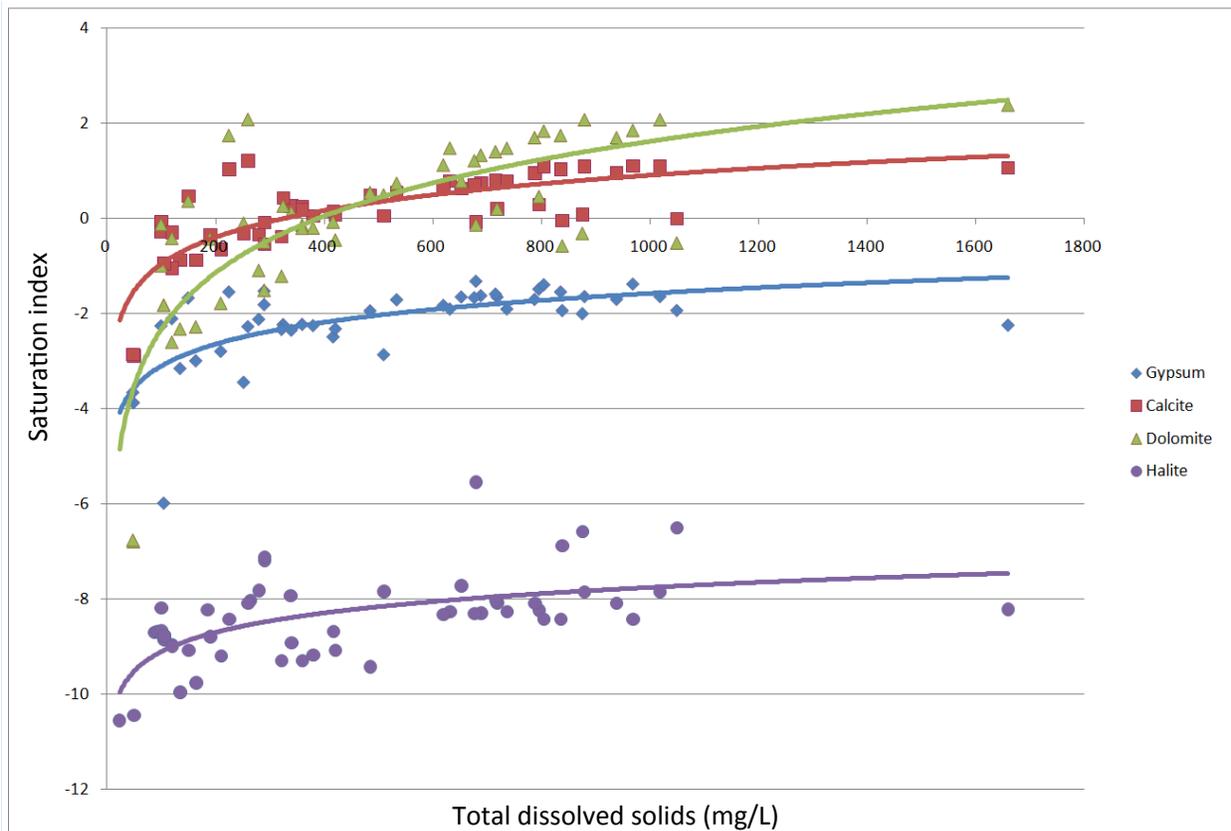


Figure 12. Plot of selected saturation indices against TDS

Temporally, certain trends were observed in a confined well in Rutland (well 1 in Figure 10) for which a record of 11 analyses over 25 years was available (Figure 13). Over time alkalinity, sodium, potassium and chloride increase. Increased sodium and chloride are a result of pumping in the confined aquifer inducing leakage of urban recharge affected groundwater from the unconfined aquifer.

