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Results of Coupled Groundwater-Surface Water Model of the Cowichan Valley Watershed

Final Report

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June 2015

Executive Summary

The Cowichan Watershed Model (CWM) was designed to simulate the hydrological system in the region. The model was created using the numerical modelling code MIKE SHE which represents a fairly new generation of coupled land surface – subsurface codes. The CWM simulates all aspects of the hydrologic cycle including evapotranspiration, groundwater recharge and discharge, surface water (rivers and lakes) routing, groundwater – surface water interactions, and overland flow. The inclusion of all of these interactions is important given the hydrogeological complexity of the Cowichan Watershed. The mountain to coastal environment contains a high degree of coarse alluvial material, and when coupled with a steep topographical setting, the surface water and groundwater systems strongly interact.

Climate variations within the watershed (seasonal fluctuations and changes in the timing of rainfall events) create complex challenges for managing water in the watershed. The variability in seasonal rainfall is large; flooding conditions can occur in the winter, while drought conditions can prevail in the summer. Water demand puts added stress onto the hydrologic system, as peak demands for water often occur during the low flow season, when the river becomes the most sensitive ecologically. The overall aim of the study is to provide hydrologic information to help water managers with the long-term water management in the watershed.

The calibrated MIKE SHE model is used to assess groundwater recharge and discharge, estimate the contributions of groundwater to the surface water system, identify key gaining portions of the Cowichan River, evaluate the impact of localized pumping on the system, and project how future climate may affect the dynamics of the hydrogeological system (over next 40 and 70 years). The simulation results indicate a transition of the Cowichan River from mostly gaining within the valley, to losing near the coast where groundwater extraction is focused. Recharge across the watershed accounts for 17% of precipitation. Each large groundwater well in the lower valley is independently and collectively evaluated for its effect on flows within the Cowichan River. Climate change is projected to alter temperature and precipitation patterns, with the largest effects being noted on the snowpack (less snowpack accumulation in the high alpine within consequent alteration of the timing of snowmelt), and flows within the Cowichan River (higher winter and spring river discharge and lower summer flows).

Acknowledgements

Funding for this study was provided from a UBCM Gas Tax allocation through the Cowichan Valley Regional District and the Cowichan Watershed Board, and the Ministry of Forests, Lands and Natural Resource Operations.

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1. Introduction

The Cowichan research study is a combined collaboration of the MoE, FLNRO, and Simon Fraser University. The overall aim of this multifaceted project is to better understand the physical dynamics of the water resources within the watershed, with an emphasis on past, current, and future Cowichan River flow rates. The various studies were carried out at several scales, with the modelling effort being the largest. The modelling study used of measurements (e.g., instream flux) made at smaller scale by other team members.

The modelling study was carried out in two Phases. Phase 1 was part of Master of Science (MSc) research by Simon Foster and supervised by Diana Allen at Simon Fraser University. Phase 1 encompassed the development of the Cowichan Watershed Model (CWM) and the simulation of well and river capture zones as well as impacts of climate change. The research was supported through a research grant from the Cowichan Regional District. Phase 2 of the modelling was carried out to investigate various effects of pumping on streamflow depletion. Phase 2 was supported by the BC Ministry of Forests, Lands and Natural Resource Operations. This report summarizes the overall findings of the modelling study. Details concerning model development can be found in Foster (2014) and Foster and Allen (2015). Model outputs related to the climate changes simulations have been provided to Kerr Wood Leidal for ongoing hydrological work related to weir operation under future climate change conditions.

1.1. Why a Watershed Scale Numerical Model?

Numerical models are commonly used to gain insight into the dynamics of water flow in an area, and to measure the effects of an action (e.g. water use) on a system. Hydrologic models are used to simulate surface water processes and typically use a simplified representation of the groundwater system. In contrast, hydrogeological models simulate groundwater processes and use a simplified representation of the surface water system. Coupled groundwater – surface water systems, however, dynamically couple processes between the land surface and subsurface, and are particularly suited for simulating the interactions of groundwater with surface water, for example, along rivers or with lakes. Moreover, the newer generation of coupled land surface – subsurface models simulate a global water balance, showing the various exchanges that take place at the land surface (e.g., evapotranspiration) and between the unsaturated and saturated zones (e.g., groundwater recharge and discharge).

At the outset of this project, a decision was made by the research team to model various aspects of the hydrologic cycle at the "watershed scale." Watersheds located within a mountain to coast physiographic setting are unique in that they have been described as having a highly connected surface water and groundwater environment (Winter et al 1998). The high degree of coarse alluvial material, coupled with a steep topographic setting, creates conditions whereby the surface water and groundwater systems strongly interact. In regions where the climate is seasonally dry, the principal source of water within a stream is often from the discharge of groundwater (Winter et al 1998, Sear et al. 1999 and Sophocleous 2002). Streams, however, may also recharge the aquifer, particularly during the freshet (Scibek and Allen 2007). These relationships are often poorly understood aspects of the hydrology within a mountainous watershed. Water balances, including estimates of recharge and discharge, are also highly variable within this type of setting, especially since the climate gradient (heavy precipitation in the mountains to relatively low precipitation near the ocean) is both seasonally and spatially variable. As well, there is a high degree of geological variability (shallow or exposed bedrock near the crest of the valley, alluvium of variable thickness and composition within the valley). Management of water in such watersheds thus requires sound understanding of a range of hydrologic processes, and particularly those factors that influence the interaction of groundwater and surface water at a range of spatial and temporal scales (Winter et al. 1998, Woessner 2000 and Sophocleous 2002).

At the watershed scale, the model necessarily has coarse resolution (a large grid size); therefore, processes that take place at a local scale (within a few metres) are not captured in detail. However, the benefit of a watershed scale model is that the overall hydrologic cycle can be simulated, thereby providing insight into the key hydrologic processes as described above. In addition to developing the model itself, the study required the collection and synthesis of hydrologic information into the modelling framework. For example, estimates of the hydraulic parameters (hydraulic conductivity and specific storage) of the various hydrogeological units have been assembled, and spatial climate related datasets (e.g., potential evapotranspiration, temperature lapse rate, and the distribution of rainfall across the watershed) have been generated. The calibrated model is used to assess groundwater recharge and discharge, estimate the contributions of groundwater to the surface water system, identify key gaining portions of the Cowichan River, and evaluate the impact of localized pumping on the system. Lastly, the model is used to project how future climate may affect the dynamics of the hydrogeological system (over next 40 to 70 years).

1.2. The MIKE SHE Code

Based on the objective of the study and the availability of data, MIKE SHE (DHI 2007) was selected for modelling the hydrologic processes within the Cowichan Watershed. MIKE SHE is a deterministic and distributed modelling system that uses finite difference representations in mass and energy and measured empirical relationships to simulate aspects of the hydrologic cycle (Jaber and Shukla 2012). At its core is a framework of modules that are used to simulate the following processes: interception and evaporation, overland flow, unsaturated zone flow, and saturated zone flow. Rivers, lakes, and other channels are simulated in the one-dimensional model, MIKE 11, which is coupled directly to the MIKE SHE model. The interception and evaporation module computes the actual evapotranspiration (AET) from an area using user-defined potential evapotranspiration (PET), using the Kristensen and Jensen (1975) model. This model requires vegetation dependent parameters, such as leaf area index (LAI), root characteristics, and an interception parameter. Unsaturated flow is calculated in 1-D, vertically. A soil moisture retention curve, along with the saturated hydraulic conductivity, is defined for each soil class. Richards' equation is solved to direct water from the unsaturated to the saturated zone, or vice versa. The overland flow component simulates runoff when infiltration capacity of the soil is exceeded, when groundwater discharges to the surface, or when streams flood their banks. In this study, the flow solution utilized the diffusive wave approximation of the Saint-Venant equation, whereby topography, and the Manning's M coefficient control the direction and rate of runoff, respectively. The saturated zone flow component in MIKE SHE is 3-D and is based on Darcy's equation. Boundary conditions such as: fixed head, zero flux, gradient, and specified flux are options which control the flow of groundwater within the model. Subsurface conditions are modelled as layers and lenses, with representative hydraulic properties assigned.

As mentioned, MIKE 11 controls the routing of water in rivers and lakes. The rivers module comprises four main components: the river network, river cross-sections, boundary conditions, and hydrodynamic parameters. MIKE 11 solves channel flow through the use of a 1-D St. Venant equation based on the complete dynamic wave formulation (Thompson et al. 2004). MIKE SHE and MIKE 11 are coupled through the use of river links (h-points). During a simulation, the amount of water entering or exiting the linking cells is calculated based on Darcy's equation. Lateral inflows and outflow from overland flow as well as river-aquifer exchanges are completed for each computational time step (DHI 2007).

2. The Cowichan Watershed Model

This section provides a brief overview of the Cowichan Watershed Model (CWM). Detailed descriptions of the datasets (climate data, land surface data, unsaturated and saturated zone data, and the stream network and hydrometric data) and how these were input to the model are provided in Foster (2014, MSc Thesis) and Foster and Allen (2015).

2.1. Watershed Characteristics

The Cowichan Watershed is comprised of several catchments, covers an area of approximately 930 km^2, attains a maximum elevation of approximately 1483 metres above mean sea level (masl) in the headwater region to the west, and terminates at sea elevation near its eastern extent (Figure 2.1). Cowichan Lake has a surface area of 62 km^2 and stretches nearly 31 km from west to east. The Cowichan River flows from the headwaters at Cowichan Lake eastward for nearly 45 km to the estuary in Cowichan Bay near Duncan. Outflow of water from Cowichan Lake to Cowichan River from spring to early fall (April to October) is controlled by a weir. The weir serves to hold back water during the wet season such that the water can be discharged during the summer low flow period, maintaining discharge rates in the river.

The watershed is a vast valley with a large accumulation of valley fill sediments, flanked by valley walls with thin veneers of soil. The climate is temperate with cool and wet fall and winter seasons, while the spring and summer months are warm and typically much drier. There is strong precipitation gradient (decreasing to the east) due to a rain shadow effect. The lower coastal portion of the watershed receives half the amount of precipitation (~1,000 mm/year) than that received at Lake Cowichan (~2000 mm/year). It is estimated that the mountainous regions at the western boundary of this watershed can receive up to 4,500 mm of precipitation annually (Wang et al. 2012). Most precipitation occurs during the winter months, while very low amounts are measured in the summer months. At most, snow accounts for ~5-15% of the total precipitation.

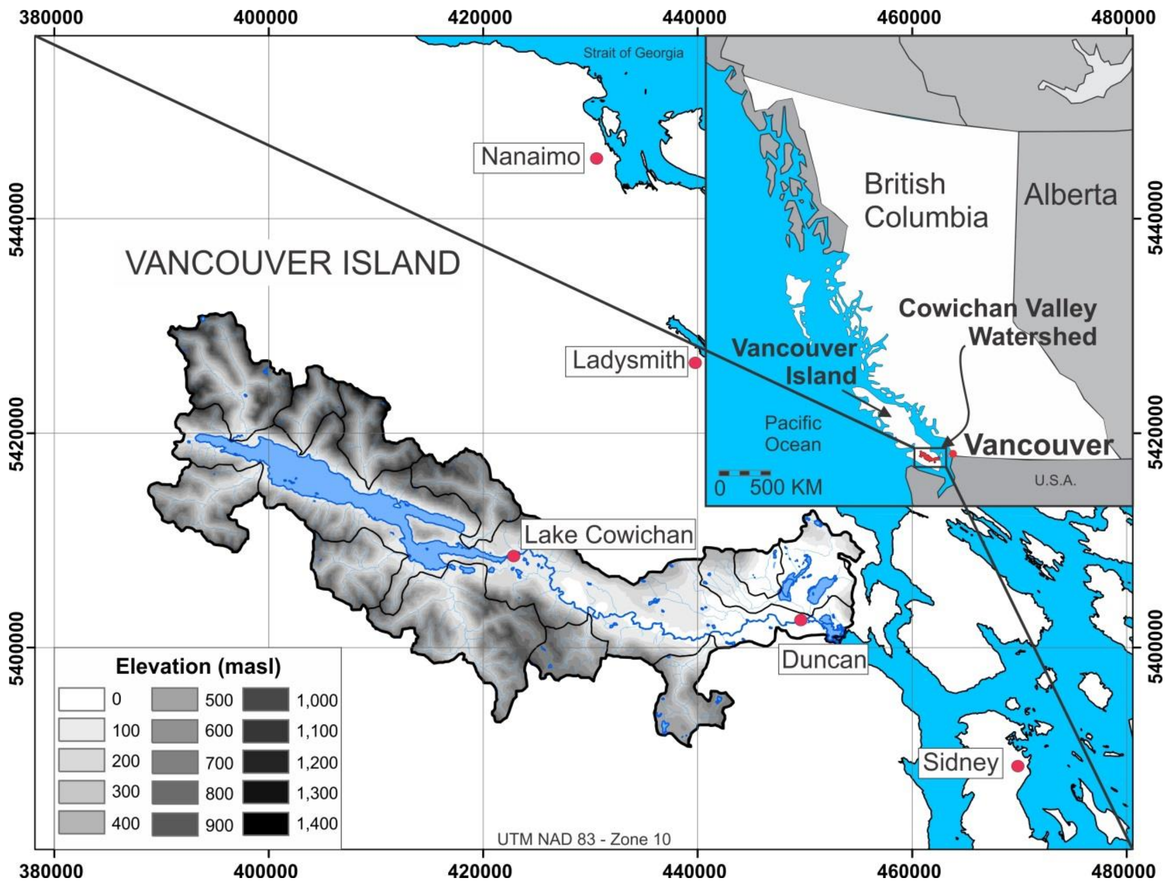

Figure 2.1. The Cowichan Watershed (from Foster and Allen 2015).

2.2. Model Setup

The model area consists of the entire Cowichan Watershed. The model grid size was 200 m by 200 m. Topography was assigned using a 200 m digital elevation model (DEM). The model boundary conditions consist of a zero flux boundary to represent the topographical extent of the watershed, and a specified head (sea level) within the alluvial layer where the model meets the ocean at Cowichan Bay. Underneath the alluvial layer, the bedrock layer is assigned as a zero flux. These boundary conditions attempt to mimic groundwater discharge in a coastal environment, whereby deep groundwater is directed upward when it intersects the freshwater-saltwater interface. Thus, any discharge from the bedrock will be directed upward to the surficial sediments and subsequently out of the model. The lake and river network was obtained from the BC Watershed Atlas (DataBC 2005). Lake and rivers were represented in 1D as single line segments, with the extent of the feature defined by the width of the cross-section. The weir on Lake Cowichan was not included in the model; therefore, naturalized flows are simulated. Once MIKE 11 is coupled with MIKE SHE, bed topography and the extent of Cowichan Lake are specified in detail (3D). Overall, the assigned boundary conditions route whatever precipitation falls onto the model domain out of the model along three potential pathways: evaporation, surface water termination at the ocean, and groundwater discharge upward along the coast and directly into the ocean.

To model the influence that large water users have on the groundwater and surface water levels within the Cowichan, the estimated extraction rates were included in the baseline model. Six large groundwater users and one large surface water user were included in the model (Figure 2.2). Large users of groundwater include three municipal water supply wells: the City of Duncan (2) and the Municipality of North Cowichan (1); and four fish hatchery operations: Vancouver Island Trout Hatchery, Cowichan River Hatchery, and Marine Harvest Canada. The Mainstream Canada Hatchery is located outside of the model boundary, and was not included within the model. Well-fields were modelled as single wells (per user). Due to limited data availability, and the large scale of the model (200 by 200 m cell size), this approach was appropriate.

The majority of the pumping occurs near the City of Duncan, clustered around the lower reaches of the Cowichan River (Figure 2.3). The estimated monthly extraction volumes for each of these users (Lapcevic et al. 2014) are summarized on Figure 2.4. The groundwater extraction rates for the municipal wells peak during the summer season, nearly doubling relative to the other seasons. The hatcheries generally have an opposite withdrawal schedule, with extraction rates doubling in the winter season compared to the summer season. The identified small and medium water groundwater users were not included in the model as most represent single domestic wells. These small domestic users of groundwater also likely have a septic system on the property (which recycles a large portion of the groundwater back to the ground), and therefore, the amount of water lost to the system is thought to be minimal.

Only one large user of surface water was included in the model. Catalyst Paper has an intake on the lower reach of the Cowichan River near Duncan and withdraws water directly from the river. The water leaves the watershed. An annual withdrawal of approximately 50 to 60 million m^3 is extracted annually at this location. To model this abstraction, a point-source inflow boundary condition was defined in MIKE 11 at the location of the intake. The inflow boundary condition was set to a maximum withdraw of -2 m^3/s for the entirety of the model simulation. This rate equates to the 63 million m^3 of water extracted annually. The paper company also operates the Cowichan Lake outflow weir, which serves to store an equal or greater amount of extracted surface water (see Figure 2.2 “total surface water storage”).

