Linking upland water sources and valley bottom aquifers in a mountainous watershed

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ABSTRACT
Groundwater recharge was estimated for the BX Creek watershed in Okanagan Basin. Distributed infiltration was modelled for data-rich areas, and a simple water budget was used for data-limited areas. Recharge was 0-20 mm/yr at lower elevations and 20-50 mm/yr at higher elevations. A flow model for the mountainous watershed illustrated that 57% of the upland source water travels through an alluvial fan aquifer, and the remaining recharge to valley bottom is divided between bedrock flow (20%) and direct recharge (22%). Geochemical and isotopic data suggest that all groundwater have a common origin, and recharge to the alluvial aquifer may occur preferentially from spring melt.

RÉSUMÉ
La recharge en eau souterraine du bassin versant de l'Okanagan a été évaluée. L'infiltration a été modélisée pour des zones où des données complètes étaient disponibles, et un simple bilan d'eau a été considéré pour les zones où peu de données étaient disponibles. La recharge déterminée est de 0-20 mm/an aux plus faibles altitudes et de 20-50 mm/an à des altitudes plus élevées. Un modèle d'écoulement pour le bassin versant montagneux a montré que 57% de la source en eau des zones d'altitude voyage à travers un aquifère dans un cône de déjection, et la recharge restante destinée au fond de la vallée se divise entre un écoulement dans la roche mère (20%) et une recharge directe (22%). Des données géochimiques et isotopiques suggèrent que toutes les eaux souterraines ont une origine commune et que la recharge pour l'aquifère alluvial (cône de déjection) aurait lieu à partir de la fonte de printemps.

1 INTRODUCTION

Valley bottom aquifers in mountainous terrain form the principal groundwater resources for much of the western U.S. and Canada. Comprised of basin-fill sediments, these inter-mountain aquifers are recharged by three mechanisms: (i) seepage from mountain streams and rivers; (ii) groundwater flow from the adjacent mountain block; and, (iii) direct recharge to the valley bottom. A single mechanism may not characterize any given region, and the relative contribution of each method will depend on climatic and geologic conditions. However, understanding the linkage between upland water sources and aquifers is required to manage groundwater resources, especially in semi-arid and arid regions (Scanlon et al. 2006).

This study investigates the contribution of source water from mountainous uplands and direct precipitation to a valley bottom aquifer using a combined hydrological and geochemical approach. The study focuses on a watershed located in the north Okanagan Basin in British Columbia, Canada. Identifying the relative contributions of recharge to valley bottom aquifers is needed to assess groundwater resources in one of Canada's fastest growing and most water-limited regions. There is a wide range in data quality and quantity between the populated valley bottom area and un-populated upland area. Thus, groundwater recharge estimates were made by two different methods for each area (water balance and numerical model), and combined in a groundwater flow model of the entire watershed. Results helped elucidate upland to valley bottom connectivity, and were complimented by analyses of stream water and groundwater for major ions and stable isotopes of oxygen and hydrogen.

2 STUDY AREA

The BX Creek watershed (130 km^2) is located toward the north end of Okanagan Basin, near the City of Vernon, British Columbia (Figure 1). The Basin is characterized by a semi-arid continental climate, with an increase in atmospheric moisture from valley bottom to upland areas (Cohen et al. 2004). Average annual precipitation for Vernon is 410 mm and the average monthly air temperature varies from -4.2°C to 19.7°C (Canadian Climate Normals 1971 to 2000; Environment Canada 2006a).

The Okanagan Basin is also characterized by snowmelt-dominated upland catchments and dry valley bottoms. Seasonal surface runoff and peak streamflow occurs in May, and low-flow occurs late in the summer months. Upland bedrock areas are fractured, and the specific hydraulic relationship between surface runoff from headwater catchments and groundwater recharge has yet to be quantified. Mid-elevation, benchland areas coincide with the mountain-to-valley transition, where stream seepage losses recharge groundwater.

The headwaters of BX Creek are located at Silverstar Mountain, which drains to Swan Lake, and which in turn discharges to Okanagan Lake. Bedrock is generally exposed at elevations greater than 500 m, and is comprised of argillaceous limestone, slate, and meta-siltstone and sandstone, and volcanics (Fulton 1975). The Swan Lake Valley has filled with unconsolidated sediments from various fluvial, glaciolacustrine, and alluvial processes, forming stratified clays and silts, and un-stratified sands and gravel deposits (Nasmith 1962).

3 METHODS

The relative contribution of water sources were quantified for the Swan Lake Valley, considering all three of the recharge mechanisms (i.e., stream seepage, bedrock groundwater flow, and direct recharge). Geologic, soil, and climatic data were abundant for the Vernon area, and supported development of a distributed model of evapotranspiration and groundwater recharge that considers overland flow and infiltration through the unsaturated zone (MIKE-SHE model domain; Figure 1). Similar data were sparse for the upland areas, so recharge was estimated from a more simplified water budget approach (upland water budget domain shown in Figure 1). The recharge estimates were combined in a groundwater flow model of the entire mountainous watershed (Figure 1), and the resulting distribution of groundwater hydraulic heads and base flow to BX Creek were compared to available data. This approach utilized the difference in data availability to provide independent estimates of each recharge mechanism.