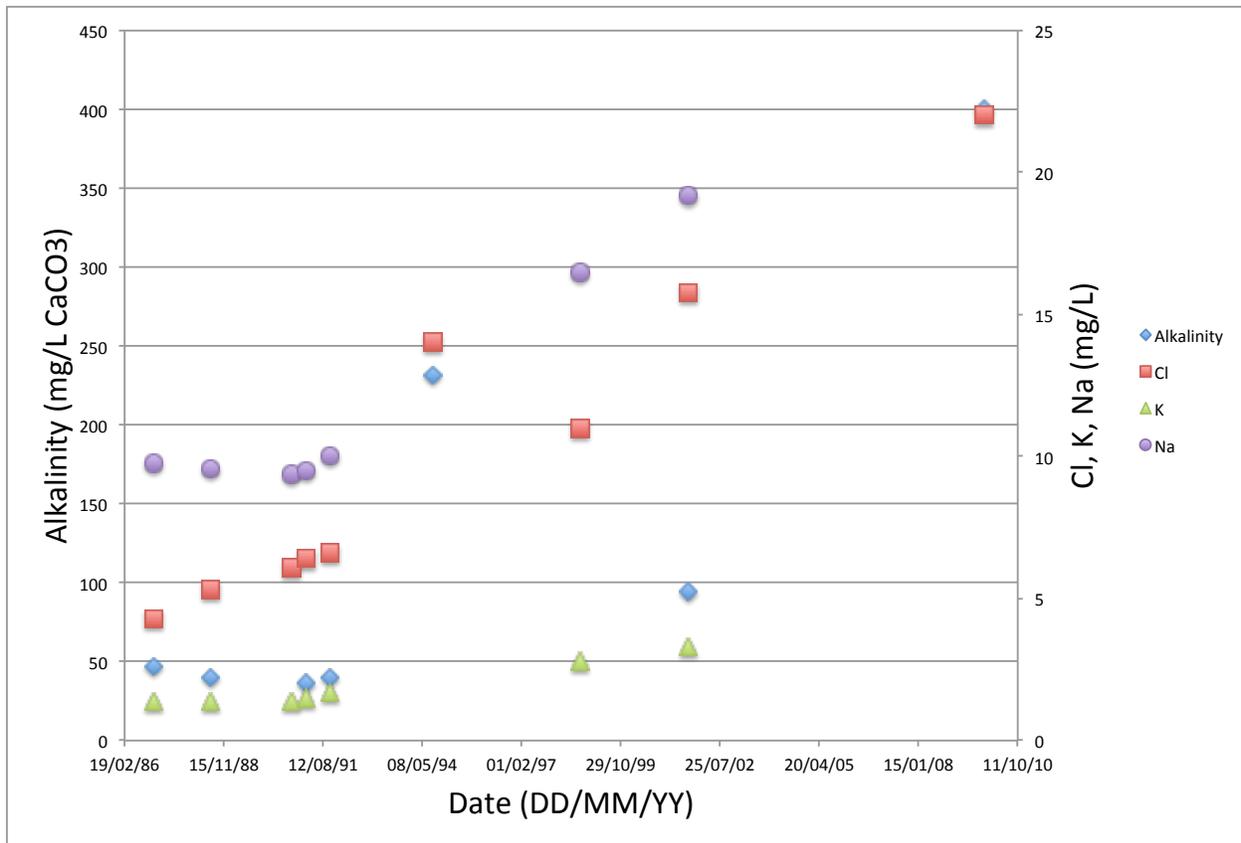


Figure 13. Variation in alkalinity, chloride, potassium and sodium in well 1 (Figure 10) over a period of 25 years

5) Discussion

Within the unconfined aquifer, high chloride exists in most wells (especially wells 44, 45, 47, 51 and 53 in Figure 10). This is consistent with the anticipated urban recharge signature. However, commonly accompanying sulphate from human and industrial waste is not elevated in most unconfined wells. This implies that the dominant processes in urban recharge are those that produce chloride but not sulphate, such as the dissolution of road salt. Chloride distribution in the unconfined aquifer does not correlate with distance from the lake, thus chloride concentrations are mostly a result of point source origin. There are insufficient geochemical analyses of other parameters commonly associated with urban recharge such as nitrate or faecal organics to incorporate these into this analysis.

In the confined aquifer, there is a visible trend away from calcium towards magnesium and sodium + potassium (Figure 11). Most of the samples on this trend are from wells located in Rutland (wells 1, 56, 57, 59, 60, 62 and 63 in Figure 10). Furthermore, the samples farther on the Mg / Na+K side of the trend (wells 1, 60 in Figure 10) are located farther upgradient (east) than those in the intermediate portion of the trend (wells 56, 57, 59, 62 and 63 in Figure 10) which are located further downgradient (west) in Rutland. This indicates that hydrogeochemical processes causing this trend are occurring primarily in the upgradient portion of Rutland and it is likely that they are returning towards equilibrium further downgradient.