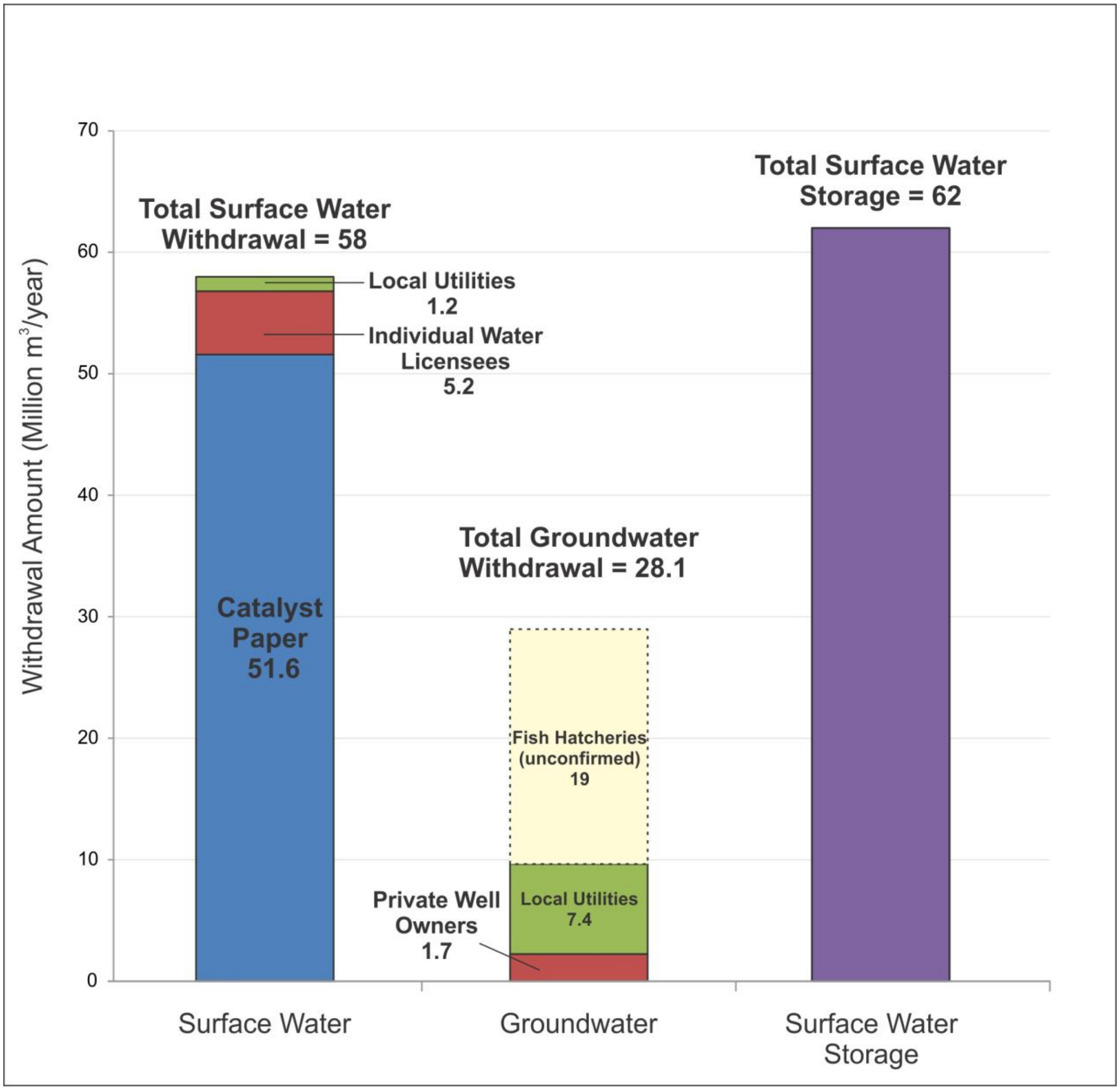

Figure 2.2. **Water use according to user group within the Cowichan Watershed (modified from Westland Resources Group 2005; Lapcevic et al. 2014).**

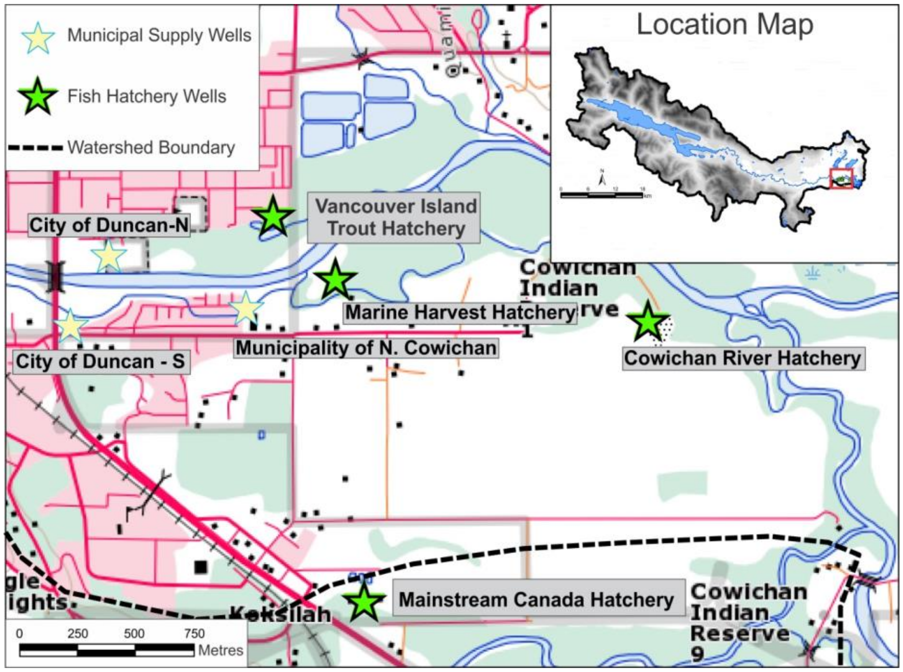

Figure 2.3. Location of the large groundwater users within the Cowichan Watershed.

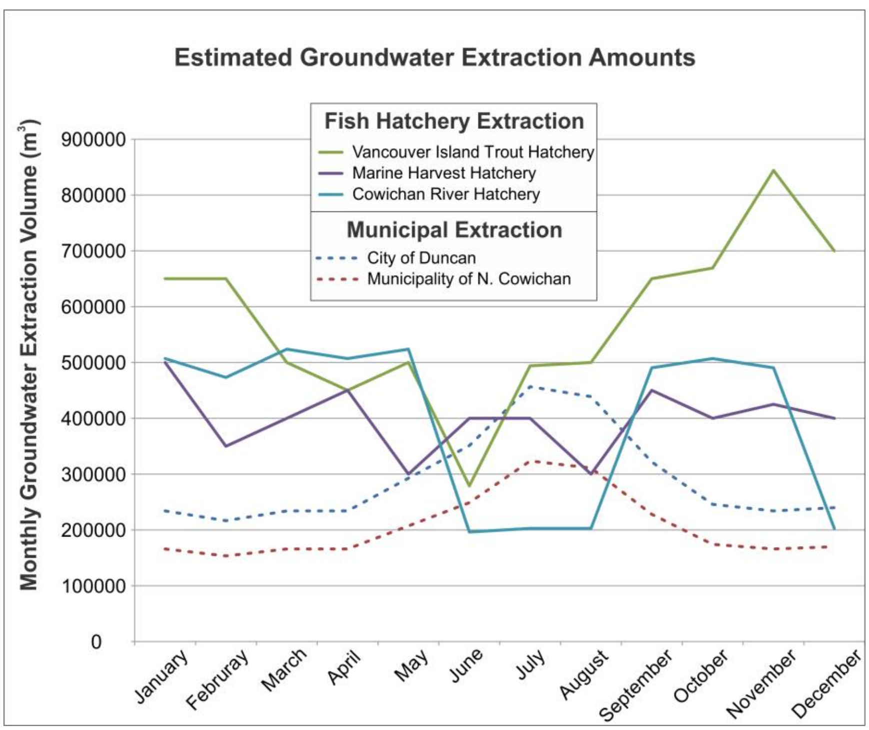

Figure 2.4. Modelled (estimated) groundwater extraction rates for large groundwater users.

The model was run for a period of 14 years (January 1st, 1998 to December 31st, 2012 – the latter being the most recent date of available data at the onset of this project). It was important to capture the year 2012, to illustrate the model's ability to simulate the anomalously low river discharge of the Cowichan River during the salmon spawning season and the timing of late summer rains in that year. The 14 year period was sufficient for the model to function properly, and to capture a range of climate conditions. For additional details see Foster (2014).

The model was calibrated using a variety of temporal and spatial datasets. Once calibrated, the model was used to explore:

- The global water balance;
- Spatial recharge and discharge;
- Groundwater – surface water interactions;
- How measured seepage compares with the model results;
- Well capture zones (for large users);
- Cowichan River capture zones;
- The effect of pumping rate on streamflow depletion;
- Well distance versus streamflow depletion; and
- Climate change impacts.

3. Cowichan Watershed Modelling Results

3.1. Model Calibration and Validation

The calibration period was 2002–2010 (8 years) and the validation period (data withheld from calibration) was 2010 to 2012.

Model calibration first focused on the climatic conditions (snowmelt modelling). Snowmelt calibration consisted of adjusting model parameters including degree day coefficient, temperature lapse rate, and the max wet snow fraction. Each parameter affected the simulated timing (onset and release of snow) and the amount of snow accumulation. Mean daily temperatures measured at the Jump Creek Snow Pillow Station were used to calibrate the temperature lapse. The snow water equivalent (SWE) recorded at the climate station was used calibrate the amount of water held in snow storage in the alpine regions. The snowmelt calibration fit statistics are given in Table 3.1.

The next phase of calibration included comparing the measured stage and discharge from MIKE 11 to observed lake level and hydrometric data. The Water Survey of Canada (WSC) maintains three stations within watershed, measuring Cowichan Lake levels (08HA009), Cowichan River stage/discharge near the junction of Cowichan Lake to Cowichan River (08HA002), and the stage/discharge of the Cowichan River near Duncan (08HA011). These stations have continuous recorders that record the data in daily time steps and are available in real time. The period of record of this dataset varies from 53 years (08HA011) to 90 years (08HA002). The lake level and discharge calibration fit statistics are given in Table 3.1. Peak lake level values were frequently overestimated, while lake levels during the summer were consistently below (~0.5 m) observed values. The difference between the simulated and observed Cowichan Lake stage levels can be attributed to the model not including the actual weir system present between the lake and river. During the spring season, the weir often holds back a large quantity of water (raising the stage of the lake significantly at this time), such that the stored water can be made available later in the summer when the river flows are low. Thus, during the spring, the lake levels are over-predicted, and then under-predicted in the summer.

The final phase of calibration consisted of comparing simulated groundwater levels to observed groundwater levels within the region, while still evaluating the hydrometric calibration. A major limitation of this phase of the calibration is the lack of long observation datasets that monitor groundwater fluctuations within the Cowichan Region. Several long series datasets are available; however, all are in close proximity to one another near the town of Duncan, and within Aquifer 186. Therefore, transient model calibration used only the hourly data from the Ministry of Environment (MOE) observation well (OBS) #204 within aquifer 186, which has the longest period of record. The available data span from approximately June 2003 to December 2010 (truncated calibration period). The validation period extended from January 2011 to August 2012. The groundwater level calibration fit statistics are given in Table 3.1.

A spatial comparison between the simulated GW elevations and the static water levels from the BC WELLS database was also made. Static water levels are measured at the end of drilling, and while they can underestimate the natural groundwater level due to slow recovery following drilling, particularly in bedrock wells, these static groundwater levels provide a regional dataset for calibration. The comparison was completed by first averaging the simulated GW elevation results for the year 2007 (a quality GW calibration year) in MIKE SHE. The second step consisted of extracting the depth to static water level within the WELLS database for all wells located within the watershed. From the available data, the information was then filtered by both well completion geology (unconsolidated and bedrock) and the predominant aquifer that the well is situated in (alluvial aquifer, or bedrock aquifer). This step focuses the comparison for wells that are completed within unconsolidated material, in an unconsolidated aquifer area, and conversely, wells that are completed in bedrock, that is, in a bedrock aquifer area. The elevation of the static water level was computed by subtracting the depth to water from the surface elevation. The results of the comparison of alluvial and bedrock static water elevations are illustrated on Figures 3.1 and 3.2 respectively. Correlation statistics such as R^2, RMSE, and ME are illustrated on each Figure.

Table 3.1. Calibration results.

Calibration Station	Data Type	ME	MAE	RMSE	STDEV Residuals	R-Correlation	Nash-Sutcliffe
Jump Creek Snow Pillow Station	Snow water equivalent (mm)	112.27	162.60	297.45	275.49	0.92	0.80
Alpine Temperature at Jump Creek	Air temperature (°C)	-0.66	2.25	2.93	2.85	0.91	0.81
08HA009 Cowichan Lake	Water level (Stage masl)	0.061	0.57	0.64	0.63	0.83	-0.63
08HA002 Cowichan River	Discharge (m^3/s)	8.59	11.93	20.55	18.67	0.91	0.79
08HA011 Cowichan River	Discharge (m^3/s)	15.95	19.56	32.59	28.42	0.89	0.72
Observation Well #204 - Aquifer 186	Shallow GW Water level (masl)	0.0025	0.24	0.31	0.31	0.86	0.74

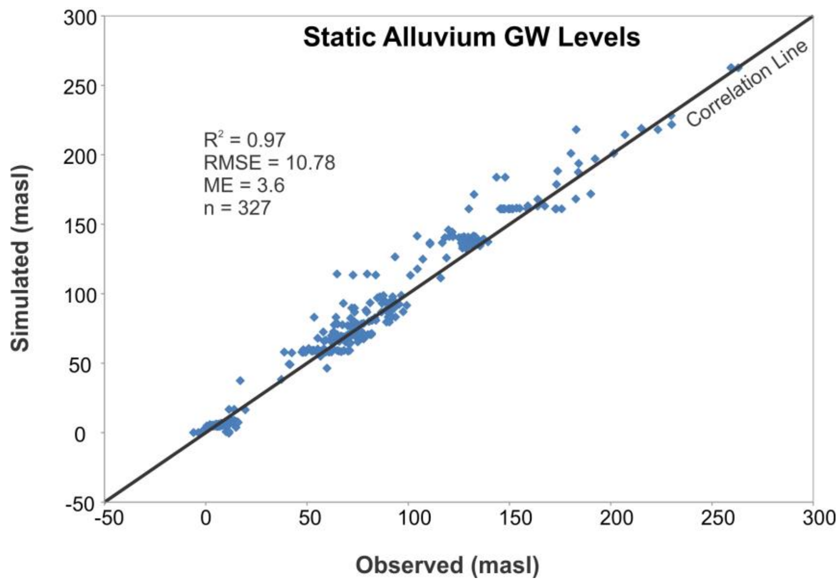

Figure 3.1. **Simulated mean annual (2007) alluvial GW elevations verses observed static GW elevations in the alluvium from the BC WELLS database.**

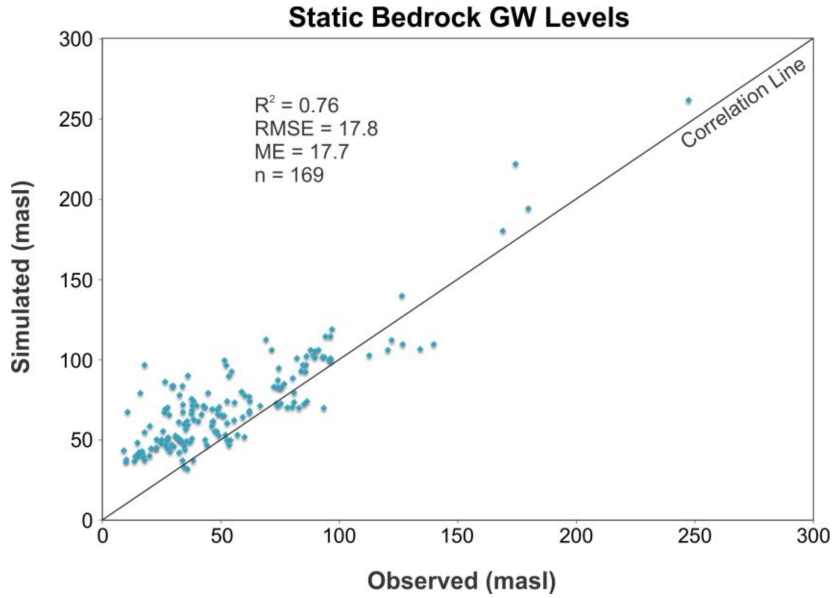

Figure 3.2. Simulated mean annual (2007) bedrock GW elevations verses observed static GW elevations in bedrock from the BC WELLS database.

3.2. Water Balance

A water balance extraction was performed following calibration. Options for extraction include seasonal, yearly, or by sub-catchment (by cell or entire catchment). Of interest to this study are the overall exchanges of water between different parts of the model (e.g. between the river and groundwater), the amount of recharge to the saturation zone, and the effect of pumping on the hydrologic system.

The total input of water to the model occurs solely as precipitation (100% in input). Water is then partitioned (runoff or overland flow, infiltration or recharge to saturated zone, evaporation) and leaves the model through evaporation, boundary flow from the saturated zone into the ocean, river boundary flow to ocean, surface water extraction, or groundwater extraction, with some water in various stores at any one time (e.g., snow storage, canopy storage overland storage, subsurface storage, etc.). The overall watershed water balance is:

$$P - ET \pm \Delta Snow\ Storage - OL\ Flow\ to\ River \pm \Delta OL\ Storage - OL\ Boundary\ Outflow \\ - Baseflow\ to\ River + River\ to\ Baseflow \pm \Delta Subsurface\ Storage \\ - Subsurface\ Boundary\ Outflow - Pumping \pm Model\ Error \quad (3.1)$$

Table 3.2 reports the total water balance for the Cowichan Region including error (mm/year). Results are reported for a water year (October 1 to September 30). Recharge is shown in the last column as a separate item. Recharge is computed from the exchange between the unsaturated zone and the saturated zone, and therefore, does not appear in the overall water balance for the watershed.

Table 3.2. Simulated total water balance for each water year (WY) and yearly averages (mm/yr).

Year	P	ET	Snow-Storage Change	OL - Flow to River	OL Storage Change	OL-BF	Base-flow to River	River to Base-flow	SZ-Storage change	SZ-BF	Pump	Total Error	R
WY-02-03	2563	-1061	0	-1458	-1	-71	-57	59	113	0	-24	62	371
WY-03-04	2804	-1187	0	-1465	-6	-71	-60	59	-58	0	-24	-10	582
WY-04-05	2484	-1207	0	-1355	-1	-66	-56	59	129	0	-24	-37	417
WY-05-06	2594	-1151	0	-1487	0	-73	-56	60	124	0	-24	-14	411
WY-06-07	3490	-1167	0	-2071	-16	-100	-69	64	-77	0	-24	31	630
WY-07-08	2393	-1161	0	-1336	10	-66	-62	60	153	0	-24	-32	385
WY-08-09	1504	-1081	0	-546	3	-34	-46	49	134	0	-24	-42	253
WY-09-10	2950	-1142	0	-1608	-7	-83	-67	58	-55	0	-24	20	539
WY-10-11	2794	-1100	0	-1631	2	-83	-68	59	61	0	-24	9	431
WY-11-12	2349	-1009	0	-1424	2	-72	-63	59	188	0	-24	6	357
Yearly Avg.	2593	-1127	0	-1438	-1	-72	-61	59	71	0	-24	-1	438
Water (%)	**100**	**-43**	**0**	**-55**	**0**	**-3**	**-2**	**2**	**3**	**0**	**-1**	**0**	**17**

P=Precipitation; ET=Evapotranspiration; OL=Overland Flow; UZ=Unsaturated Zone; BF=Boundary Flow; SZ=Saturated Zone; R=Recharge

The water balance results must be examined carefully because there are numerous exchanges that take place. Therefore, the annual percentages do not add up. Overland flow to river (Cowichan River) and ET are the dominant fluxes of water within the Cowichan, constituting 55 and 43%, respectively, of the annual budget water budget. ET is lost from the watershed; however, overland flow to river may at other points in the watershed contribute to groundwater (through the river to baseflow component), and perhaps return to the river downstream (baseflow to river). Thus, these terms are linked, and likely elevate the overland flow to river component. Another reason why overland flow to river may be elevated is because only the Cowichan River was included in the model; therefore, processes such as channel flow from tributaries, and any groundwater discharge associated with the channels is incorporated in this number. The baseflow (groundwater) to river and river to baseflow (groundwater) represent exchange flows between the MIKE SHE and MIKE 11 models. These exchanges take place at h-points within the river/grid domain. The water balance results suggest that the Cowichan River is approximately equal in the amount of water the river loses and gains throughout its length. This relationship is very consistent throughout each water year period. The spatial representation of this relationship is explained in detail in Section 3.4. Small negative and positive values are reported for changes in overland flow and snow storage, while 3% of the average annual budget is accounted for by storage changes in the saturated zone. Over the long term, unless the saturated zone is being depleted, this should be zero. The amount of water pumped from the major groundwater users in the lower valley accounts for less than 1% of the total water balance. The average error associated with the convergence of processes in the model was approximately 1% over the calibration and validation periods of the model.