Surface and groundwater samples were collected throughout the BX Creek watershed and analysed for water chemistry and stable isotopes, with the objective of using these data to compliment and support the development of a conceptual model.

3.1 Valley Bottom Recharge Model

Groundwater recharge was simulated for the 1961 to 1990 period (30 years) on a 100 m by 100 m grid for the valley bottom area (Figure 1) with the MIKE-SHE code (DHI 2007). Two-dimensional overland flow was modelled by solving the diffusive wave approximation by finite-difference method, actual evapotranspiration was modelled by the Kristensen and Jensen (1975) method, and vertical unsaturated flow was modelled by Richards' equation for a static water table condition.

Ground surface topography was derived from 25 m horizontal resolution digital elevation data that was smoothed using a Spline algorithm, to the 100 m model grid. For the simulation of overland flow, Manning's n was assumed to be 0.3 for the entire landscape, and detention storage was set to 10 mm. Daily precipitation and temperature records were used (annual summary shown on Figure 2; Environment Canada 2006a), with a degree-day-factor of 2 mm/d/°C and threshold melt temperature of 0°C to approximate snowmelt.

Calculation of actual evapotranspiration (AET) required an estimate of potential evapotranspiration, leaf area index (LAI) and root zone depth. Potential evapotranspiration was calculated by the Thornthwaite (1948) method from average monthly air temperature. LAI was estimated from Fernandes et al. (2003) and peak values were generally found to be either 0.5 or 3.5 for the study area. LAI was assumed to increase linearly

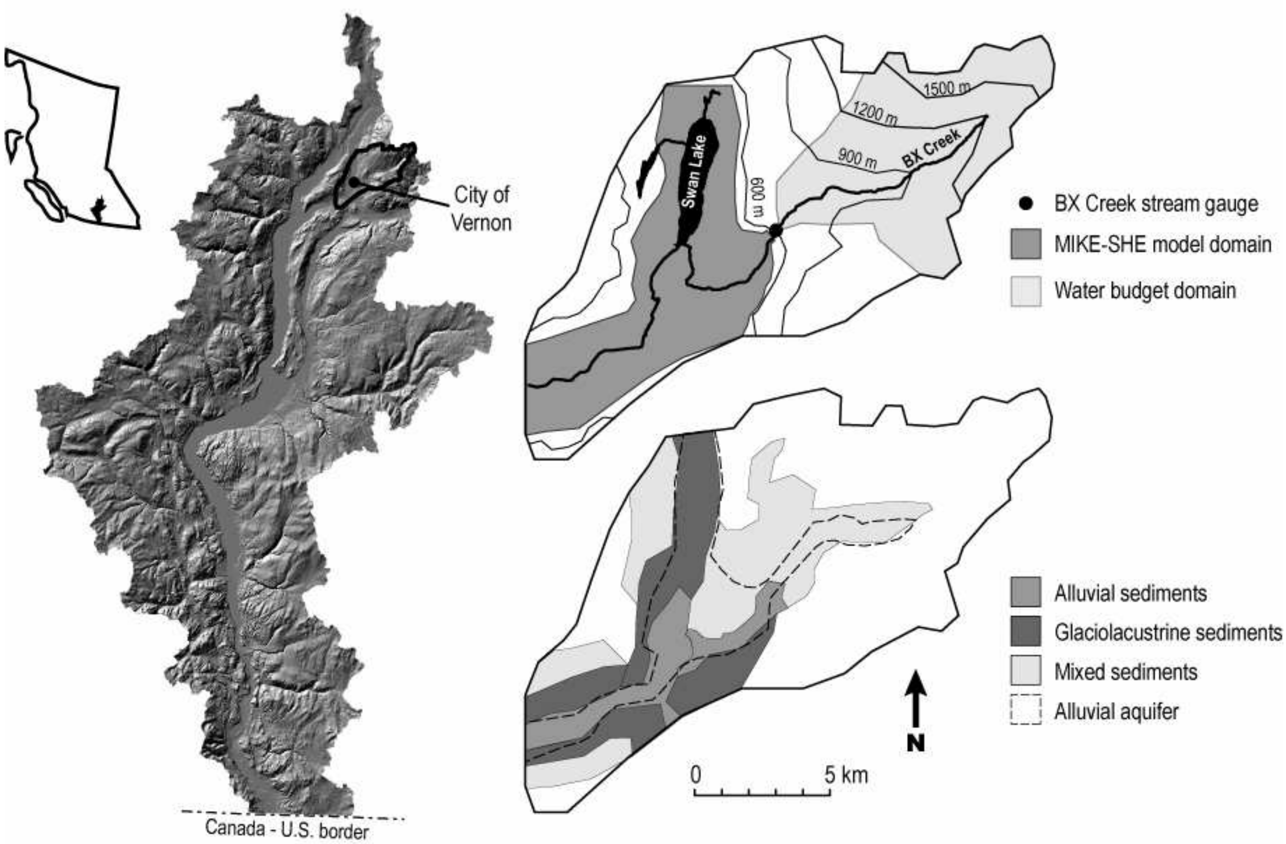

Figure 1. Location of BX Creek watershed with outline of model domains, stream gauge, spatial distribution of surficial geologic deposits, and alluvial aquifer. Elevation bands identified for upland water budget area (600 to >1500 m)