If the trend towards sodium + potassium were a result of the dissolution of halite (NaCl) or leakage of urban recharge containing dissolved road salt, a roughly 1:1 ratio between sodium and chloride would be expected. A plot of sodium versus chloride

(Figure 14) shows that this is not the case. In all samples, there is an excess of sodium with respect to chloride, thus there must be another source of sodium within the system. This trend is commonly observed at freshwater - saltwater interfaces due to ion exchange sorbing calcium and dissolving sodium as in Equation 1 (Freeze and Cherry 1979). This increase in sodium and decrease in calcium concentrations is exactly what is occurring in the aquifer. In particular, the presence of disequilibrium indicated by the occurrence of ion exchange processes suggests that pumping by RWD's well field is driving this process.

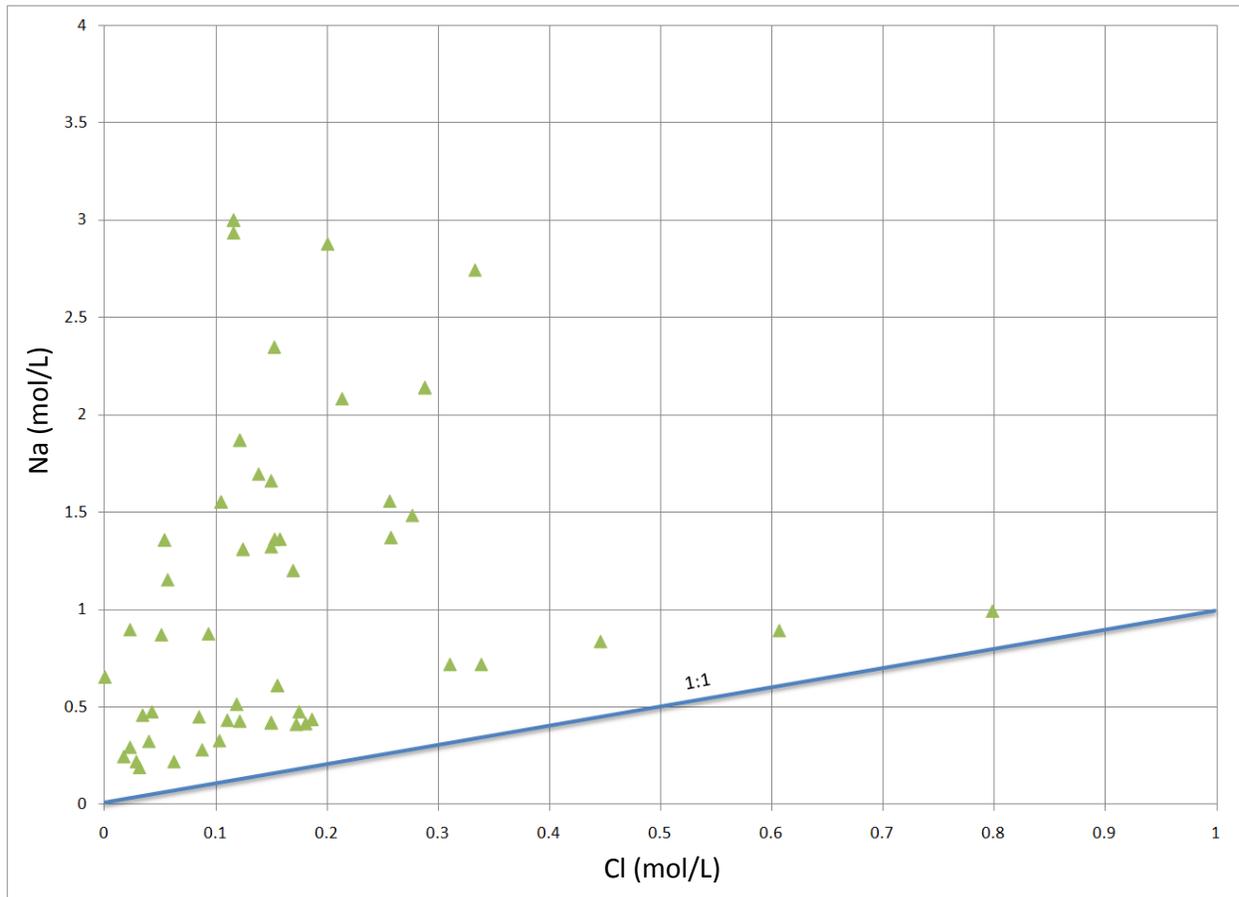


Figure 14. Plot of molar sodium versus molar chloride for confined aquifer samples

Samples in the confined aquifer also show a trend towards magnesium concurrent with the trend towards sodium + potassium. In order to increase dissolved magnesium and decrease dissolved calcium concentrations, the dolomite-calcite equilibrium reaction in Equation 2 must proceed forwards. This requires an excess of calcium from another source aside from calcite or dolomite.