Based on the detailed saturated zone water balance (not shown), annual recharge (determined as the amount of water exchanged from the unsaturated to the saturated zone) is 438 mm/yr, or 17% of the annual precipitation (last column in Table 3.2). This amount is determined from a yearly average over the calibration and validation period (2002-2012). During this period, the amount of recharge to groundwater varies (253–630 mm/yr) accordingly with yearly variations in precipitation. Taking into account the total variation in precipitation, recharge to groundwater ranges from 14 to 21% of the total annual (WY) precipitation. Hydrogeological studies within the Cowichan watershed, or in close proximity (Lowen 1994, Kreye et al. 1996, EBA 2006) have estimated recharge rates to be from 23 to 45% of annual precipitation.

However, these recharge rates reflect recharge to individual unconsolidated sand and gravel aquifers, rather than the net recharge across the entire watershed (including low conductivity bedrock valley walls) (Worley Parsons 2009).

Table 3.3 reports the water balance for the Cowichan Region as mean monthly values. This format illustrates temporal changes on a monthly basis, indicating the critical months that contribute the most to the yearly values reported above. Of note, precipitation ranges from 33 to 467 mm/month, and is highest in November to January, and lowest in June through September. ET ranges from 52 to 148 mm/month, with peaks occurring in May through August, and lows from October to February. The temporal variation in exchanges with surface water and groundwater mimic closely precipitation variations. Groundwater entering the Cowichan River dominantly occurs from December to May (6-7 mm/month) and is slightly lower (3-4 mm/month) from June to November. The exchange from surface water to groundwater follows a similar trend.

Recharge varies significantly throughout the year. The highest recharge occurs in October and November (> 100 mm/month), while a recharge deficit (P-ET) is indicated in the months of June, July and August, with peak deficits at -28 mm/month (loss of water from the saturated zone to the unsaturated zone). This deficit is not only evident in recharge, but also when comparing ET to precipitation over that same time period. In the month of May, negative moisture conditions are shown (ET being greater than incoming precipitation); however, recharge is still positive. These results likely reflect the effect of the melting snowpack in the alpine. As the snow melts, it infiltrates the unsaturated zone and eventually reaches the saturated zone.

Table 3.3. Simulated mean monthly water balance results (2002-2012) (mm/month).

Mean Monthly	P	ET	Snow-Storage Change	OL - Flow to River	OL Storage change	OL-BF	Base-flow to River	River to Base-flow	SZ-Storage change	SZ-BF	Pump	Total Error	R
Jan	458	-59	-16	-333	-3	-15	-7	7	-16	0	-2	15	61
Feb	184	-72	-3	-124	7	-8	-7	5	22	0	-2	1	24
Mar	319	-87	14	-218	-4	-10	-7	6	-6	0	-2	4	56
Apr	166	-110	31	-119	7	-7	-6	5	32	0	-2	-2	20
May	98	-142	23	-39	3	-4	-6	4	53	0	-2	-11	20
Jun	53	-148	8	-8	4	-2	-5	4	82	0	-2	-13	-7
Jul	33	-138	3	2	5	-2	-4	3	87	0	-2	-13	-28
Aug	34	-107	1	3	3	-1	-4	3	60	0	-2	-10	-26
Sep	104	-83	0	-7	-1	-1	-3	3	-14	0	-2	-4	13
Oct	257	-67	0	-73	-8	-2	-3	4	-98	0	-2	7	107
Nov	467	-53	-24	-249	-8	-8	-3	7	-104	0	-2	22	131
Dec	425	-52	-41	-276	-4	-12	-6	7	-29	0	-2	10	67

P=Precipitation; ET=Evapotranspiration; OL=Overland Flow; UZ=Unsaturated Zone; BF=Boundary Flow; SZ=Saturated Zone; R=Recharge

The year 2012 was particularly bad in terms of sustained discharge within the Cowichan River. Discharge levels were extremely low, and there was very little precipitation in the later summer months. Table 3.4 reports the monthly averages of each water balance component for the year 2012. The red boxes indicate large differences in water balance components compared to the multi-year values (Table 3.2). August and September differ the greatest from the average conditions in the Cowichan Watershed. August 2012 had unseasonably low precipitation, resulting in a very large moisture deficit (-102 mm/month) compared to the average of -73 mm/month. This also resulted in greater than 100% reduction in recharge during that month. September was much the same; the moisture deficit in September was -57 mm/month compared to the +21 mm/month average. The climatic variations also caused a recharge deficit in September (-26 mm/month) as compared to the average groundwater recharge of 13 mm/month.

Table 3.4. Simulated monthly water balance results for 2012 (mm/month).

(2012) Month Total	P	ET	Snow-Storage Change	OL - Flow to River	OL Storage change	OL-BF	Base-flow to River	River to Base-flow	SZ-Storage change	SZ-BF	Pump	Total Error	R
Jan	475	-40	-74	-296	-11	-12	-7	7	-27	0	-2	13	65
Feb	242	-76	26	-193	10	-11	-8	6	10	0	-2	5	37
Mar	397	-65	-34	-261	-5	-12	-8	6	-10	0	-2	7	49
Apr	171	-97	73	-158	5	-9	-8	5	21	0	-2	2	30
May	79	-123	29	-43	4	-5	-6	5	57	0	-2	-5	4
Jun	83	-136	17	-22	3	-3	-5	4	53	0	-2	-8	15
Jul	30	-139	4	-4	7	-2	-4	4	96	0	-2	-9	-30
Aug	5	-107	1	4	4	-1	-4	3	89	0	-2	-9	-45
Sep	4	-61	0	1	2	-1	-3	3	53	0	-2	-5	-26
Oct	323	-51	0	-52	-17	-2	-3	3	-193	0	-2	6	129
Nov	489	-48	-11	-292	-13	-9	-3	7	-91	0	-2	26	155
Dec	466	-43	-106	-279	10	-13	-7	7	-17	0	-2	16	56

P=Precipitation; ET=Evapotranspiration; OL=Overland Flow; UZ=Unsaturated Zone; BF=Boundary Flow; SZ=Saturated Zone; R=Recharge

The water balance results presented in this section are uncertain for a variety of reasons: model error (as illustrated in the Tables), calibration error, and uncertainty in the parameters that have no calibration data (ET, the unsaturated zone parameters, and most the saturated zone parameters outside of the lower valley). However, generally, the water balance results appear reasonable and can be used to explore linkages between climate and watershed response.

3.3. Spatial Recharge and Discharge

Recharge, also referred to as net infiltration or deep percolation, is the amount of water transferred from the unsaturated zone to the saturated zone. Figure 3.3 shows recharge over the entire Cowichan watershed (averaged and classified over the calibration and validation period). A classification scheme was used to represent the recharge qualitatively; low represents 0-7% of the highest recharge, moderate 7 to 16%, high 16 to 33%, very high > 33%, and all negative values as discharge zones. Figure 3.3 also shows areas where higher recharge occurs and where important discharge zones (wetlands or spring areas) are situated. While the water balance results presented above represent the net flux of water from the unsaturated zone to the saturated zone over the entirety of the watershed, the recharge map displays the various processes spatially. Areas with a thin soil cover, high amounts of precipitation, and a permeable subsurface material with a groundwater table close to surface have recharge that is orders of magnitude greater than areas with less precipitation, a low permeability substrate and a deep groundwater table. Also evident in Figure 3.3 is a gradient of recharge from west to east, which results primarily from the precipitation patterns within the valley, as yearly precipitation values in the west are several times larger than the east. There are several relatively small circular areas of highly focused recharge. These anomalous areas likely represent topographic depressions in the DEM, where water ponds and infiltrates throughout the simulation.

To assess the accuracy of the discharge features simulated by the model, the location of observed groundwater discharge features, such as springs and wetlands, are superimposed over the simulation results (Figure 3.3). The simulated linear seepage faces along the northern valley slopes correspond quite well to observed locations of springs. As well, observed wetland features tend to correspond with low topographic depressions within the lower valley where groundwater discharge occurs. Most discharge features throughout the watershed are situated in the valleys flanked by steep ridges. The discharge occurs as saturated zone to overland exchange.

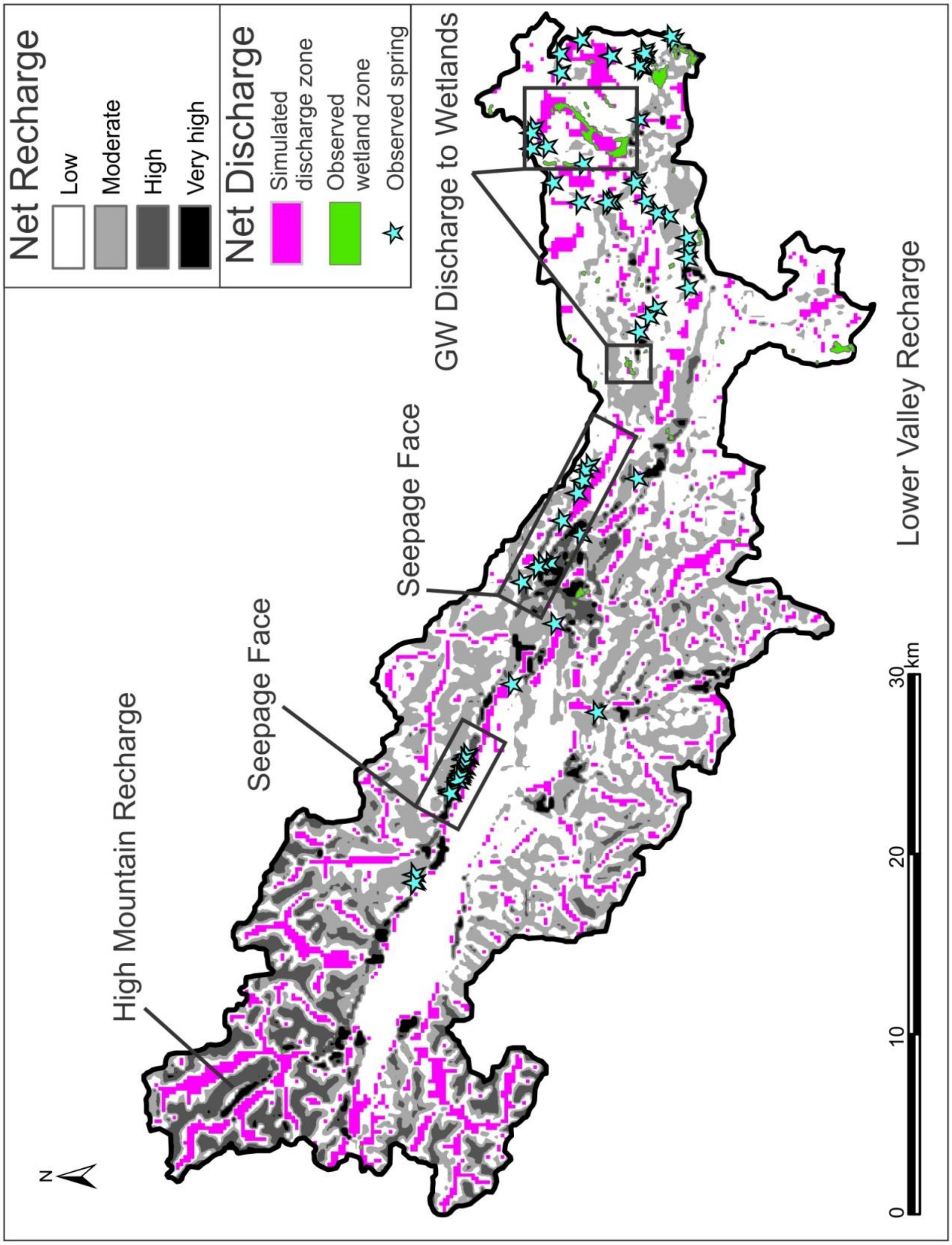

Figure 3.3. Averaged (2002-2012) and classified spatial distribution of net recharge and net discharge throughout the Cowichan Watershed (from Foster and Allen 2015).

3.4. Groundwater - Surface Water Interactions

Exchanges at the watershed scale are largely controlled by variations in subsurface lithology, including depth to bedrock and aquifer properties (Stanford and Ward 1993, Buss et al. 2009). For example, exchanges that occur in reaches of the Cowichan River where surface water overlies bedrock directly are controlled largely by the hydraulic conductivity of the bedrock, whereas, in other locations, the Cowichan River passes through zones of permeable alluvial deposits where the river channel is deeply incised into the alluvium. Valley width may also affect exchanges (Stanford and Ward 1993, Buss et al. 2009).

To illustrate the influence of geology on exchanges, the Cowichan River itself (A-A') was used as a cross-Section (Figure 3.4). This Figure illustrates the material in contact with the river bed, the depth to bedrock or where bedrock is exposed in the river bed, and the thickness of the alluvial sediments. The river only comes in contact with four main geological units: the undifferentiated sediments (K=1E-5 m/s), bedrock (K=1E-7 m/s), Aquifer 186 (K=1E-2 m/s), and Aquifer 179 (K=1E-3 m/s). Also imposed on the figure are the relative positions (at y-metres away from the river) of the surface water diversion and groundwater extraction wells to the nearest point of the river. All of the groundwater extraction wells are within unconfined sand and gravel Aquifers. Defined Aquifers 186 and 187 are a layered aquifer system; however, the vertical distinction is not well defined. Therefore, at the scale of the model, the layered system is treated as a single homogenous aquifer, and labelled as Aquifer 186.

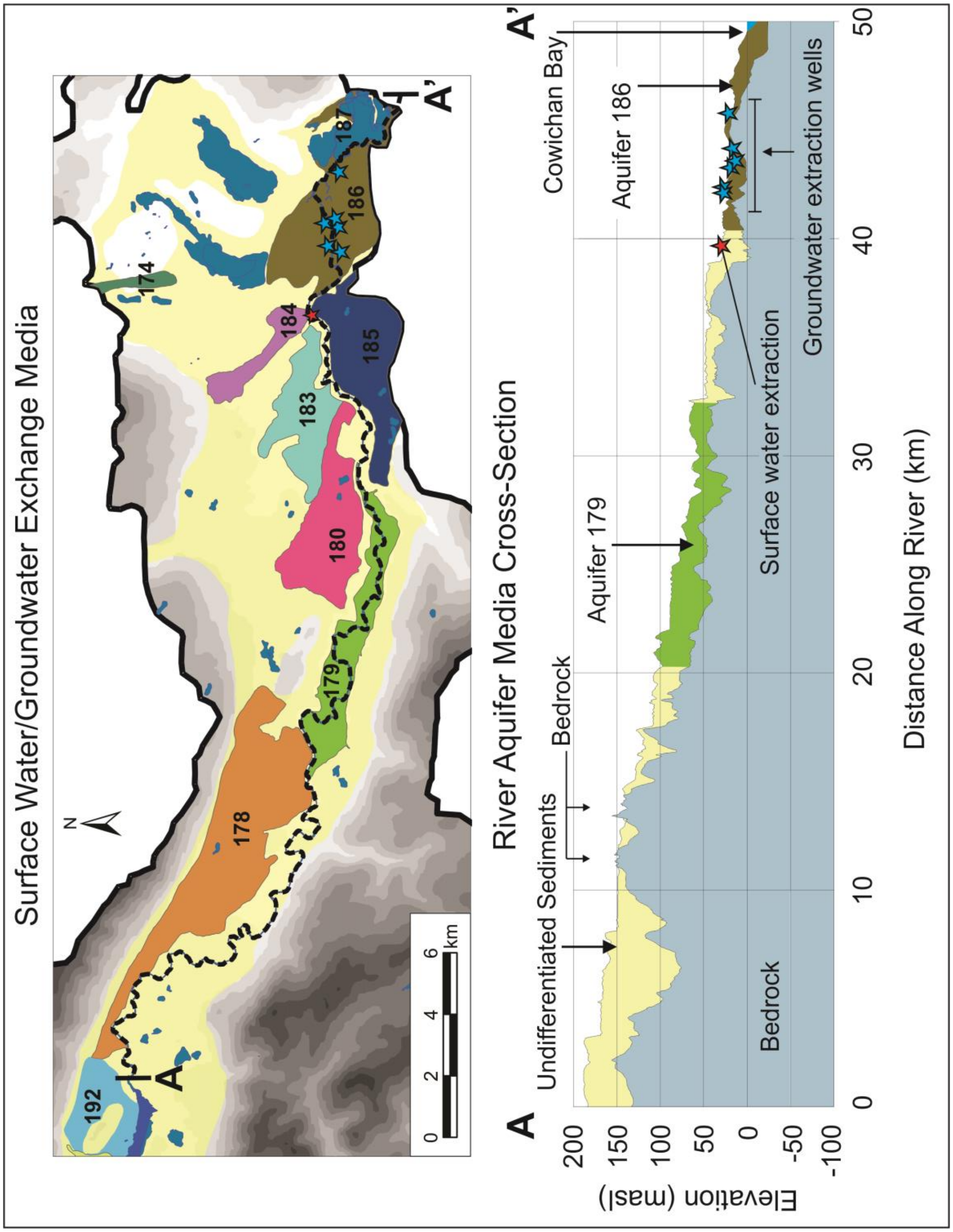

Figure 3.4. **The subsurface geology underlying the Cowichan River. Blue stars show groundwater wells and the red star shows the surface water diversion.**

Figure 3.5 shows the gaining and losing portions of the river, alongside the geology based on the annual exchanges simulated in 2008 (a year where a good groundwater calibration is observed). For the majority of the up-river reaches, the Cowichan River is a gaining system (with the exception of a reach from 19500 to 21000 m, near Stoltz Pool). However, further down valley where the relief is lower, the river becomes predominantly losing. Right at the coast, the Cowichan River gains water as would be expected in a coastal setting due to the presence of the saltwater-freshwater interface at depth, which directs groundwater discharge upwards along a seepage face. As this was a freshwater model, the actual interface was simulated by placing zero flux boundaries in the bedrock and forcing discharge to exit the model domain through the alluvium.