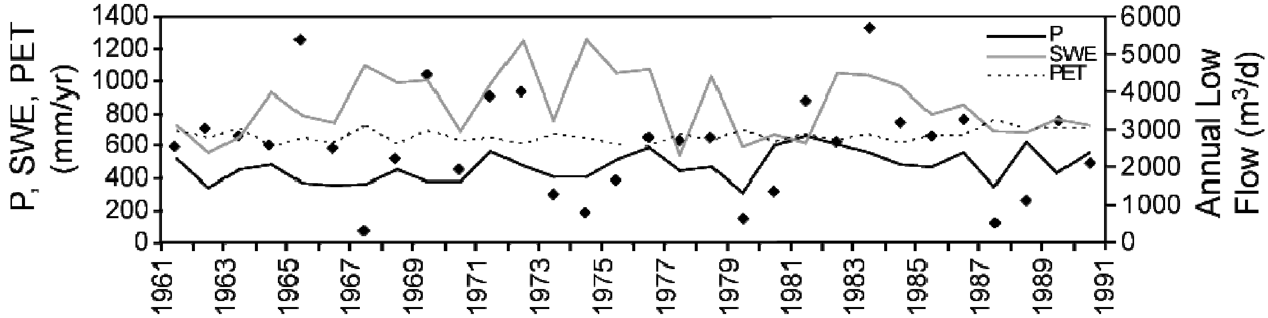

Figure 2. Annual summary of precipitation for Vernon (P), snow water equivalent for Silverstar Mountain (SWE), potential evapotranspiration (PET), and low flow for BX Creek (discrete data points).

throughout the growing season to these maximum values (Figure 3a). Rooting zone depths were assumed to be 500 mm for areas of little vegetation (i.e., urban), 1000 mm for recreational and some residential areas, and 2000 mm for agricultural and rangeland areas (Canadell et al. 1996). The combination of two LAI values and three possible rooting depths created a distribution of land cover properties for use in MIKE-SHE (Figure 3b).

The unsaturated zone module in MIKE-SHE calculated one-dimensional (vertical) flow for each 100 m by 100 m grid cell in the valley bottom area (for a total of 5455 1-D columns). Profiles were compiled from digital soils maps for the north Okanagan (Walmsley and Maynard 1987), and surficial geology maps (Nasmith 1962). Relationships for capillary pressure, water saturation, and relative permeability were assigned based on textural descriptions and corresponding hydraulic parameters (Carsel and Parrish 1988, data not shown). The lower boundary condition was a specified water table, interpolated from water well data from the BC WELLS database (MoE 2006) that were completed in valley fill sediments (Figure 4).

3.2 Upland Water Budget

For elevations above 500 m, soil survey, groundwater, and climatic data were sparse. Continuous stream discharge measurements were available from a gauging station on BX Creek maintained by the Water Survey of Canada (gauge 08NM020; Environment Canada 2006b), which is located at the margin of the valley bottom (Figure 1). To estimate the magnitude of groundwater recharge for the upland area, a seasonal water budget was developed for 4 month periods from 1961 to 1990 for the 52 km^2 topographic catchment area for the streamflow gauge on BX Creek. The water budget area was subdivided into elevation bands, and water budget components were defined for each band, interpolating between known values for the valley bottom (i.e., lowest band) and Silverstar Mountain (i.e., highest band). The water budget accounted for known inputs and outputs, using the following equation:

$$\pm r = P - ET - SW_{out} - GW_{pump} \qquad [1]$$

where P is precipitation, ET is actual evapotranspiration, SW_{out} is surface water discharge, and GW_{pump} is groundwater extracted from the alluvial aquifer in the vicinity of the stream gauge on BX Creek (Figure 1). The residual (r) represents the sum of errors and an estimate of groundwater recharge.

Snow survey data from Silverstar Mountain (site 2F10, 1840 masl) were reported from January to June (MoE 2007). These data include snowpack height and snow water equivalent (SWE; annual values shown in Figure 2), and are assumed to represent the majority of precipitation to uplands areas (Cohen et al. 2004). For the lowest elevation band (Figure 1), daily precipitation was summed at a monthly interval, and actual evapotranspiration results from the MIKE-SHE recharge model (described above) were used for the water budget.