Furthermore, a plot of Mg/Ca molar ratio versus sulphate (Figure 15) shows that the Mg/Ca ratio increases with increasing sulphate. This indicates that the excess calcium is likely provided by the dissolution of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or anhydrite (CaSO_4).

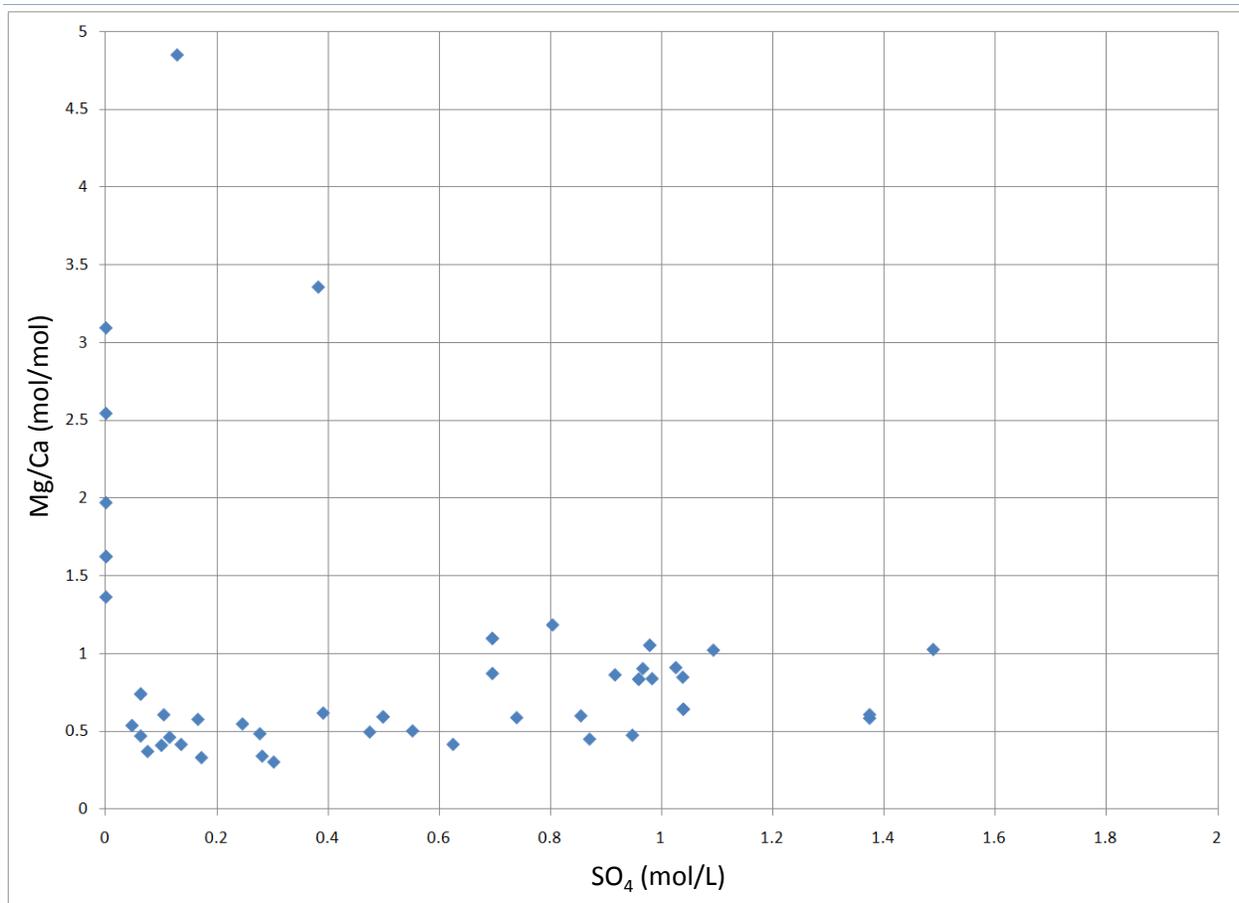


Figure 15. Plot of Mg/Ca molar ratio versus molar sulphate for confined aquifer samples