Figure 3.6 illustrates the average annual river/aquifer exchanges in 2008 (mean of all monthly outputs), in map view and in cross-section. Figure 3.6a reveals the geomorphologic characteristics (surrounding topography, river morphology), which may influence the exchange relationships. The steep valley walls throughout the central valley generate strong gaining conditions, whereas on the flat alluvial plain (towards the terminus of the river), groundwater levels drop below the river bed levels, and losing conditions occur. River sinuosity has also been shown to influence exchange (e.g. Larkin and Sharp 1992, Boano et al. 2006). However, no relationship was observed in the Cowichan (Figure 3.6c). Commonly, river morphology is studied at the reach scale (Buss et al 2009), as streambed topography drives small changes in pressure differentials (pool and riffles). Unfortunately, the scale of this study is to coarse to attempt to model these variaions.

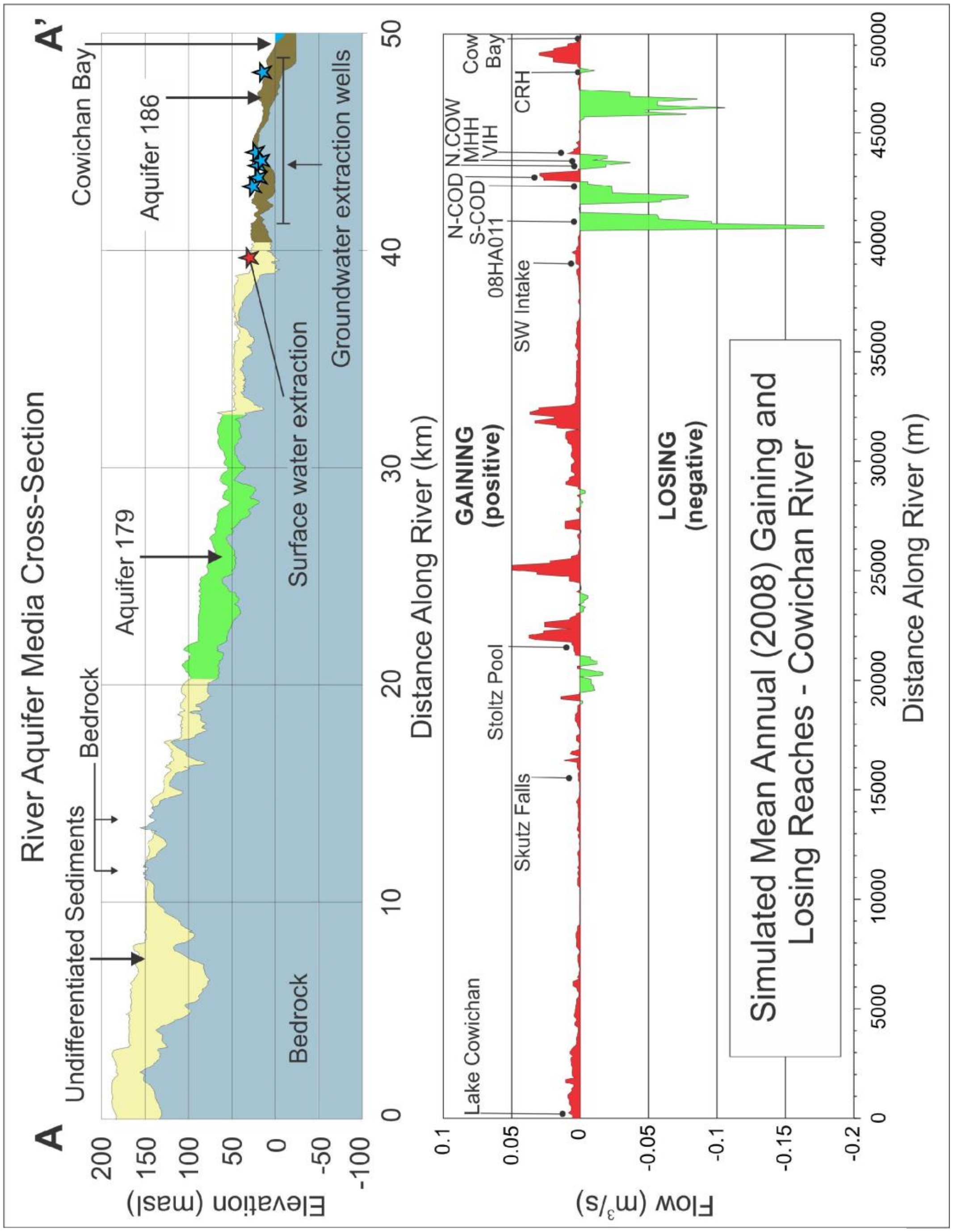

Figure 3.5. **Simulated annual exchanges between the Cowichan River and the aquifer in relation to the aquifer geology (pumping wells: S-COD/N-COD – City of Duncan wells, MHH – Marine Harvest Hatchery, N.Cow – North Cowichan well, VIH – Vancouver Island Hatchery, and CRH – Cowichan River Hatchery) (from Foster and Allen 2015).**

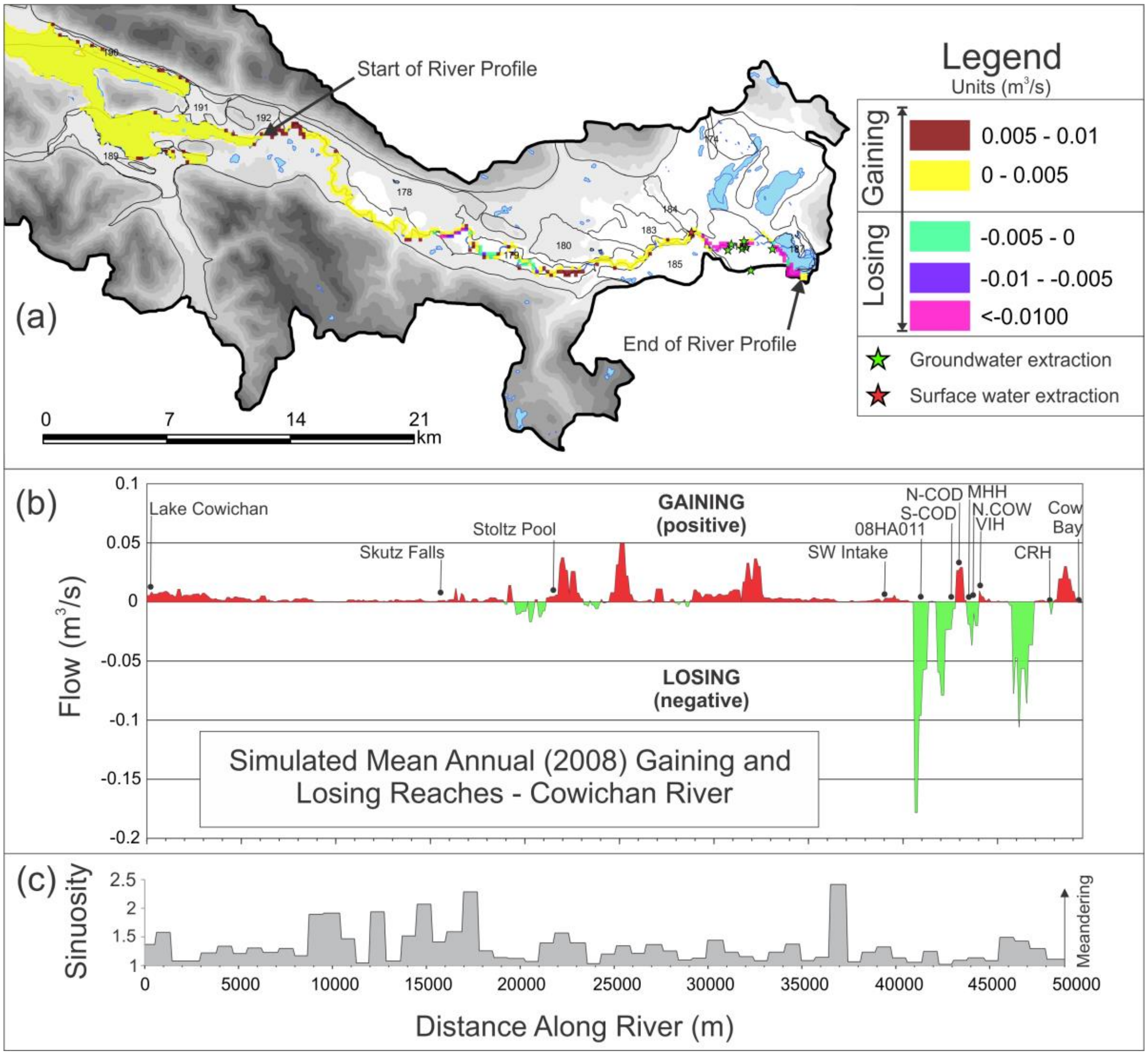

Figure 3.6. Simulated annual (2008) gaining and losing Sections of river in (a) plan view, and (b) profile view (c) sinuosity of the Cowichan River.

Saturated zone exchange data were also extracted seasonally in 2008 and also through both geologic layers (alluvium, and bedrock) to illustrate the spatial and temporal variations in the exchange dynamics. Figure 3.7a shows the hydraulic conductivity of the exchange media. The river gains water through Aquifer 179. Large volumes of water are lost where the river crosses Aquifer 186. Figure 3.7b shows the seasonal variations in gaining and losing conditions, which are discussed further below. Figure 3.7c illustrates where bedrock contributes water to the Cowichan River just above Skutz Falls, where the river directly overlies bedrock. Here, even during the summer season, groundwater can be seen discharging from the highly fractured bedrock.

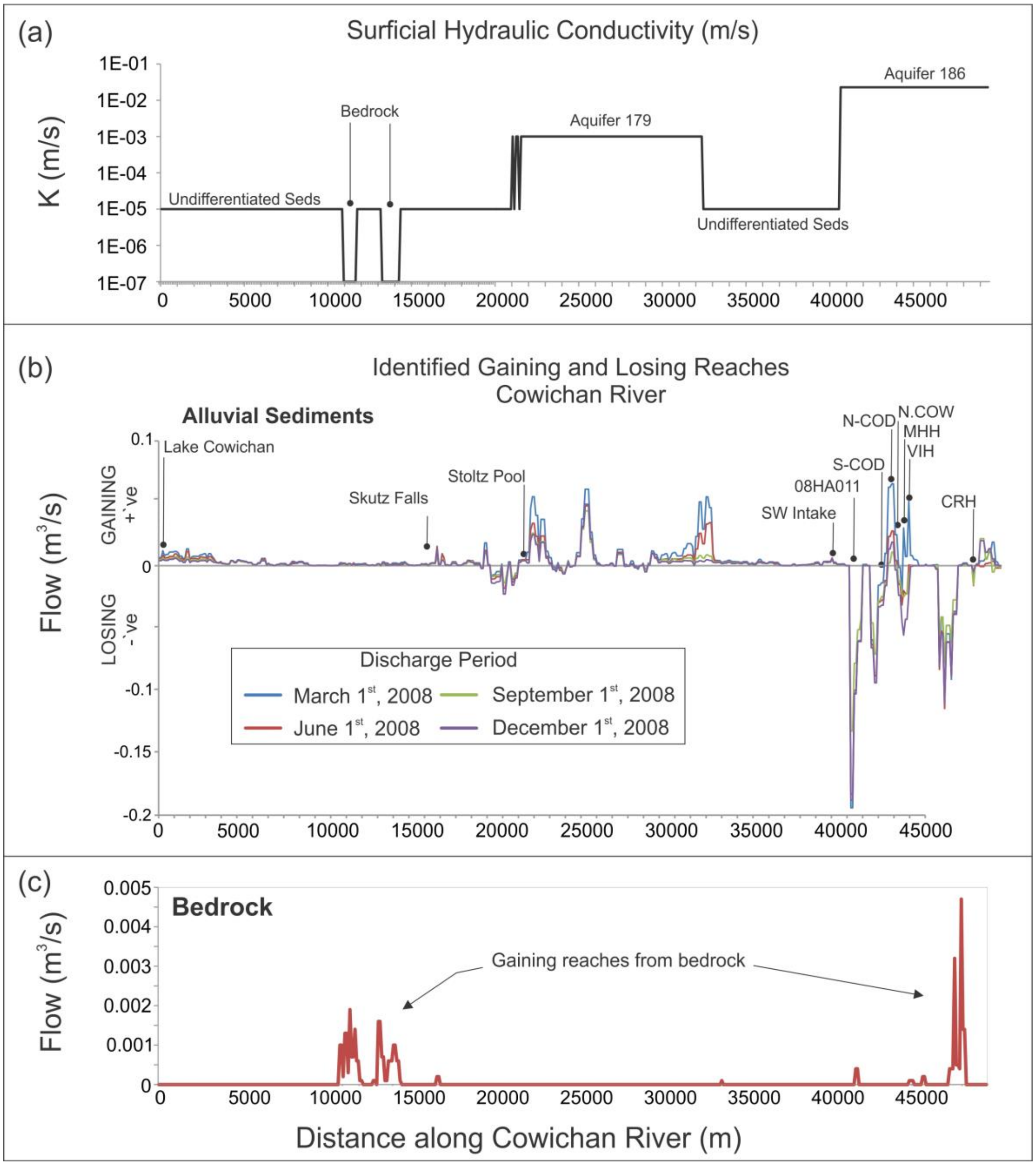

Figure 3.7. The relationship between (a) aquifer hydraulic conductivity, (b) seasonal variations to GW-SW interactions, and (c) the contribution of bedrock aquifers.

Figure 3.8 shows a more detailed view of the seasonal interactions shown in Figure 3.7. Groundwater discharge into the river is highest during the spring season (when groundwater levels are highest), and lowest during the fall (when groundwater levels are low). Losing conditions are the greatest (most negative) during the winter months when the stage of the river is high and the groundwater table may still be low (due to lag time), resulting in a higher hydraluic gradient. At 44000 m, the exchange conditions shift from predominantly losing to predominantly gaining, but the magnitude of the exchange varies seasonally. When groundwater levels are greater than the river stage (evident in March of 2008), the river is gaining, which illustrates how important groundwater levels are to conditions in the river. To investigate the role of groundwater level, three datasets were extracted within this area: river stage, groundwater levels, and the exchange flow amounts (Figure 3.8). Where the groundwater level is higher than the river stage, the river is gaining, where the groundwater level is low, the river is losing, and when both the river stage and groundwater levels are at similar elevations little exchange take place.

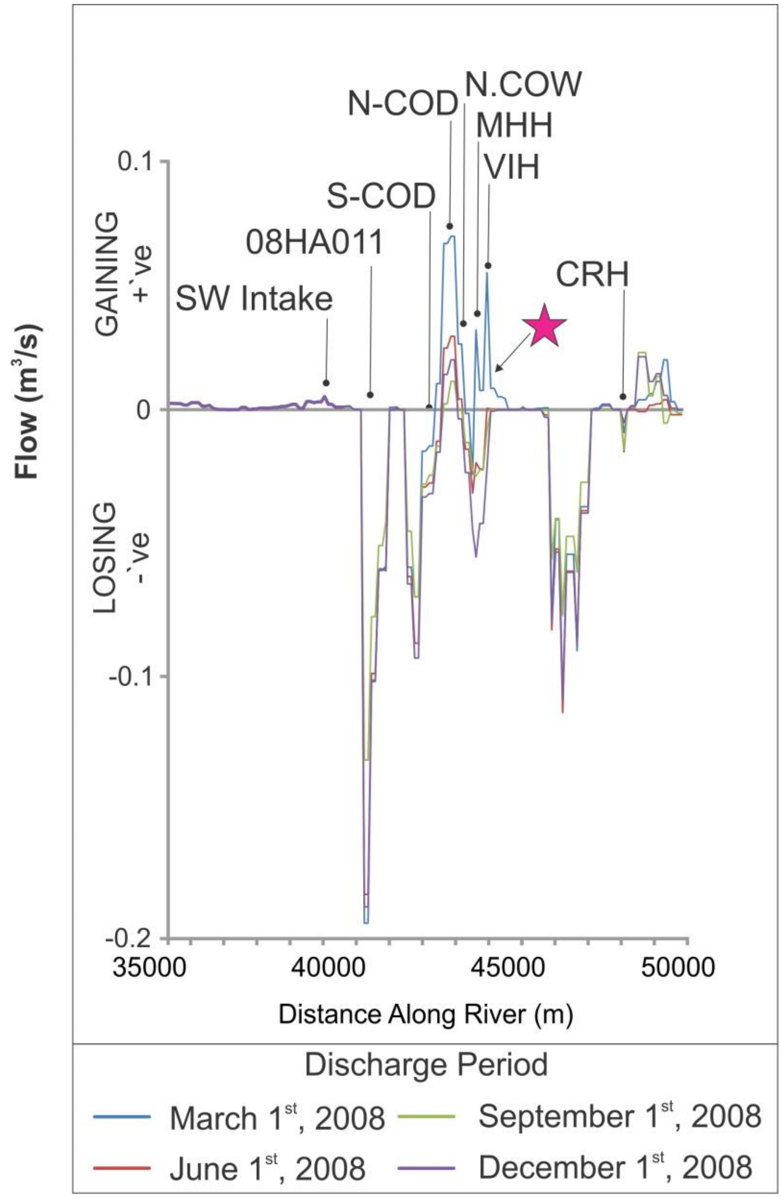

Figure 3.8. **Seasonal variations in GW-SW interactions for the lower reaches of the Cowichan River. Note, the red star shows the location of seasonal variation of exchange conditions (see Figure 3.9) (from Foster and Allen 2015).**

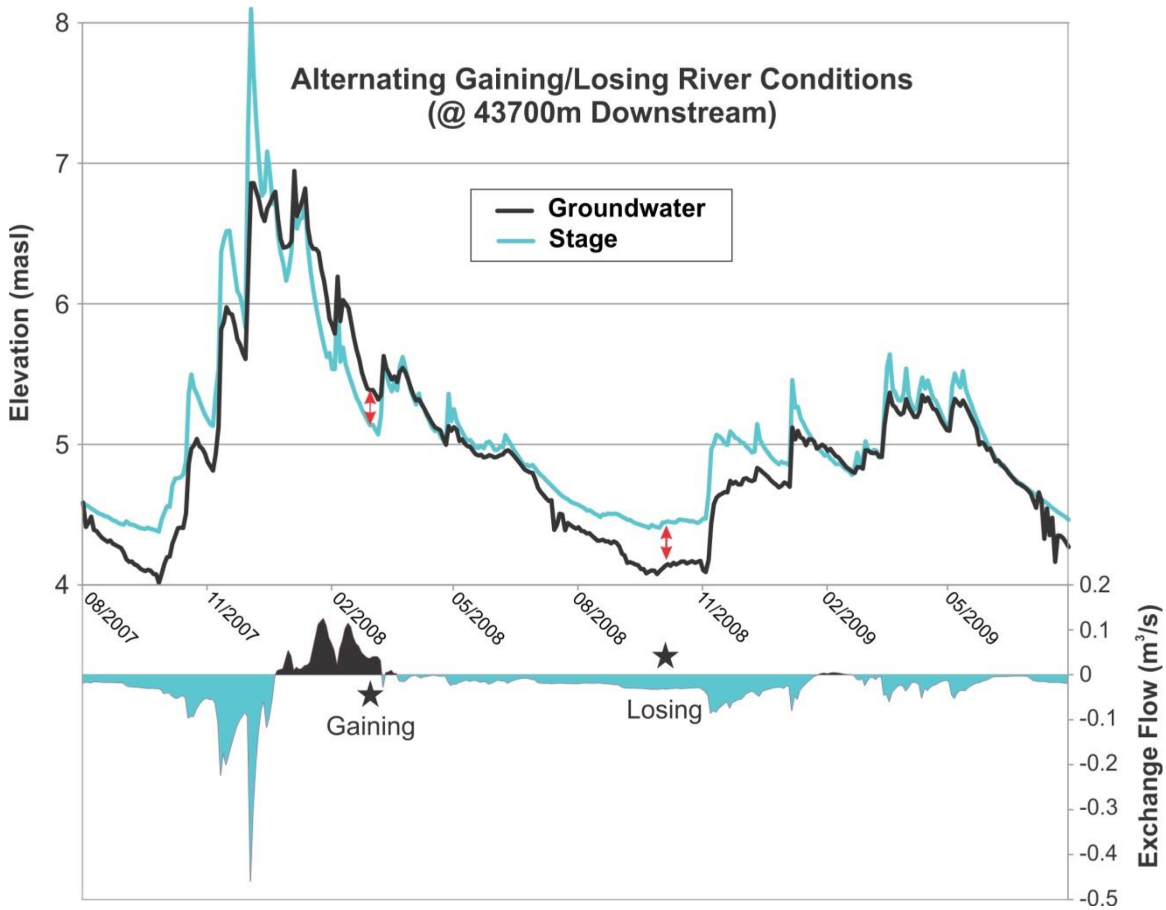

Figure 3.9. Relationship of stage, groundwater levels, and GW-SW exchange.