Since insufficient climate data for estimating evapotranspiration in the upland areas were available, actual evapotranspiration rates were assumed to follow average rates measured and modelled (2002 to 2005) for the Upper Penticton Creek watershed (unpublished data from D. Spittlehouse, BC Ministry of Forests and Range).

Total groundwater extraction from the alluvial aquifer in the lowest portion of the upland water budget area was approximately 130,000 m^3/yr (Golder Associates 2006), which equates to less than 1 mm/yr for the entire water budget area.

3.3 Watershed-Scale Flow Model

To integrate the recharge estimates, and investigate the relative contributions of streambed seepage compared to subsurface flow through bedrock, a 3D steady-state flow model of the entire watershed was constructed (MODFLOW). The model area extends from the north end of Okanagan Lake to the peak of Silverstar Mountain (Figure 1), covering an elevation range of 350 to 1850 metres above sea level (masl), and is comprised of 50 x 50 m grid cells and 8 layers. Similar to the valley bottom recharge model, ground surface topography was derived from 25 m horizontal resolution digital elevation data that was smoothed using a Spline algorithm. The bottom of the model domain is set to 300 masl.

A conceptualized representation of hydrostratigraphic units (Figure 3) was developed from a combination of borehole log data (BC MoE 2006), distribution of surficial geologic deposits (Nasmith, 1962), and aquifers delineated according to the BC Aquifer Classification System (Berardinucci and Ronneseth 2002). Each hydrostratigraphic unit (Figure 1) was specified with a hydraulic conductivity value (K; Table 1) that was

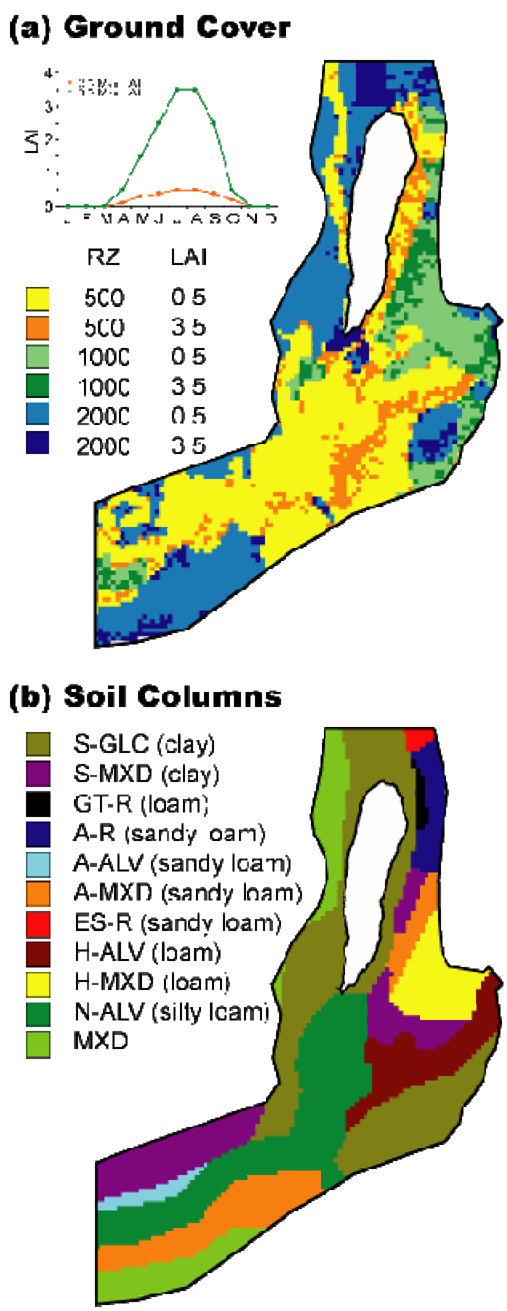

Figure 3. (a) Distribution of ground cover zones and associated root zone (RZ) and leaf area index (LAI). (b) Distribution of unsaturated zone columns (combined from soil survey and surficial geologic data)

reasonable for the geologic deposit (e.g., Carsel and Parrish 1988) and ratio of horizontal to vertical hydraulic conductivity (i.e., K_{xy}:K_z; Table 1). The K values and anisotropy ratio were adjusted slightly to better match steady-state hydraulic heads with water level records (BC MoE 2006).

With the exception of Okanagan the Swan Lake and Vernon Creek valleys, the lateral sides of the model area correspond to topographic divide, which was assumed to coincide with underlying groundwater divide and set as no-flow boundaries. Okanagan Lake and Swan Lake were defined as constant head boundary conditions of 345 m and 390 m, respectively. Creeks were defined using river, stream, and drain boundary conditions following the parameters listed on Table 1. Groundwater recharge was specified based on results from the valley bottom recharge model and upland water budget.