Gypsum or anhydrite could be expected to exist within the aquifer system from a variety of sources. The samples circled in Figure 15 exhibiting high Mg/Ca ratio with low sulphate can be discounted as they either have charge balance error >5% or have zero sulphate in a well that has always contained sulphate in appreciable amounts in other analyses, indicating likely transcription errors by the MOE in digitizing old analyses. It could have come from the Fraser Till as glaciers moved marine sedimentary rock containing evaporites into the Okanagan. Another likely source is the marl layer present within the Westwold Sediments (Figure 2). It is also possible that evaporation of waters in the arid Okanagan climate precipitated gypsum in paleosols.

As dissolution of gypsum proceeds, both dissolved calcium and sulphate concentrations increase. This increased calcium shifts the calcite-dolomite equilibrium (Equation 2) to the right, precipitating calcium in calcite and dissolved magnesium from dolomite. This has resulted in an increase in dissolved magnesium and a decrease in dissolved calcium as sulphate concentrations increase, consistent with the mechanism of dedolomitization.

Smerdon and Allen's (2009) modeling along with the presence of an area of artesian wells (Figure 4) show potential for vertical mixing within the aquifer system, subject to significant uncertainties. In this case, concentration gradients would be expected to exist from upgradient areas of no vertical mixing towards downgradient areas where vertical mixing was occurring. This is not the case as spatial analysis in ArcGIS has indicated that no such concentration gradients exist as anticipated. The presence of artesian conditions in the area around wells 15, 20, 22 and 42 in Figure 10 is also notably not accompanied by any significant change in hydrogeochemistry. This

indicates that localized processes are more significant in controlling hydrogeochemistry and suggests that vertical mixing between aquifers could be minimal. This also implies that the confining layer above the confined aquifer is non-leaky. Unfortunately, insufficient hydrogeochemical data is available near discharge which would enable mixing modeling to confirm these notions.

Along a NE-SW transect from Rutland perpendicular to Mission Creek shown in Figure 10, a gradient of decreasing dissolved species exists (wells 18,19, 23, 24, 26-30, 32-34 in Figure 10). Inverse mixing modeling of creek water and more distant groundwater performed in PHREEQC was incapable of yielding a chemical composition consistent with that observed in wells intermediate between the two endmembers. However, PHREEQC 1D geochemical transport modeling including ion exchange using the same well and creek hydrogeochemical data yielded intermediate compositions consistent with observations from intermediate wells, save for chloride (Table 5). Note that 0.0011 mol/L exchanger was used in this modeling as this is considered an average for a coarse sand similar to the aquifer materials in the Kelowna area (Appelo and Postma 2005).

	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Alkalinity (mg/L CaCO ₃)	SO ₄ ²⁻ (mg/L)	Cl ⁻ (mg/L)
Distal sample (well 29)	33.2	9.8	10.9	1.5	117	26.6	1.5
Mission Creek (at East Kelowna Road)	19.4	6.29	6.27	1.17	68.2	12.2	1.12
Modeled intermediate composition	21.54	6.70	6.95	1.22	74.2	13.2	1.17

	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Alkalinity (mg/L CaCO₃)	SO₄²⁻ (mg/L)	Cl⁻ (mg/L)
Observed intermediate sample (well 19)	22.3	6.27	6.4	n/a	75	11	3.1

Table 5. Input sample compositions, observed intermediate and modeled intermediate compositions from PHREEQC transport modeling with ion exchange

Natural groundwater – surface water mixing would have taken place historically and would have thus reached equilibrium. However, its inability to account for groundwater chemical composition near the creek indicates that is not the controlling factor in hydrogeochemical gradients along the creek. Rather, ion exchange processes that have only started recently and are still ongoing in modifying hydrogeochemistry are responsible. Recent development and use of RWD’s pumping well field is likely inducing recharge with generally lower dissolved species concentrations from Mission Creek to the aquifer for the first time, initiating ion exchange processes and thereby decreasing dissolved species concentrations within the aquifer near the creek.