A lowering of the water table due to pumping near the river can result in an “induced recharge” situation, whereby the aquifer losses are replaced by the surface water directly. As shown in Figure 3.8, the river is dominantly losing in the area where a number of wells are concentrated. To assess whether the pumping conditions within the lower reaches of the river are the cause of losing conditions, the model was re-run with the groundwater extraction rates set to zero. Figure 3.9 shows the results of the simulation with and without pumping for 2008. While the overall shapes of the curves are consistent, there are differences in the magnitudes of exchanges (highlighted within the ovals). With no pumping, the losing condition that is evident at 43000 and 44000 m during pumping becomes dominantly a gaining condition. Within the losing segments, the large negative peaks are lessened with no pumping, nearby, and at a fairly large distance (kms) from the wells. This result suggests that the pumping wells can lower the water table such that the effects are manifested at large distances.

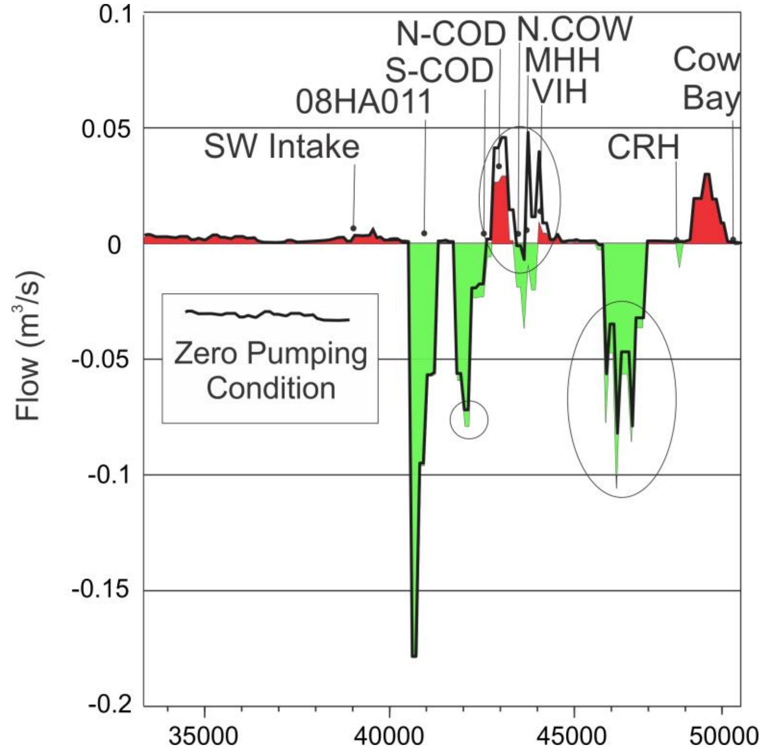

Figure 3.10. Simulated influence of GW pumping on GW/SW interactions (from Foster and Allen 2015).

3.5. Comparison of Simulated GW-SW Exchanges with Field Data

In-stream data throughout the Cowichan Region are limited due to data collection challenges including: the bedrock and gravel river substrate makes installing piezometers difficult; river discharge is high throughout much of the year rendering it unsafe to make in-stream measurements; and the perceived dangers of using of chemical tracers (e.g. solute and fluorescence tracers) on a Canadian Heritage River. However, some data were collected during the summer low flow season at a few in-stream locations. In-stream piezometer and seepage field data were made available from the BC Ministry of Forests, Lands and Natural Resources Operations (S. Barroso, personal communication). The data include a series of in-stream mini-piezometer measurements of hydraulic head differences between the river stage and shallow groundwater levels within the river bed (using a pressure manometer board), as well as seepage rates between the shallow aquifer and the riverbed (using the same piezometer apparatus as a seepage meter). The field measurements were recorded throughout September 2013, at several locations (CA, 208, TP, TP14, LJ, and HR) along the Cowichan River (Figure 3.11). At each location, several measurements were made along a river transect. The seepage measurements (volumetric flow) and the modeled MIKE SHE exchange flow values were converted to a flux (m/s), by dividing the measured flow by the surface area. The flux results are presented in Table 3.5.

Table 3.5. Range of flux (m/s) measured in the Cowichan River (September 2013). All measurements represent an exchange flux in m/s (-'ve values losing conditions /+'ve gaining).

Measurement Locations	CA	208	TP	TP14	LJ	HR
DS Distance (m)	**40600**	**43200**	**43350**	**43400**	**43650**	**45600**
Min	-7.6E-04	-2.1E-02	-3.8E-03	-3.8E-03	-6.4E-03	-1.1E-03
Q1	-2.2E-04	-1.6E-02	-2.2E-03	-2.2E-03	-8.6E-04	-1.0E-03
Median	-9.1E-05	-1.3E-02	-1.6E-03	-7.8E-03	-5.4E-04	-6.1E-03
Mean	-8.1E-05	-1.0E-02	-1.5E-03	-7.2E-03	-1.2E-03	-4.3E-03
Q3	7.9E-05	-3.4E-03	-3.7E-04	-3.7E-04	-1.9E-04	-8.9E-04
Max	4.0E-04	-4.3E-04	6.4E-04	6.4E-04	4.6E-04	-5.8E-04

DS – downstream distance from Cowichan Lake/ Cowichan River border

The mean and median flux results for each transect indicate that the Cowichan River at this location is largely a losing reach, as all averages are negative. The minimum and maximum values indicate that there are variations (up to two orders of magnitude at 208) in the flux across each transect. The CA measurement location alternates from gaining to losing conditions during the month as the upper quartile (Q3) shows positive flux. Highest loses are evident at location 208, coinciding with a position close to pumping wells. Figure 3.11 compares the average monthly exchange fluxes for the piezometers and the simulated Cowichan River model results for September 2008. Unfortunately, the field data do not fall within the model simulation time period; however, a generalized comparison can be made. Recognizing the differences in scale between the two, local measurements vs. watershed model results, all the observed losing conditions correspond with negative simulation results. The overall simulated fluxes are one to two orders of magnitude lower than the observed results at all locations. This is not surprising given the different scales of heterogeneities captured by the two approaches.

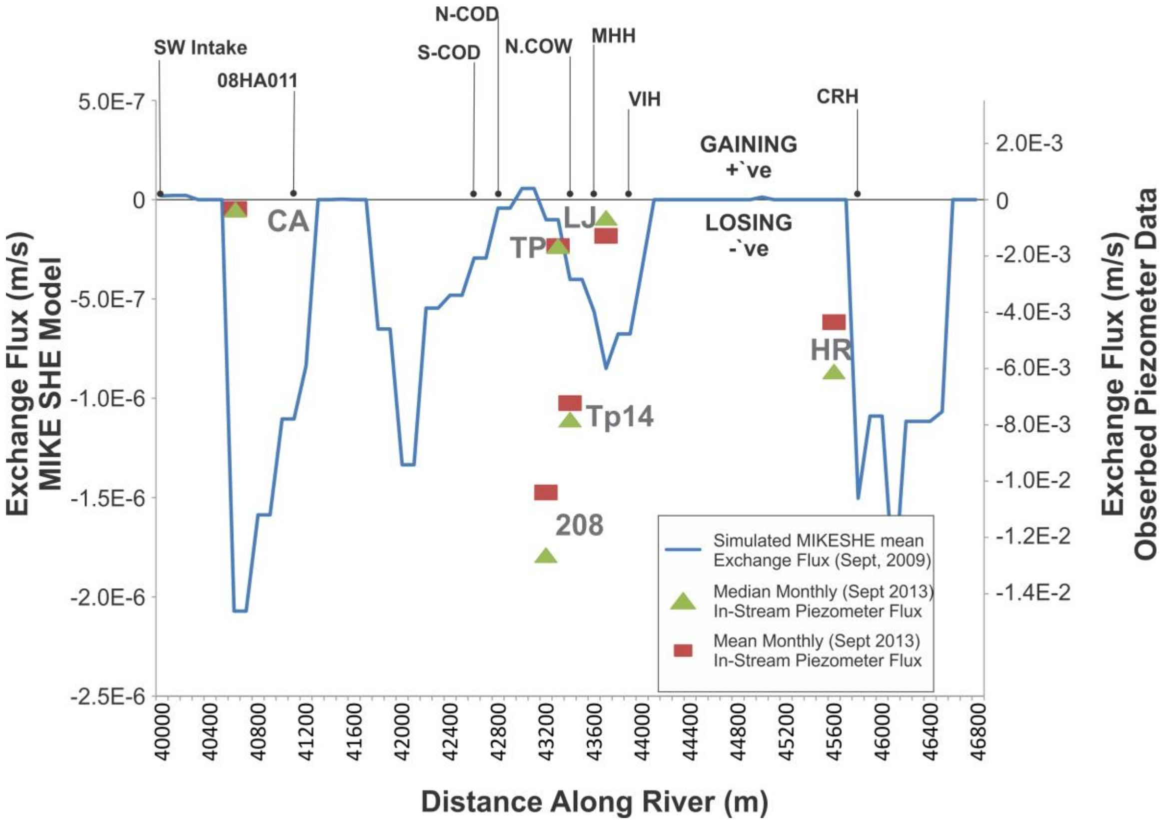

Figure 3.11. Comparison of simulated MIKE SHE instantaneous exchange conditions on September 2008 and monthly averages from in-stream piezometer data (September 2013).

An additional source of data came from snorkel surveys (fish count and habitat) that have been historically conducted within the Cowichan River (Mike McCulloch, FLNRO, personal communication). Fish count numbers, as well as descriptions of the habitat are made. Indications of groundwater welling (gaining reaches of the river) often coincide with areas where fish counts are large, as well as decreases in the temperature of the water. Figure 3.12 shows the geographic positions of the gaining portions observed from snorkel surveys (blue markers), the locations of losing portions from seepage measurements (red markers), alongside the model results. The model is accurate overall in representing the gaining and losing conditions along the Cowichan River. Groundwater welling indicated by the snorkel surveys correlate well with the gaining conditions in the majority of the upper Cowichan River, although the gaining conditions from the model are not strong due to the low hydraulic conductivity of the sediments and bedrock within that portion of the river. Overall the first 40000 m (40 km) of the river is dominantly gaining (small magnitude), while the bottom 10,000 m (10 km) is losing (large magnitude).

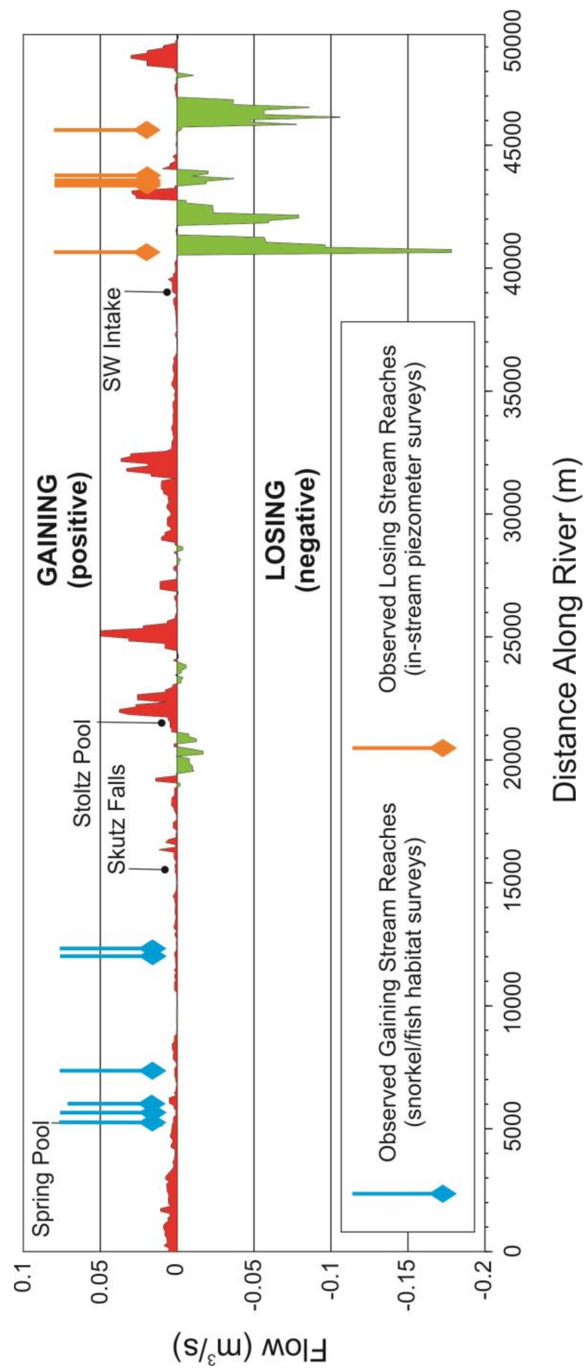

Figure 3.12. Comparison between simulated exchange conditions and observed springs (GW inflow) and in-stream losing piezometric survey locations (from Foster and Allen 2015).

3.6. Modelled Capture Zones of the Major GW Users

A capture zone analysis was completed for the large groundwater extraction wells that are located in the vicinity of the Cowichan River. Capture zones refer to three-dimensional regions that contribute water to the source of extraction, over a given time period (Grubbs 1993). Capture zone analysis can be used to define a “source protection zone,” which corresponds to a geographic area that is responsible for contributing source water, over a given time interval. For example, source protection zones are largely used for land use planning near wells that supply water to communities. Practices that use fertilizers, oils, or other contaminants should not be permitted within the capture zone of those wells to limit the risk of contamination of the community’s drinking water supply. In the current study, capture zone analysis is used to identify: 1) where the extracted groundwater originates during the summer low flow season and the time of travel (time it takes for groundwater to flow from a given point to the well) (Figure 3.13); and 2) the 5-year capture zone from the model, which can be used for wellhead protection (Figure 3.14). Previous capture zone analyses have been completed for the Lower Cowichan area by Thurber (2001), using both analytical methods (pumping radius of influence) and computer models (SEEP/W[1]). The MIKE SHE determination of capture zones differs from the previous report in that the model is a transient simulation, taking into account differences in recharge and pumping rates over a simulation period.

MIKE SHE computes well capture zones for a transient model based on a registration process, whereby particles are assigned to all model cells. Once the particles are removed from the saturated zone, via groundwater extraction wells, discharge to a river, discharge to the surface, or discharge to a boundary condition, the program records the starting station and ending station for each particle registered. Particles were registered based on the model’s available sink type (well, river, unsaturated zone, boundary outflow), and further registered in detail based on the extraction well. Registration can also be defined by geological layer, although in this simulation it is assumed that the deeper bedrock aquifers are of lesser interest.

From the initial particle placement in the saturated zone, particles are moved in three dimensions within the saturated zone based on simulated groundwater flow. Particles were specified as conservative and movement was determined through advection only (dispersion, diffusion, and retardation were set to nil). Because only advection was considered, the capture zones represent the mean position of a plume that would form if a contaminant were actually present. Particles are only tracked in the saturated zone; therefore, analysis of the shape of the capture zone (extending to the river and beyond) aids in indicating whether or not the extraction wells could potentially be influencing the losing conditions of the river in this area.

Figure 3.13 represents the capture zones of the major groundwater extraction wells for summer low flow season (June through end of October, 2012). The Vancouver Island Trout Hatchery well has the largest capture zone. The large conical shape of the capture zone is likely due to the relative flatness of the groundwater table in this area, and the fact that this well is being pumped at the highest rate of all wells during this period. The capture zones of the North Cowichan municipal well, the Marine Harvest Hatchery well, and the City of Duncan wells (south and north) share a very similar shape. The catchment zones are elongated in the direction of groundwater flow, reflecting the higher groundwater velocity in that region. In general, most capture zones extend approximately 1-2 km from the wells over the 5 month period, with the exception of the Cowichan River Hatchery capture zone. The Cowichan River Hatchery capture zone only extends at most 300 m from the well. The reason for this small capture zone is likely a combination of the low rate pumping over the majority of the summer and the dynamics of groundwater flow in that area.

Regarding the source of the groundwater for each well during this time period, the following well capture zones intercept the Cowichan River: the North Cowichan municipal well, the Marine Harvest Hatchery well, the City of Duncan south well, and potentially the Cowichan River Hatchery. Given the simulated groundwater flow direction, and the pathlines the groundwater particles take, the City of Duncan north well and the Vancouver Island Trout Hatchery potentially do not intercept groundwater near the Cowichan River during this time period.