Table 1: Hydraulic conductivity of hydrostratigraphic units shown on Figure 1. Summary of boundary conditions for lakes and creeks in the groundwater flow model

Material	K (m/s)	K_{xy}:K_z
Alluvial sediments and aquifer	$1x10^{-5}$	10:1
Glaciolacustrine sediments	$7x10^{-7}$	50:1
Mixed sediments	$1x10^{-6}$	10:1
Bedrock	$4x10^{-8}$	1:1

Boundary	Boundary Condition	Value(s)
Swan Lake	constant head	390 m
Okanagan Lake	constant head	345 m
Coldstream valley	general head	395 m C = 0.012
Valley creek	river	1 m bgs width = 2 m Kbed = $1x10^{-7}$ m/s
BX Creek (below gauge)	stream	1 m bgs 1 m (H) x 3 m (W) roughness = 0.3 C = $1x10^{-5}$ m/s Qin = 2590 m^3/d
BX Creek (above gauge)	drain	1 m bgs
Upland creeks	drain	1 m bgs

C - conductance
bgs - below ground surface

3.4 Surface water and Groundwater Sampling

The motivation for sampling was to assess if geochemical proxies could be used to determine relative contributions of groundwater and surface water from different zones (i.e., highland, benchland, valley bottom) within the BX Creek watershed, and thereby provide an independent constraint to numerical modelling results.

Groundwater samples were collected from 26 wells, BX Creek, and Swan Lake in August 2005 and analysed for metals and major anions, and stable isotopes of oxygen and hydrogen in water at the Geological Survey of Canada laboratories in Ottawa and Quebec City. Due to increased development in the valley bottom area (i.e., unknown well locations, abandoned/destroyed wells), groundwater samples were only collected from the benchland and uppermost part of the watershed (Silverstar Mountain).

4 RESULTS AND DISCUSSION

4.1 Valley Bottom Recharge Model

For the 1961 to 1990 period, average annual AET varied from 489 to 634 mm/yr, with an average of 550 mm/yr. The majority of AET occurred in the spring (237 mm or 43%) and summer (301 mm or 55%) seasons, for the 4 month periods defined for the upland water budget. Since AET is a dominant hydrological process in semi-arid regions, the values calculated by MIKE-SHE were compared to measured values by the AAFC for an alfalfa crop study (1969 to 1973) in the Vernon area (Stevenson 1978). For the higher LAI areas in the valley bottom model (LAI of 3.5, comparable to an alfalfa crop), the AET calculated by MIKE-SHE for the 5 year period was 1% lower than measured in May, 9% higher than measured in June, 3% higher in July, 8% higher in August, and 28% higher in September. The general agreement between AET calculated by MIKE-SHE and the AAFC study suggest that AET is adequately represented in the valley bottom recharge model. Therefore, seasonal AET values (4 month periods) were considered accurate for the upland water budget, and the resulting groundwater recharge estimates modelled in MIKE-SHE to be realistic for the valley bottom.

For the 1961 to 1990 period, the spatial average groundwater recharge rate was 6.4 mm/yr (1.3% of average annual P). Average annual direct recharge varied from -8 mm/yr (i.e., an upwards flux of water, indicating absence of recharge conditions) to 135 mm/yr across the valley bottom (Figure 4, negative values set to 0). The maximum value (135 mm/yr) occurred in the few cells that were flooded, and further analysis revealed that only 21 model grid cells had recharge values greater than 40 mm/yr. Spatially distributed average recharge rates were grouped into 9 categories (Figure 4) and input to the groundwater flow model.

4.2 Upland Area Water Budget

The average water budget residual for winter, spring, and summer seasons was +40, +130, and -135 mm, respectively, where positive values indicate water surplus conditions and negative values indicate water deficit. The standard deviation (61 mm) and absolute range (+/- approximately 125 mm) were highest for the spring season, illustrating the sensitivity of water budget to annually variable snow accumulation. Annual water budget residual values varied from -117 to +156 mm/yr, with an overall average of 35 mm/yr for the 1961 to 1990 period (Figure 5a). For the water budget approach, the residual value includes the sum of errors and components not considered, which in this case would only be groundwater recharge. While a robust error analysis was not completed, we assume that the overall average value of 35 mm/yr represents a suitable first-order approximation for broad-scale recharge rate. Thus, 35 mm/yr was re-distributed for the upland areas, based on the elevation bands. Four recharge zones were input to the groundwater flow model (Figure 4), with values increasing from 20 to 50 mm/yr with increasing elevation.