However, the presence of significantly elevated chloride in the observed sample compared to the modeled sample suggests an urban recharge influence as well. As this urban recharge signature was not observed in the creek, it is likely coming from leakage from the unconfined aquifer. Thus, pumping of the confined aquifer by RWD is creating drawdown in the confined aquifer, driving leakage from the unconfined aquifer into the confined aquifer. In turn, this leakage is creating drawdown in the unconfined aquifer and inducing recharge from Mission Creek into the unconfined aquifer. Ion exchange

processes in the confining layer between the unconfined aquifer groundwater and the confined aquifer groundwater would be able to better explain this groundwater - surface water interrelationship.

6) Future Work

Bedrock groundwater characterization is limited by the small number of wells with publicly available hydrogeochemical analyses (Figure 10, Table 4). Greater well coverage of bedrock aquifers, especially in areas suspected of contributing mountain block or mountain front recharge to the unconsolidated aquifers, would help to better characterize the aquifer system's hydrogeochemistry.

With respect to the unconfined aquifer, well coverage is lesser than the confined aquifer. Most unconfined wells in the dataset are closer to Okanagan Lake than upland recharge areas and tend to cover Ellison, Glenmore and Central/South Kelowna (Figure 10). There are no wells screened in the unconfined aquifer with publicly available groundwater geochemical analyses in the Rutland and Mission areas. Wells (or analyses from existing wells) in these areas would be very useful in further assessing the processes controlling hydrogeochemistry in these areas, especially in response to the pumping well fields present. Furthermore, analyzing samples from the unconfined aquifer for a more complete suite of parameters including faecal organics, ammonium and phosphate amongst others would enable an improved characterization of urban recharge impacts.

Specifically, analyses from wells in the unconfined aquifer in Rutland near Mission Creek would be very useful in confirming whether the pumping well field is inducing recharge from Mission Creek or if it is inducing leakage from the unconfined aquifer. A more extensive groundwater - surface water study of Mission Creek expanding on Lowen and Letvak (1981)'s work would yield further insights in this area and remove uncertainties present due to short observation periods of existing data.

For the confined aquifer and generally the rest of the aquifer system, further physical modeling should be conducted in order to remove the uncertainties in all current work on vertical mixing. While some modeling was conducted by Smerdon and Allen (2009), this was done at a regional scale with simplified geology before Paradis et al. (2010) had completed their geophysical work in the area. Also, this modeling was conducted within a limited area, timeframe and budget. Thus, a larger modeling effort incorporating Paradis et al.'s (2010) geophysical work and considering the results of this research as well as other ongoing work would be essential to characterizing the hydrogeology of the Kelowna aquifer system.

7) Conclusions

Within the unconfined aquifer, the dominant process controlling major ion hydrogeochemistry is urban recharge. Urban recharge has dissolved many anthropogenic pollution sources including road salt, sewage, septic tank leakage and fertilizer. All of these contain chloride and are thus responsible for the elevated chloride observed in the unconfined aquifer.

In the confined aquifer, two dominant processes are evident in the major ion hydrogeochemistry. Interaction between groundwater and aquifer sediments is responsible for the increase in magnesium by the process of dedolomitization. Freshening ion exchange has resulted in the increase in sodium as fresher water infiltrates more saline water. Physical modeling and artesian conditions outline the potential for upwards vertical mixing near discharge at Okanagan Lake, however the limited groundwater chemistry in the area does not agree with this. Downwards vertical mixing as leakage from the unconfined aquifer to the confined aquifer is locally present in areas exhibiting urban recharge signatures in the confined aquifer, commonly caused by pumping drawdown.

Induced leakage from the upper unconfined aquifer to the lower confined aquifer, and groundwater - surface water interactions near Mission Creek are responsible for a decreasing gradient in dissolved species approaching the creek. PHREEQC modeling has indicated that ion exchange reactions are occurring between the groundwater and surface water, thus implicating recent changes in groundwater flow. RWD's recently installed pumping well field is thus inducing recharge from Mission Creek into the aquifer. Higher chloride in the observed sample than in the modeled sample suggests

that urban recharge affected water is entering the confined aquifer. As the creek water does not display such elevated chloride, it is likely that pumping of the confined aquifer is causing leakage from the urban recharge affected unconfined aquifer to in turn drive induced recharge of creek water into the aquifer system.

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