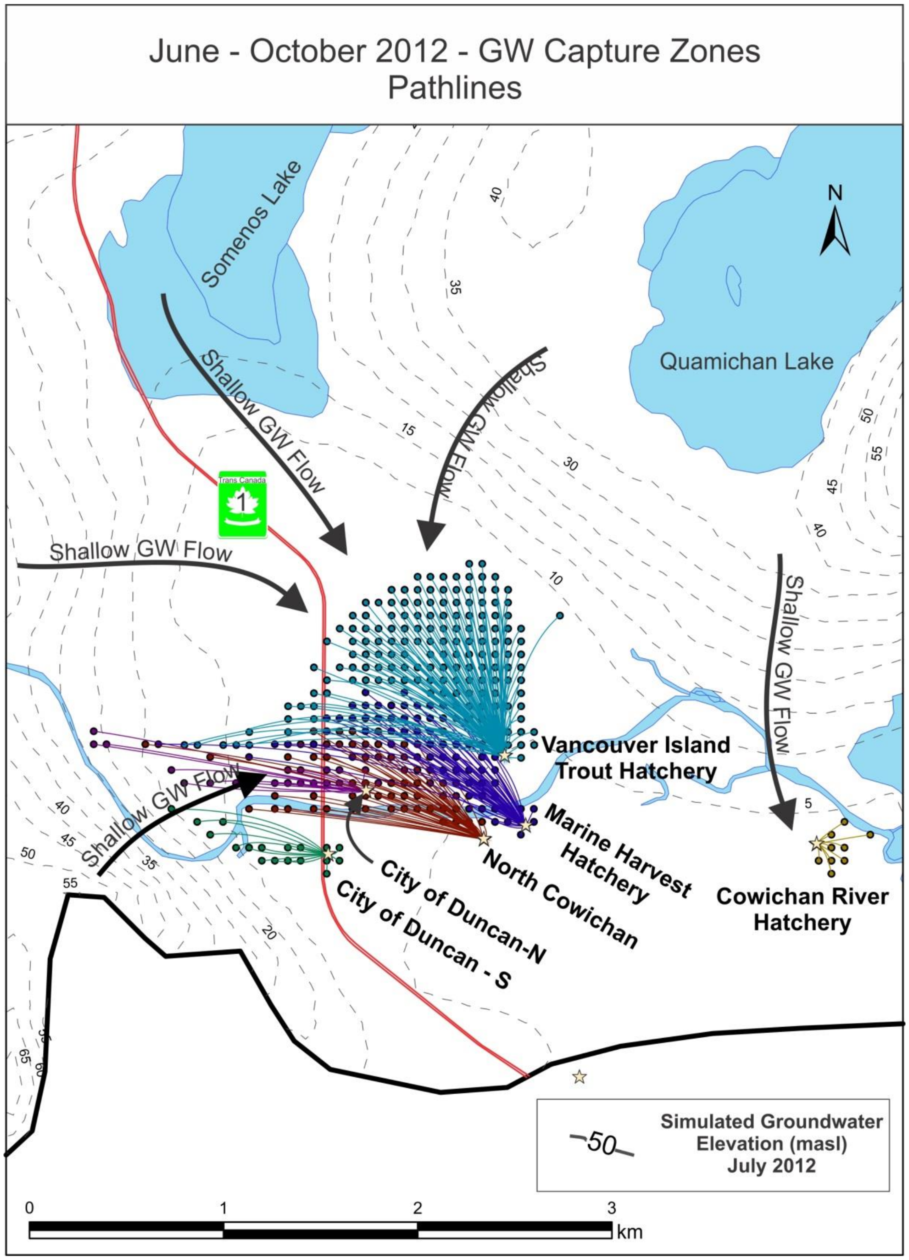

Figure 3.13. Summer low flow season transient capture zone analysis results for the major GW extraction users within the lower valley. Shown are the particle pathlines within the shallow aquifer materials.

Figure 3.14 illustrates the capture zones of the major groundwater extraction wells over a 5-year simulation period (2008-2012). The general shape of each zone is much the same as the summer capture zones (Figure 3.13).

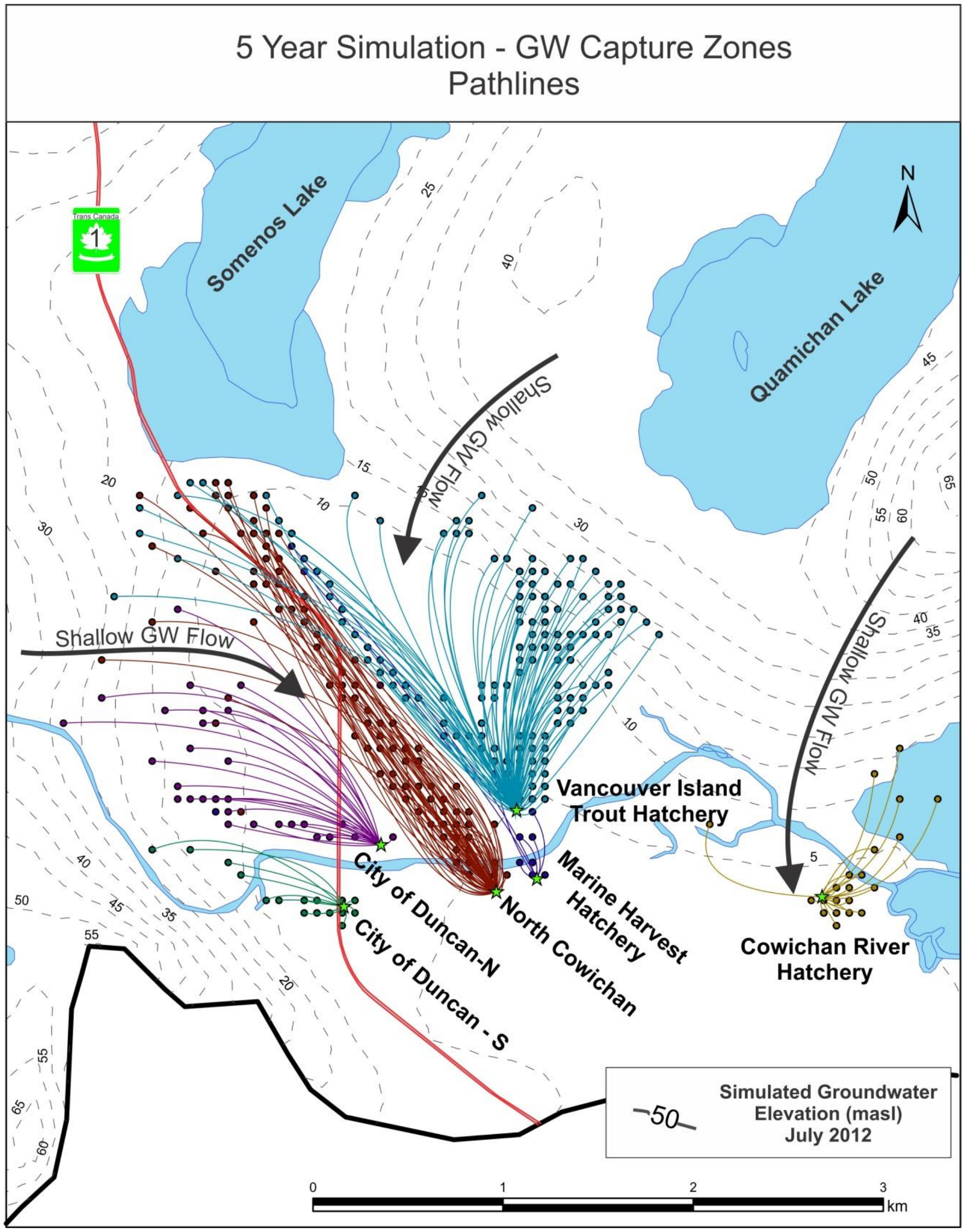

Figure 3.14. 5-year transient groundwater capture zone analysis (2008-2012). Shown are the particle pathlines within the shallow aquifer materials.

3.7. River Capture Zones

A capture zone analysis was also undertaken for the Cowichan River using the same approach described in the previous section. Figure 3.15 shows the locations where groundwater discharges to the Cowichan River and how long it takes to get there (travel time). This simulation was run for a 5-year period (2008-2012). In a sense, this map represents a floodplain capture and protection zone, indicating where groundwater originating on the floodplain would reach the Cowichan River, and how long it would take to discharge into the river. Interestingly, the figure shows that within the lower reaches of the Cowichan River (near the groundwater pumping wells), a smaller number of particles reach the river. This agrees with the previous finding that the wells do have a large effect on the exchange of water within the lower reaches of the Cowichan River. Overall, groundwater recharged between 200 m to >2 km away from the river eventually reach the Cowichan River.

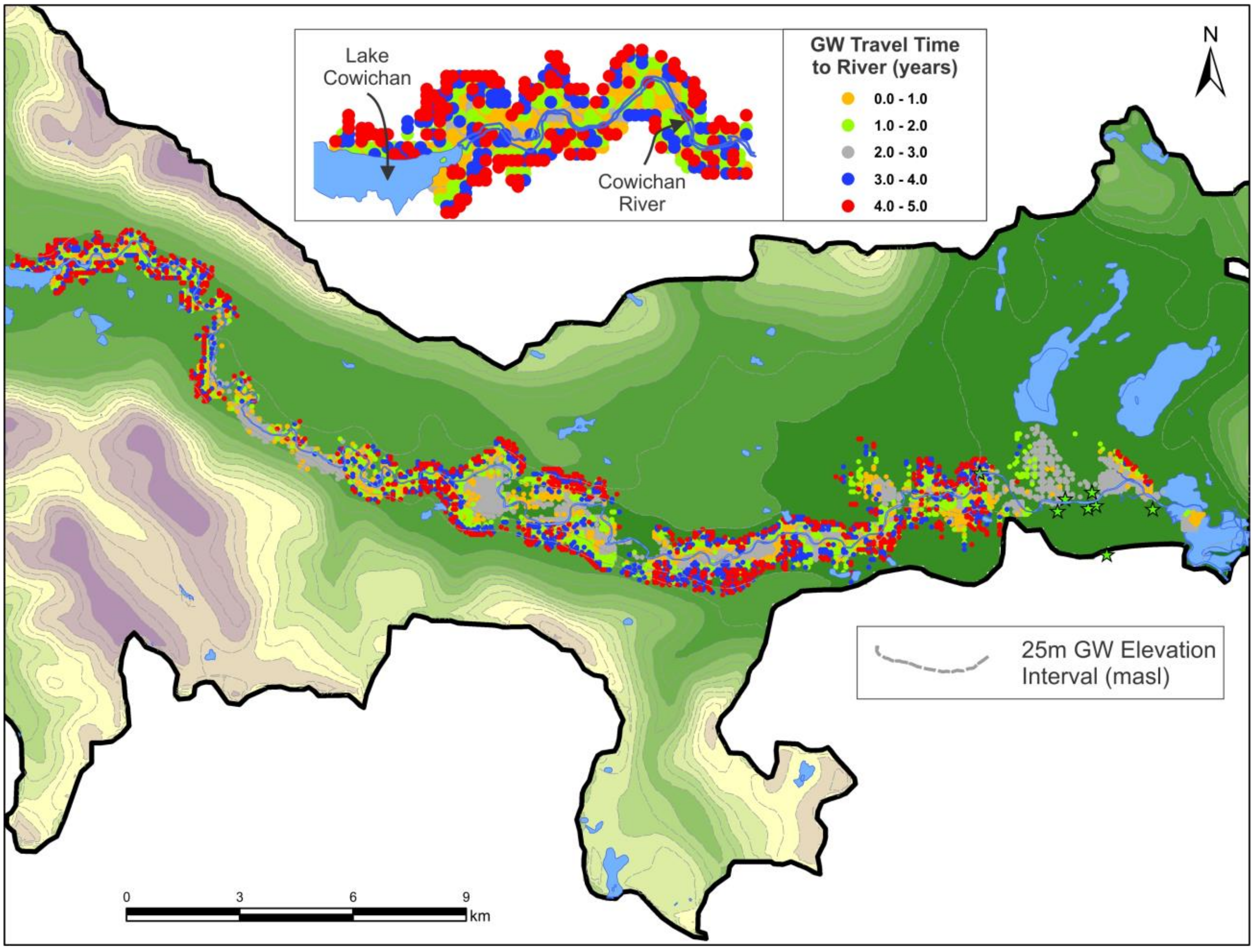

Figure 3.15. 5-year transient "river capture zone analysis" of the Cowichan River.

3.8. Extraction Well Pumping Rate vs. Streamflow Depletion

A pumping well, especially in close proximity to a river, can change both the quantity and direction of flow between an aquifer and surface water body (such as a river in this case). The interactions do not necessarily have a large impact on the overall flow of the river over a large part of the year; however, impacts may be especially noticeable under low flow periods, and particularly in times of drought, when small changes in discharge can have ecological impacts to the river. Also, depending on the physical characteristics of the system, the effects may not be noticeable instantly; it may take years for the system to respond to the withdrawal. The proximity of the well to the river, connectedness of the aquifer and river, and the hydraulic conductivity of the aquifer are all factors that influence this interaction (Alley et al. 1999).

When groundwater extraction near a river takes place, initially, the water supplied to the well will be from storage of the groundwater system (dewatering of an unconfined aquifer). Over time, a cone of depression will form and, subject to physical conditions, the source of water to the well transitions from storage, to streamflow capture. The cumulative streamflow capture may approach the quantity of water pumped from the well. Depending on the pumping rate of the well, this may be significant or insignificant to the flow in the river. Figure 3.16 illustrates that as pumping time increases, the percentage of groundwater pumpage derived from groundwater storage shifts to streamflow capture (in this hypothetical situation).

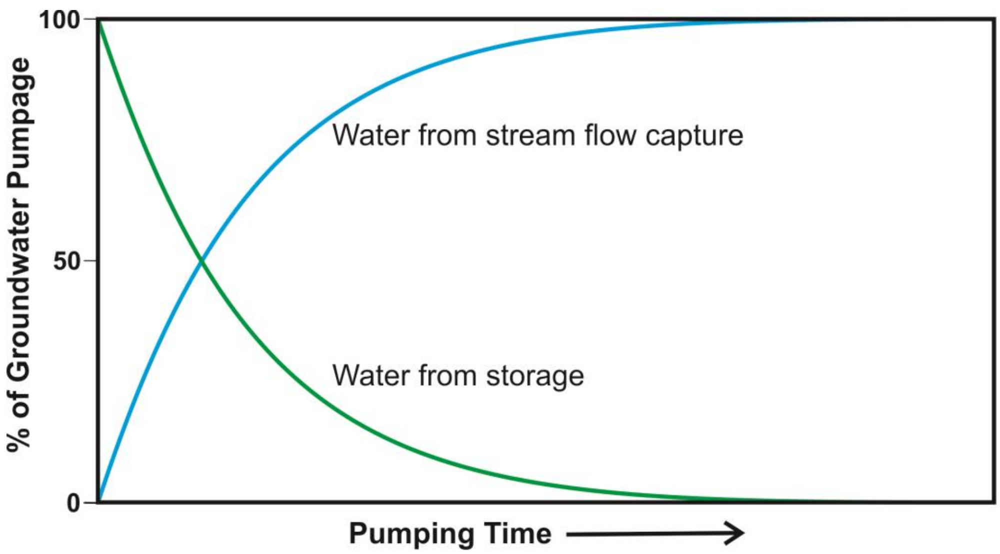

Figure 3.16. Hypothetical situation where the principal source of water to a well can change with time from groundwater storage to capture of streamflow (from Alley et al. 1999).

The Cowichan Watershed Model was used to explore the effects of pumping on Cowichan River discharge on a well by well basis. It is important to note, however, that this model was designed to represent regional scale hydrologic processes; therefore, the results described in this section provide only approximate estimates of the effects of groundwater extraction on streamflow capture. A finer scale (smaller grid size) model is needed to explore these interactions more accurately. Section 4.2 lists recommendations for further detailed studies.

To estimate the effects of individual pumping wells on the Cowichan River, the model was first run for a period of 14 years with all of the groundwater extraction wells turned off.

Discharge time series were extracted from river nodes (RN) closest to the extraction wells (as illustrated in Figure 3.17). Sequentially, the modelled effect of each groundwater extraction well on discharge within the Cowichan River was simulated (RN1 through RN6). The pumping simulation trials were initialized using a hot start from previous complete full length (1998-2012) zero pumping simulation (assumed steady state condition). The pumping model simulations started in June 2011, with analysis and reporting recorded during the year 2012. This 7 month delay in analysis allows for the model to adjust for the slight differences in the hot start output to the current simulation conditions. During this delay, pumping creates a cone of depression as groundwater storage is depleted. The extraction rates were stepped at intervals of 0.1, 0.5, 1, 2, and 10 times that of the current estimated extraction rate using the same temporal variation in pumping as shown in Figure 2.4. The river discharge for each extraction rate was then compared to the zero pumping condition (see Figure 3.18 as an example for RN4 at 10X current pumping rate).

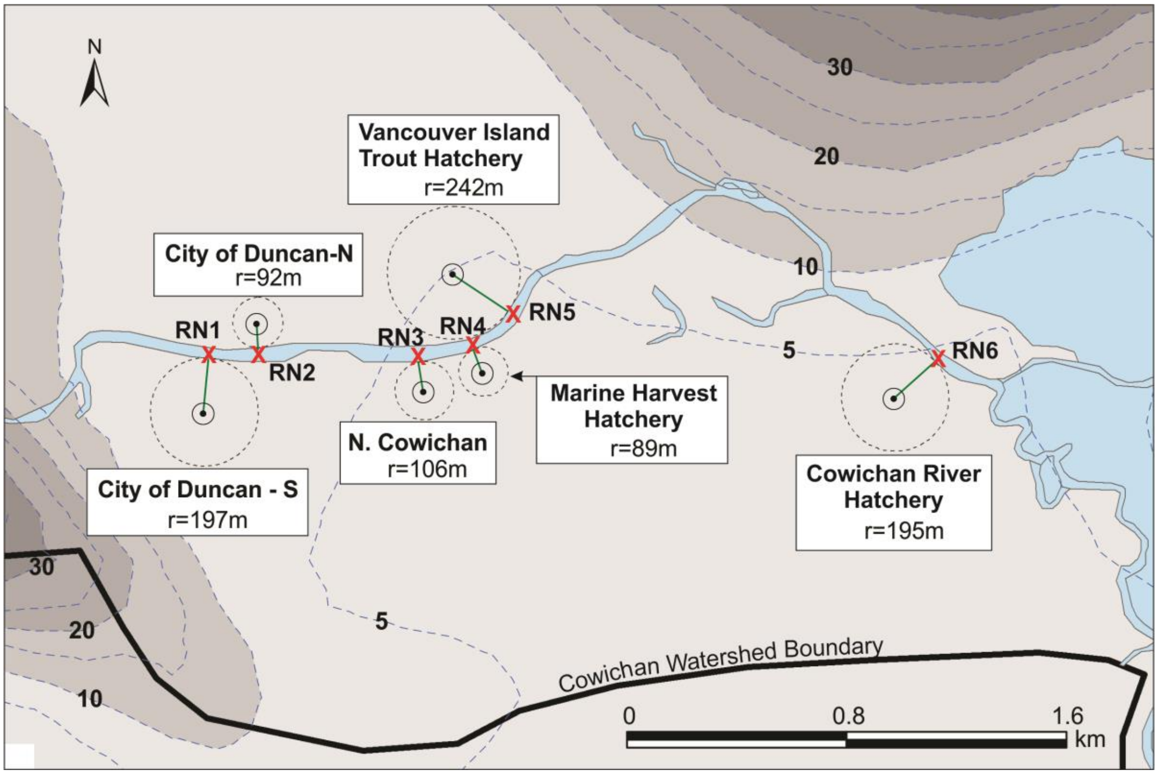

Figure 3.17. Modelled groundwater extraction wells along the Lower Cowichan River. The red Xs represent the closest surface water river node.