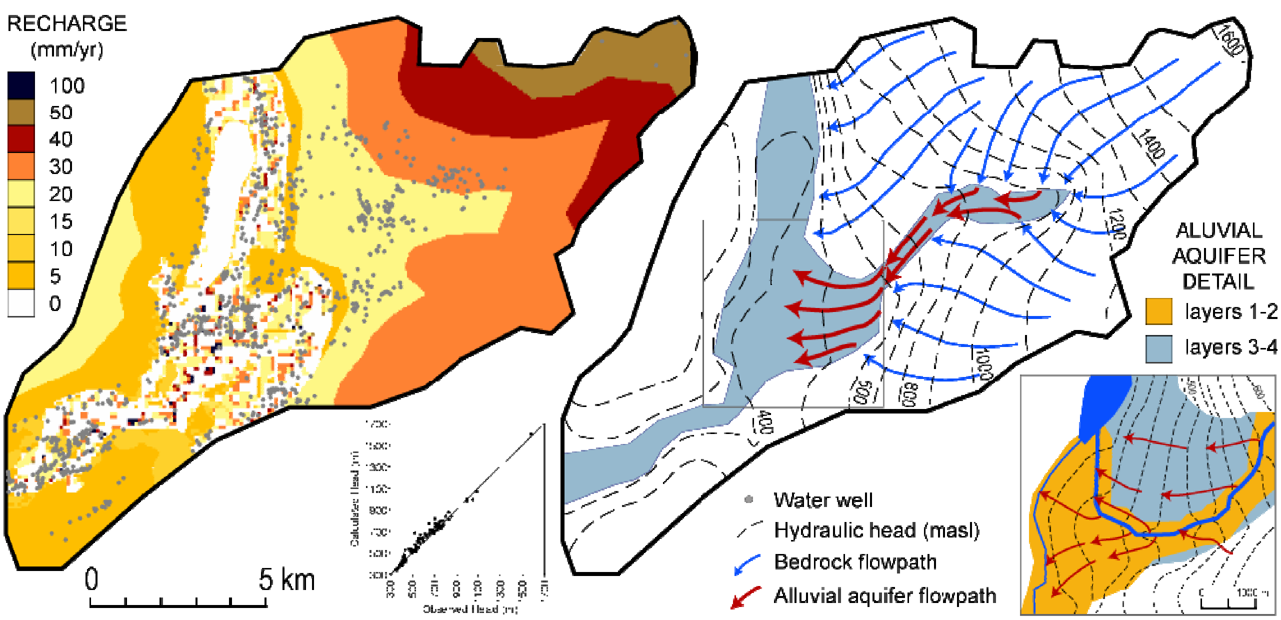

Figure 4. Distribution of annual groundwater recharge and contours of simulated hydraulic head (100 m interval). Simulated and observed hydraulic heads on left inset for 174 water wells. Simulated water table elevation (20 m interval) on right inset, to illustrate creek-aquifer interaction across the alluvial fan (represented by surficial sediments in layers 1-2 that overlie mapped aquifer in layers 3-4).

4.3 Groundwater Flow at the Watershed Scale

Simulated hydraulic heads appeared to follow topography (Figure 4), and were compared to water level data for 174 water wells from the BC WELLS Database (BC MoE 2006). The normalized root mean square error was 3.6% and the standard root mean square error was 44.6 m, indicating that hydraulic heads might represent the watershed-scale flow system, but may not be suitable for addressing finer-scale analyses.

Groundwater discharge for upland creeks, including the portion of BX Creek located above the stream gauge (implemented as drain boundary conditions) were compared to annual average low flow observed at the stream gauge. For the 1961 to 1990 period, the average low flow condition was 2590 m^3/day, and assumed to represent average base flow conditions for the upland creeks. Simulated groundwater discharge for the upland creeks was 2332 m^3/day, which is 90% of average low flow.

In this study, there was an absence of time-series groundwater data to develop a transient flow model. However, groundwater recharge rates were calculated a-priori to the flow model, the hydraulic heads and groundwater discharge flux rate compared well with measurements, and the K values are appropriate for the conceptual flow model. Thus, the groundwater flow model can be considered an adequate first-order approximation for quantifying recharge to the valley bottom aquifer.

The volumetric fluxes of groundwater passing through this narrow alluvial aquifer (red flowpath lines on Figure 4) were compared to groundwater recharging the valley bottom area through the surrounding bedrock deposits (blue flowpath lines on Figure 4). The volumetric groundwater flow rate for the narrow alluvial aquifer was 3127 m^3/day, compared to 1101 m^3/day for the surrounding bedrock deposits.

These findings suggest that the narrow alluvial aquifer, which leads to an alluvial fan in the valley bottom (Figure 4), supplies approximately 74% of the total groundwater flow to the valley bottom. The presence of the narrow alluvial aquifer and BX Creek valley across the benchland area, establishes a subsurface capture zone for upland groundwater.

At the base of the alluvial fan, BX Creek appeared to gain water, and the net rate of water loss for between the stream gauge and Swan Lake (location of stream boundary condition) was 64 m^3/d. Hydraulic head contours and flowpath arrows illustrate the potential surface water-groundwater exchanges that could occur across the alluvial fan (Figure 4), which will govern physical, chemical, and biological processes in the hyporheic zone.