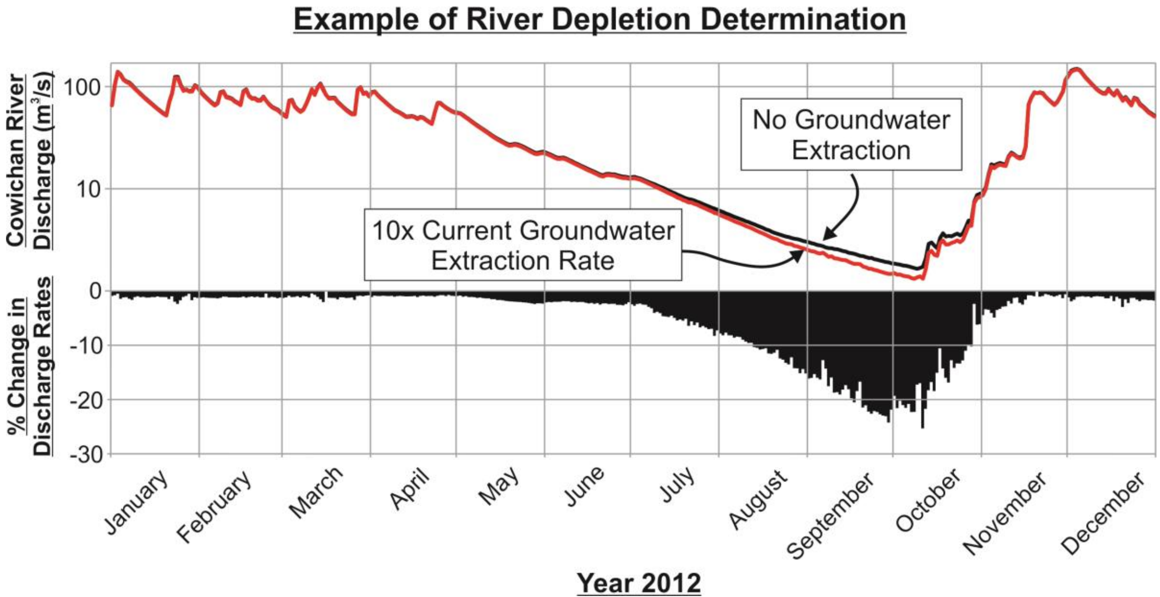

Figure 3.18. Example of the method used for estimating river depletion from pumping an individual well. Shown are the results for RN4 (Marine Harvest Hatchery) in 2012 at 10X current extraction rate.

Appendix 1 shows the results for each individual well for the year 2012. The percent difference from the zero pumping rate to the rate-adjusted simulation is shown on the y-axis in each graph (and is referred to as streamflow or riverflow depletion). The results are often variable, especially during the summer low flow season as amount of water in Cowichan River is small, making any differences between the different pumping rates seem significant. However, some trends are observed. The following is a summary of the key observations for each extraction well.

RN1 - City of Duncan South Well (Figure A1.1)

- A modelled distance of 198 m from the Cowichan River;
- At an extraction rate below 2x current (0.17 m^3/s), little to no change (<2%) in Cowichan River discharge is observed;
- At an extraction rate of 10x current (0.85 m^3/s), observed effects are noticeable as depletions of 5-7% within the Cowichan River occur.

RN2 - City of Duncan North Well (Figure A1.2)

- A modelled distance of 92 m from the Cowichan River;
- At an extraction rate below 2x current (0.17 m^3/s), little to no change (<2%) in Cowichan River discharge is observed;

- At an extraction rate of 10x current (0.85 m^3/s), observed effects are noticeable as depletions of 5-7% within the Cowichan River occur.

RN3 – Municipal of North Cowichan Well (Figure A1.3)

- A modelled distance of 106 m from the Cowichan River;
- At an extraction rate below 2x current (0.24 m^3/s), little to no change (<2%) in Cowichan River discharge is observed;
- At an extraction rate of 10x current (1.20 m^3/s), observed effects are noticeable as streamflow depletions of 8-10% within the Cowichan River occur.

RN4 – Marine Harvest Hatchery Well (Figure A1.4)

- A modelled distance of 89 m from the Cowichan River;
- At an extraction rate below 2x current (0.36 m^3/s), little to no change (<2%) in Cowichan River discharge is observed;
- At an extraction rate of 10x current (1.87 m^3/s), observed effects are noticeable as streamflow depletions of 15-20% within the Cowichan River occur.

RN5 – Vancouver Island Trout Hatchery (Figure A1.5)

- A modelled distance of 242 m from the Cowichan River;
- At an extraction rate under 2x current (0.36 m^3/s), little to no significant change (<2%) in Cowichan river discharge is observed;
- At an extraction rate of 10x current (1.87 m^3/s), observed effects are noticeable as streamflow depletions of 15-20% within the Cowichan River occur.

RN6 – Cowichan River Hatchery (Figure A1.6)

- A modelled distance of 195 m from the Cowichan River;
- At all modelled extraction rates up to 10x current (1.95 m^3/s), little to no consistent streamflow depletion occurs.

In summary, at the current modelled discharge rates, individual wells generally result in streamflow reductions of nil to 5% during the low flow seasons. When discharge rates are increased by 2x the current rate, certain river nodes (RN4, RN5) show significant increases in streamflow depletion (up to 10%). When the extraction wells are pumped at 10x the current rates, all river nodes show significant streamflow depletion (up to 30%).

These simulations were carried out on a well by well basis. While individual wells pumped at their current rates have relatively small impacts on streamflow, the cumulative effect of pumping can be much greater. When multiple wells pump from the same aquifer, the cones of depression can coalesce (Fetter, 2001). When this composite cone of depression reaches a source boundary (a river in this case), vertical recharge from the river to aquifer takes place. To determine the cumulative effect of pumping, all of the wells were set to their approximate current pumping schedules, and the river discharge recorded downstream of the last pumping well. This discharge rate was compared to the initial simulation in which the extraction wells were turned off. The resulting streamflow depletion and composite drawdown cone created is illustrated in Figure 3.19. The results illustrate that, overall, the pumping accounts for (in the year 2012) a maximum 20% reduction in streamflow during the low flow period. The composite cone of depression is quite large, and its extent seems to be largely controlled by the boundaries of the aquifer (stippled marks – unconfined aquifer 186).

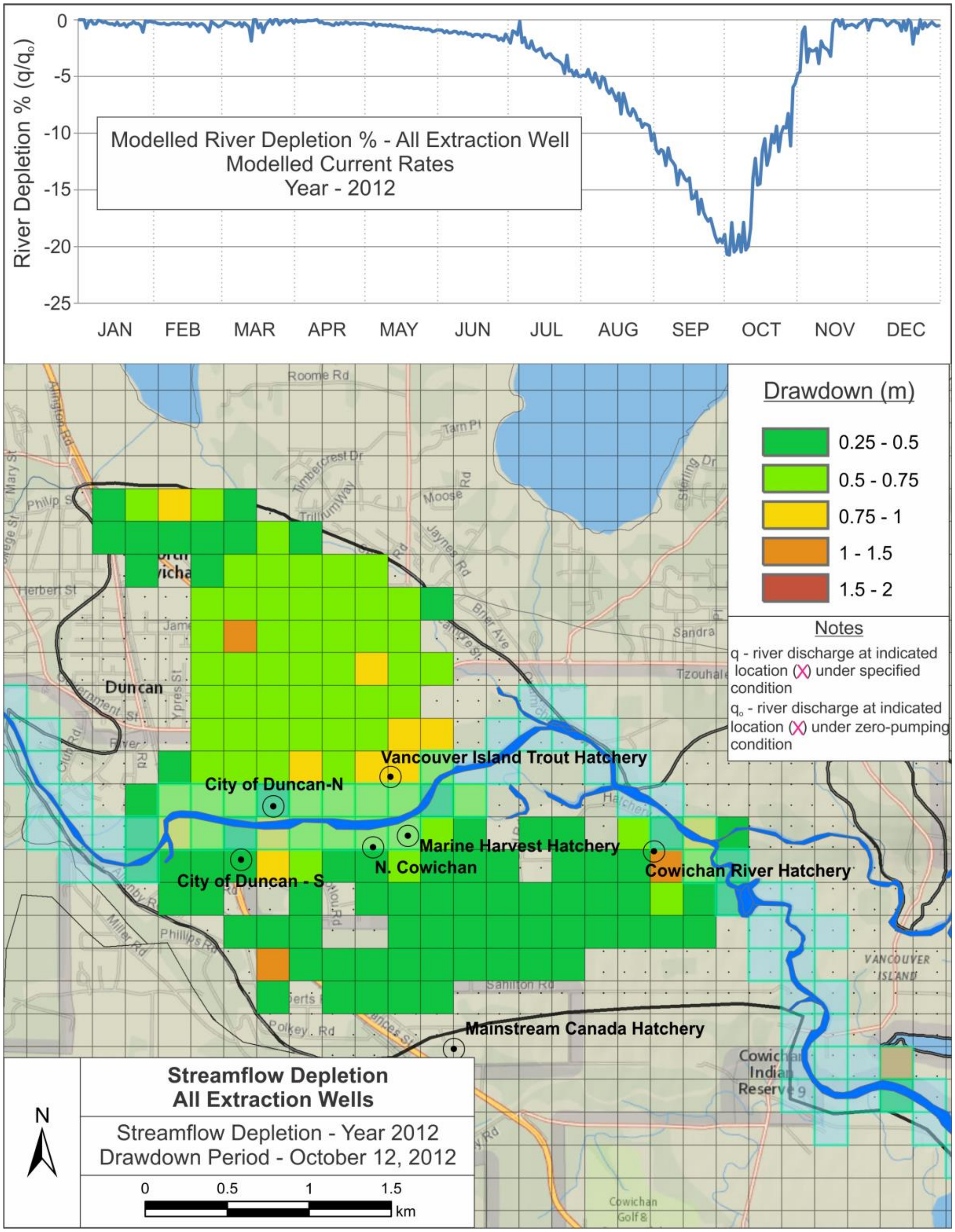

Figure 3.19. Drawdown assessment for all extraction wells pumped at their current rates during the low-flow period in 2012.

3.9. Well Distance vs. Streamflow Depletion

One of the many factors involved in assessing the degree to which pumping of an aquifer affects streamflow depletion is proximity of the pumped well to the surface water body. The size of the cone of depression created by the depletion of aquifer storage is an important factor that determines the degree of impact.

This section attempts to illustrate the sensitivity of the Cowichan River discharge to wells placed in unconfined Aquifers 186, and 179 at varying distance away from the river. The method for determining the impacts is similar to that used in the previous section; streamflow depletion percentage as a ratio of discharge rate under pumping to zero-pumping simulations (q and q_o, respectively).

Aquifer 186 is an unconfined aquifer, 18.3 km^2 in area, which is located in the floodplain of the lower portion of the Cowichan River. It is comprised of shoreface, deltaic and fluvial gravel and sand of the Salish Sediments. Vulnerability is high as depth to static water level is shallow, and productivity is high due to the high permeability of the sediments. The direction of groundwater flow is southeast towards Cowichan Bay. Recharge is from precipitation, and from the Cowichan River (Lapcevic 2014).

The simulations were designed such that wells were placed at 200 m intervals away (south and north) from a registered river node (RN3). This large spacing coincides with the grid size of the model. Ideally, the grid should be refined around pumping wells, but this was not possible in this regional scale model. Therefore, it is important to note that the drawdown in the cell coinciding with the well will be significantly underestimated compared to what is would be in reality, as the cell provides a large storage volume. However, at greater distances away from the well, the simulated drawdown will be closer to actual values (Anderson and Woessner 2002).

Well screens were set to a uniform depth of 10-15 m bgs, with a 5 m screen length. The numbering of wells reflects the distance north or south of the river (e.g., P200N is pumping 200 m north of the river node). The pumping schedule was set to a constant rate. The simulation was initialized using a hot start from previous complete full length (1998-2012) zero pumping simulation (assumed steady state condition). The pumping model simulations started in June 2011, with analysis and reporting recorded during the year 2012. This 7 month delay in analysis allows for the model to adjust for the slight differences in the hot start output to the current simulation conditions. During this delay, pumping creates a cone of depression as groundwater storage is depleted. The results are analyzed over one entire year, and aerial drawdown maps are created using a consistent date corresponding to the lowest value measured during the low-flow season in 2012 (October, 12 2012). Each output time series was smoothed using an exponential smoothing technique (damping factor of 0.9) to help remove the frequent spikes in the data to better illustrate trends.

Initially, the simulated pumping rate was set to 1 m^3/s. This rate represents the high range of current pumping, which is modelled to be approximately 50% of the total amount of discharge within the Cowichan River during the lowest of flow conditions (October). The results of the simulations are compiled in Figure 3.20, which shows the modelling setup (bottom), and two graphs showing the amount of streamflow depletion occurring north and south of the Cowichan River. The following summarizes the results:

- Pumping wells situated north of the Cowichan River at this location lead to streamflow depletion ranging from 8-12%, occurring in September and October of 2012.
- The expected trend of increasing depletion with increased proximity of pumping did not apply to wells north of the river. Wells closer to the river surprisingly resulted in less streamflow depletion. This phenomenon may simply be due to model error due to the large grid size, or possibly due to the cone of depression extending down the river, thereby impacting a downstream river node rather than the river node where depletion is being recorded by the model. This is considered a limitation to this method.
- The wells located south of the Cowichan River had less of an effect on streamflow depletion compared to the north, as they ranged from nil to 10%. The impact decreased by 1-2% per 200 m away from the river. However, uncertainties as noted above limit certainty in this conclusion.
- A well pumped at 1 m^3/s at a distance of 1000 m south of the Cowichan River has relatively no impact on streamflow depletion (critical distance at 1 m^3/s).

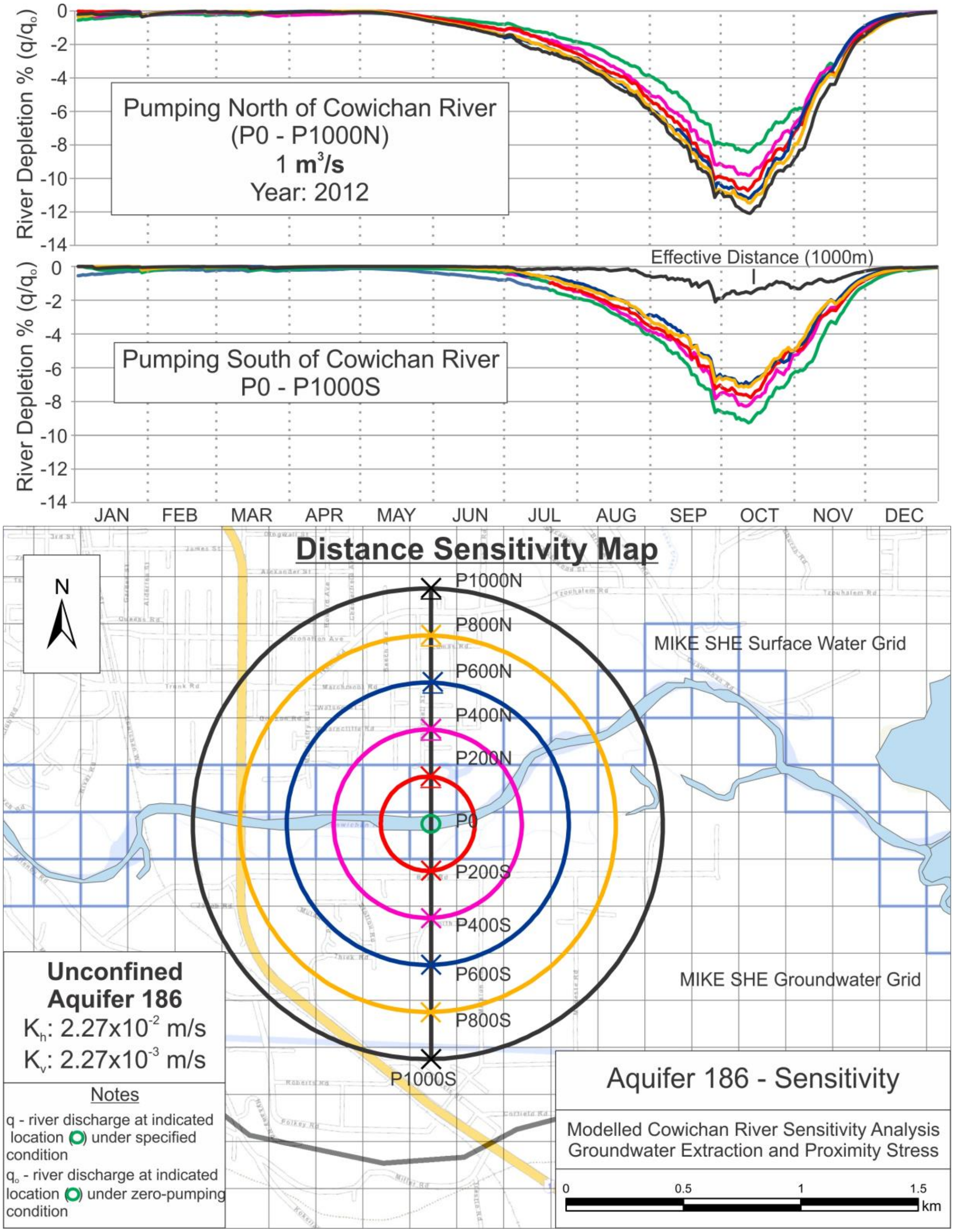

Figure 3.20. Modelled Cowichan River distance - sensitivity assessment for Aquifer 186 (1 m^3/s pumping rate).

A series of maps were generated to represent the extent of drawdown attributed to pumping of a well at increasing distance from the river, relative to zero pumping conditions. The analysis was created by subtracting the interpolated zero-pumping groundwater elevation surface from the pumping simulation for each of the groundwater pumping simulations. All maps represent a “snap-shot” in time, specifically, October 12, 2012. Results for the P1000N, P0, and P1000S pumping simulations are shown in Figures 3.21 to 3.23, respectively. Contour values begin at a drawdown of 0.5 m.