4.4 Water Sources for Valley Bottom Aquifers

Groundwater flow to the valley bottom from the uplands occurred along the eastern boundary of the Swan Lake Valley, and either traveled through (a) the alluvial aquifer (3127 m^3/day, 74% of the subsurface flux), and (b) the adjacent bedrock deposits (1101 m^3/day, 26% of the subsurface flux). In addition to these subsurface pathways, direct groundwater recharge was found to be an average of 6.4 mm/yr for the valley bottom (1211 m^3/day). Therefore, recharge to the valley bottom aquifer is from a combination of subsurface groundwater flux from upland areas and direct recharge to the valley bottom (Figure 5b). The majority of water appears to flow through the alluvial fan, which would be derived from bedrock groundwater in the headwater of BX Creek (i.e., captured from the uppermost portion of the watershed), and seepage loss from streamflow occurring in the vicinity of the stream gauge.

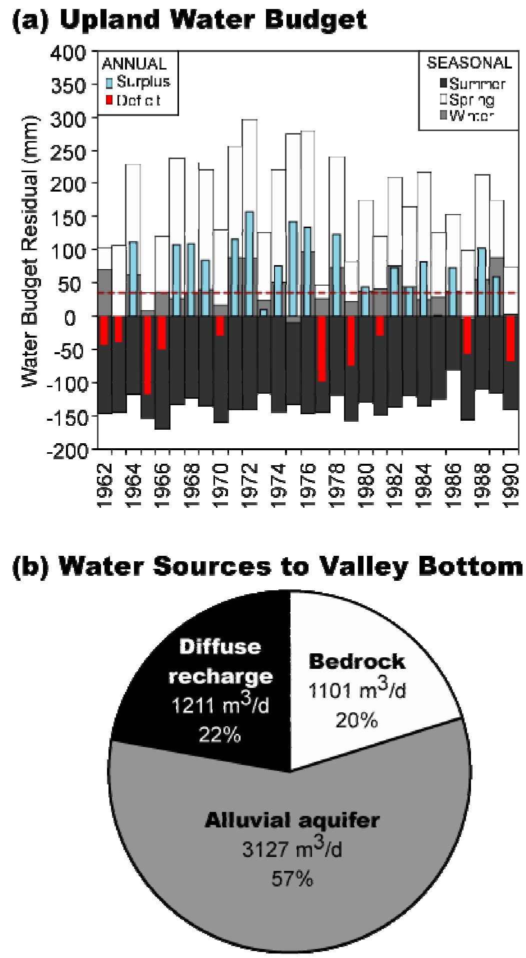

Figure 5. (a) Results of water budget calculation (residual) for 4 month seasonal (shaded grayscale bars) and annual periods (colour bars). Positive values indicate water surplus conditions for the period (season or annual), and negative values indicate water deficit. (b) Relative contribution of recharge to the valley bottom aquifer, calculated from the groundwater flow model mass balance report.

4.5 Isotopic and Geochemical Signatures of Waters

Since no groundwater samples could be collected from the valley bottom area (wells no longer accessible), it was not possible to determine contributions to valley bottom recharge using geochemical and isotopic techniques. However, stable isotope data reveal interesting results that relate to hydrologic processes in mountainous watersheds, and have been classified into three groups based on clear clusters in Figure 6a. We have also included isotopic results from groundwater sampling in the Upper Penticton Creek watershed (southern Okanagan Basin) for comparison and to aid interpretation.

Group 1 waters cluster at lower δ^{18}O and δ^{2}H values and are situated within the benchland alluvial aquifer. Group 2 waters cluster at slightly higher δ^{18}O and δ^{2}H, and are mostly derived from bedrock. Group 3 waters have the highest values, and show evidence of ^{18}O enrichment. Groundwater samples from bedrock wells (Group 2) have higher values than samples from the alluvium (Group 1). The bedrock wells are interpreted to have an isotopic signature that is close the mean annual isotopic signature of waters within the catchment. This average isotopic composition would correspond to the average isotopic composition of snow, since most recharge occurs during the snowmelt period. Group 3 water may either reflect evaporation (possible slope of 3.5 identified), or progressive enrichment of isotope concentrations due to progressive residual snow melt fraction

Fractionation processes during snow melt can significantly alter isotope values, with the first meltwater being more depleted relative to the original snow, and residual snowmelt becoming more enriched relative to the starting snow composition (Clark and Fritz 1997). This leads to a range in meltwater composition that would be reflected in the isotopic composition of any groundwater sampled at different times of the year. The bulk composition of the groundwater would likely correspond to the initial average snow composition. Data from Group 3 have higher values, possibly reflecting later remaining snowmelt water. Wells in the alluvium, having distinctly lower values, that are indicative of a different source recharge water, although the origin of this recharge water is unclear and cannot be discerned on the basis of the isotopic results. One possibility is that being at lower elevation than the headwater of BX Creek, the snowmelt period is quite short, and thus water in the alluvium represents this first meltwater composition that is more depleted than the remaining snowmelt at higher elevation.

Overall, the chemical results (Figure 6b) point to a general similarity between most samples in the watershed. There is evidence that the groups identified on the basis of isotopic compositions are similarly distinct in their chemical composition, although the evidence is not as strong. These results suggest that chemically and isotopically, it is possible to distinguish between groundwaters collected from bedrock and from alluvium in the watershed and, furthermore, that groundwater within the alluvial aquifers has a similar origin to groundwater in the bedrock aquifers.

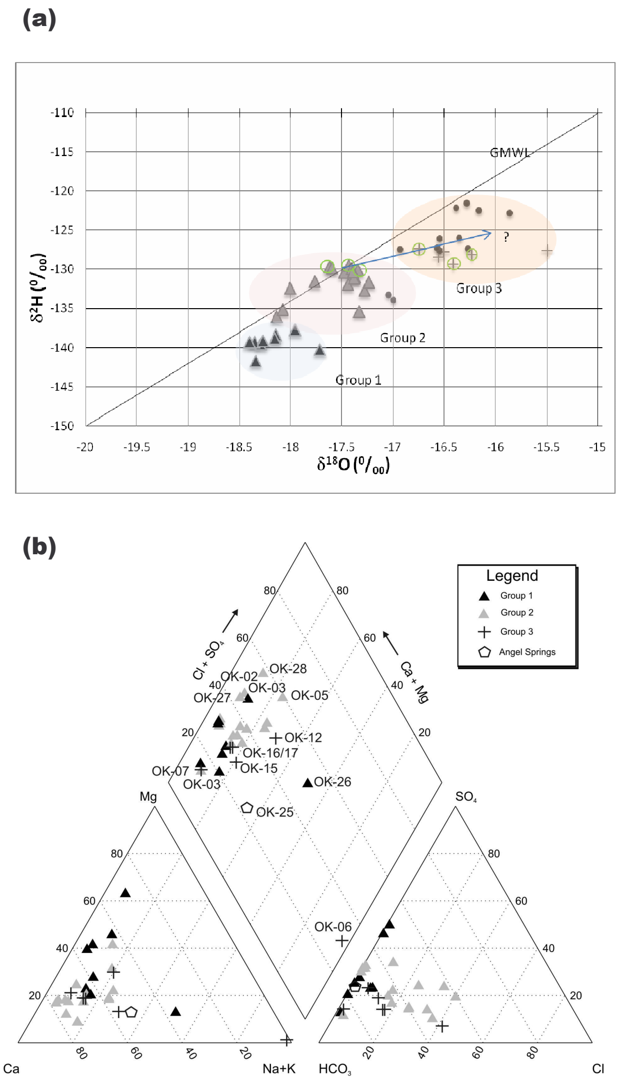

Figure 6. (a) Stable isotope results for δ^{18}O and δ^{2}H in water. Three groups are identified; Group 1: black triangles; Group 2: grey triangles; Group 3: plus signs; samples for the Penticton Creek Watershed in the Central Okanagan (solid dots). Circled in green are samples are surface waters in BX Creek Watershed. The global meteoric water line (GMWL) is shown for reference. (b) Piper plot showing major ion composition of groundwater and surface water. Selected samples identified. Compositionally, all waters are similar in BX Creek Watershed.

5 CONCLUSIONS

In this study, the linkage between upland water sources and valley bottom aquifers was evaluated for an entire mountainous watershed, which accounted for the distribution and abundance of available data. Actual evapotranspiration, unsaturated flow and the resulting groundwater recharge rates were modelled with the

MIKE-SHE code for data-rich areas, and recharge was calculated from a seasonal water budget for data-limited areas. The predicted recharge values for both areas were combined with realistic parameters and boundary conditions in a groundwater flow model, which was calibrated to steady-state hydraulic heads and upland creek base flow. Results of the modelling analyses indicate that recharge rates vary from 0 to 20 mm/yr in lower elevations of the watershed (6.4 mm/yr average), and approximate mean recharge of 35 mm/yr for higher elevations, which was assumed to follow an increasing rate with elevation (20 to 50 mm/yr).

The watershed scale flow model indicates that the majority of recharge (57%) to valley bottom aquifers occurs due to an alluvial fan and narrow aquifer that extend upward in the BX Creek valley. The remainder of recharge occurs nearly equally from lateral flow through the bedrock (20%) and directly to the valley bottom area (22%). The distribution of recharge rates and conceptualization of the geologic setting, generated an adequate first-order approximation of groundwater flow in the watershed when tested in a flow model.

Modelling results are supported by geochemical data, which suggest that water in the alluvial aquifer and bedrock are generally similar (i.e., common origin); however, the isotopic data also indicate that groundwater in the alluvial aquifer may occur from recharge at the onset of spring melt. Lack of groundwater samples from the valley bottom area, and more comprehensive isotopic data at varying elevation precludes more in-depth analysis or tighter integration with the modelling results.

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