The results of the drawdown maps are:

- Drawdown decreases (by several metres) when wells are < 200 m from the river, suggesting that the pumping results in increased aquifer recharge from surface waters (Figure 3.21).
- The cones of depression of all wells (with the exception of the P1000S well – Figure 3.23) extend through the river nodes, resulting in streamflow depletion as the groundwater table falls below the river stage.
- The critical distance noted in Figure 3.20 above is confirmed in the drawdown analysis, as the drawdown zone created from well P1000S does not intersect the river.

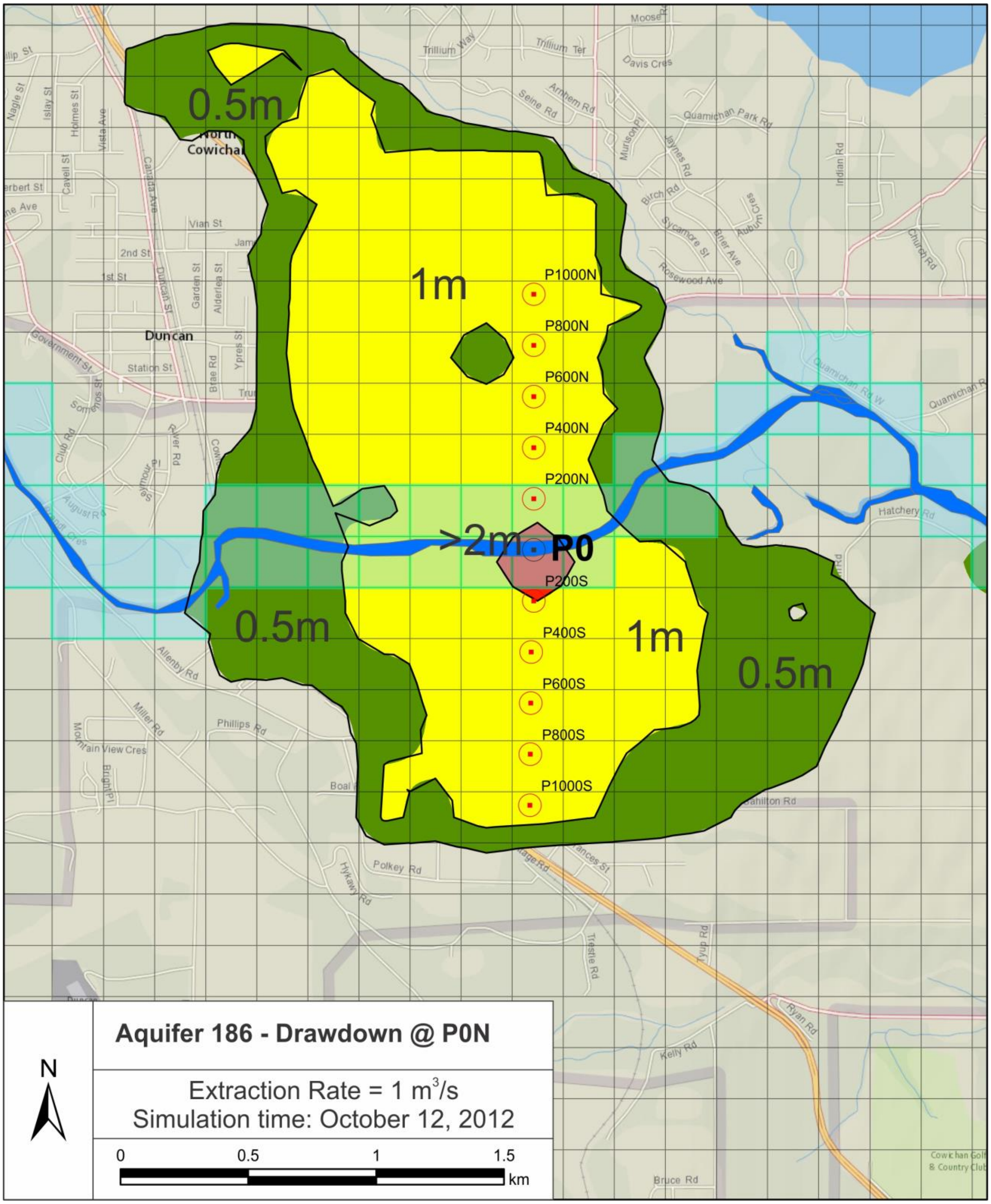

Figure 3.21. Drawdown during distance - sensitivity test. Pumping occurring at P0 location (1 m^3/s).

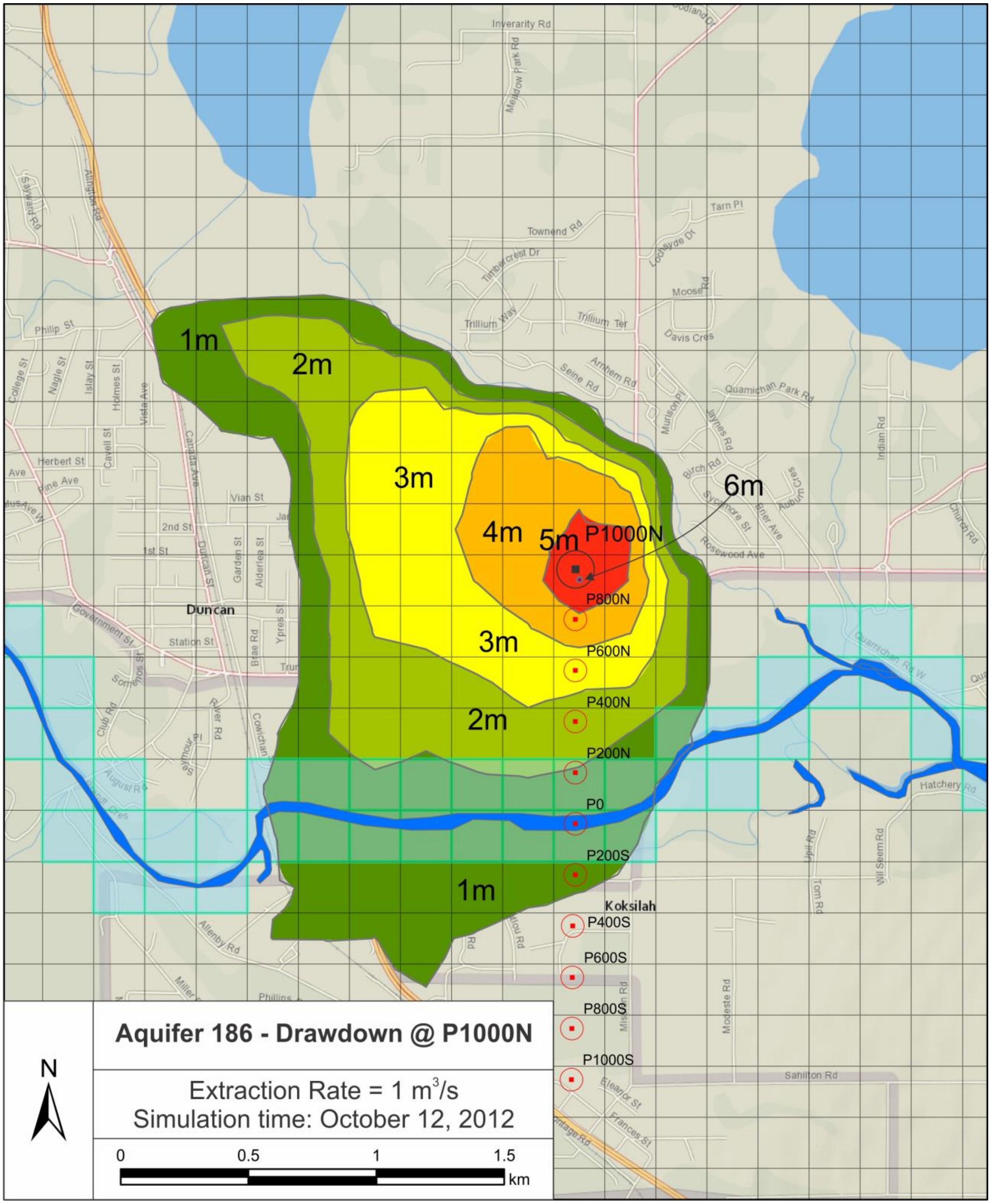

Figure 3.22. Drawdown during distance - sensitivity test. Pumping occurring at P1000N location (1 m³/s).

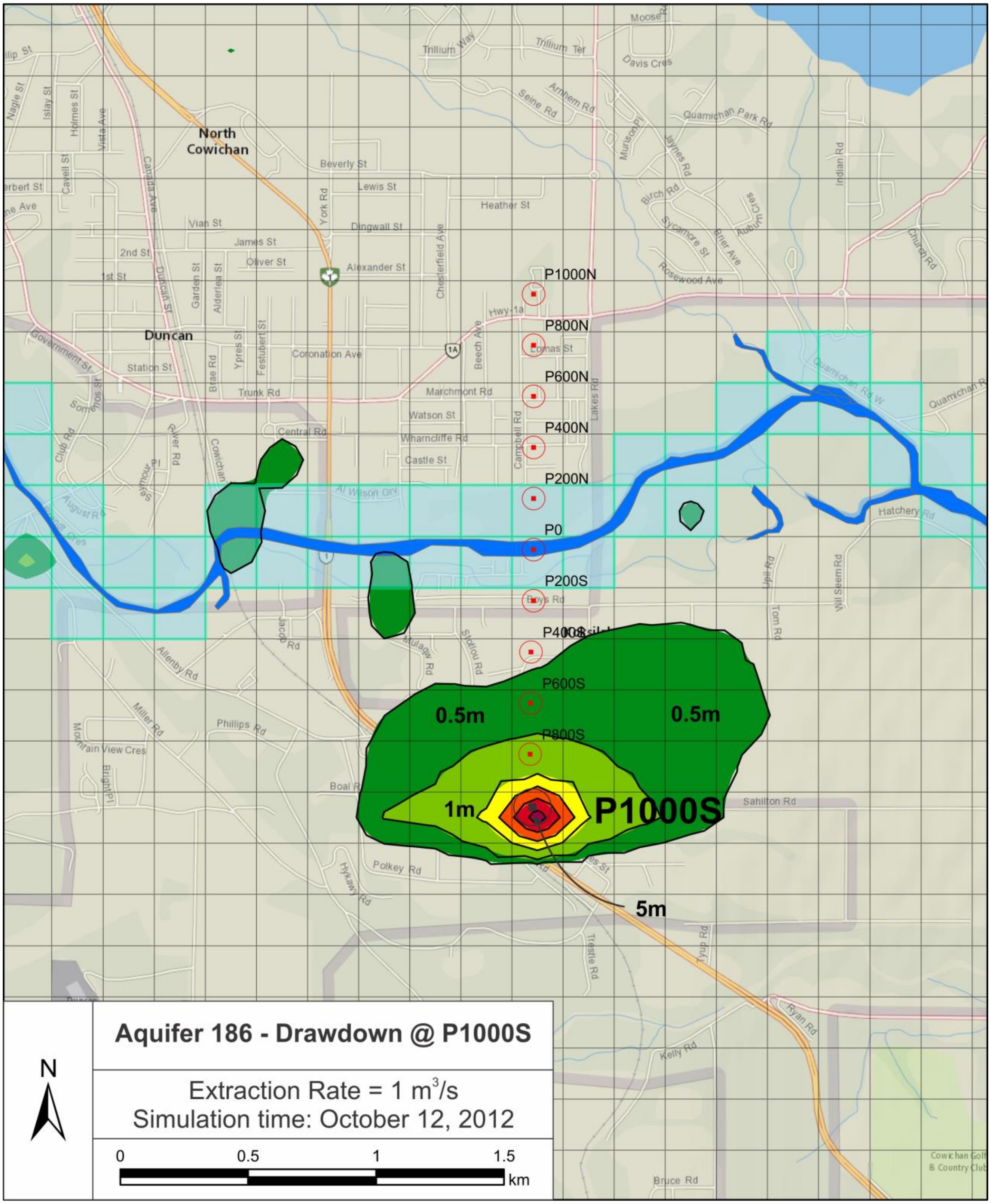

Figure 3.23. Drawdown during distance - sensitivity test. Pumping occurring at P1000S location (1 m^3/s).

After creating the 1 m^3/s drawdown maps, the same process was repeated using a pumping rate of 0.2 m^3/s, which represents the average pumping rate of the major groundwater water wells in the area and, at most, 10% of the modelled low flow discharge of the Cowichan River. The results are shown in Figure 3.24. Unlike the simulations at 1 m^3/s, the results suggest that wells pumped at 0.2 m^3/s for any distance away from Cowichan River have little effect on streamflow. All simulations resulted in streamflow depletions less than 3%.

Figure 3.25 shows the drawdown map for pumping at P0. The small amount of drawdown results in several small, isolated cones of depression, which are artifacts created by the interpolation process (point data to raster). The poor quality results suggest that with the large grid size used the approach is potentially accurate to within 0.5 m or so. A finer grid scale model would likely show a single cone of depression near the river that is much deeper and smaller in area.

Appendix 2 presents similar results for Aquifer 179, which are summarized as follows:

- The stream depletion results for Aquifer 179 are much more consistent than for Aquifer 186, as daily variations (and errors) are minimal.
- Similar to Aquifer 186; streamflow depletions results for wells north of Cowichan River do not correlate with distance, and south of Cowichan River streamflow depletion decreases with increasing distance of the well from the river.
- Slightly higher streamflow depletions are evident with a 0.2 m^3/s pumping rate in Aquifer 179 when compared to the Aquifer 186 results.
- Drawdown is significantly larger in Aquifer 179 than Aquifer 186 at the 0.2 m^3/s pumping rate, owing possibly to the lower hydraulic conductivity of the aquifer.
- The cone of depression of all wells extends through the river nodes, resulting in streamflow depletion as the water table falls below the river stage.
- The cone of depression is largely restricted to the more conductive aquifer materials, extending largely west and east. This may also be controlled by topography, as the aquifer is located in the apex of the valley.
- The drawdowns created by the P400N and P400S wells are very similar to each other.

In summary, the Cowichan Watershed Model provides some insight into the potential impacts of pumping as a function of distance from the river. Comparing the results at 1 m^3/s to 0.2 m^3/s, both aquifers are highly sensitive to extraction rates, more so than proximity to river. However, the results are not accurate given the large grid size of the model. A model with a much finer grid (5 -10 m) near pumping wells is needed to accurate resolve impacts on the Cowichan River discharge and drawdown effects.

Another simplification made is the approximation of the pumping rates, as they only varying slightly monthly. In reality, the fish hatcheries and municipal wells operate on a highly variable daily or hourly pumping schedule, with rates likely greatly exceeding those of the modelled rates. Therefore, the drawdown may be quite different than simulated here.

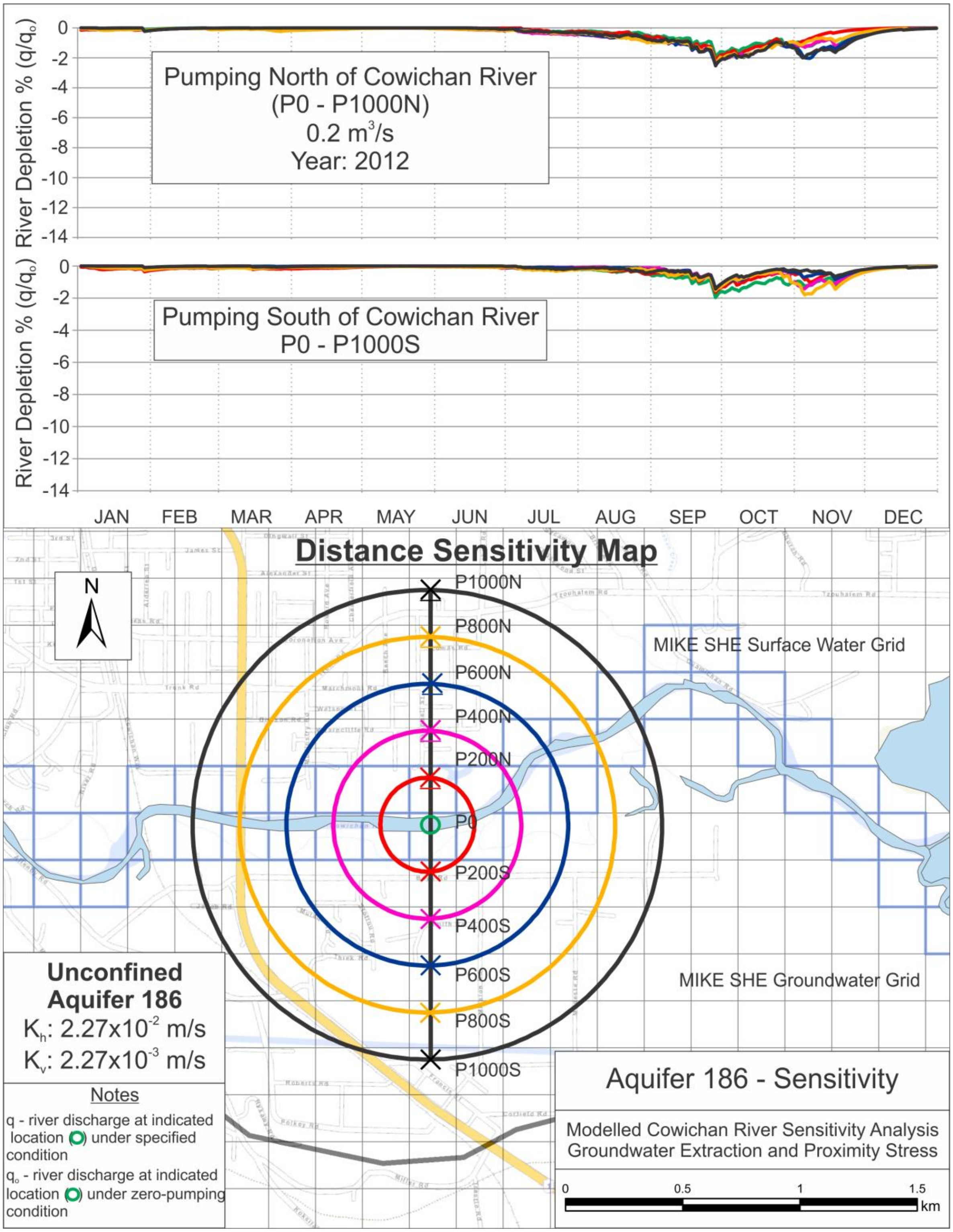

Figure 3.24. **Modelled Cowichan River distance - sensitivity assessment for Aquifer 186 (0.2 m^3/s pumping rate).**

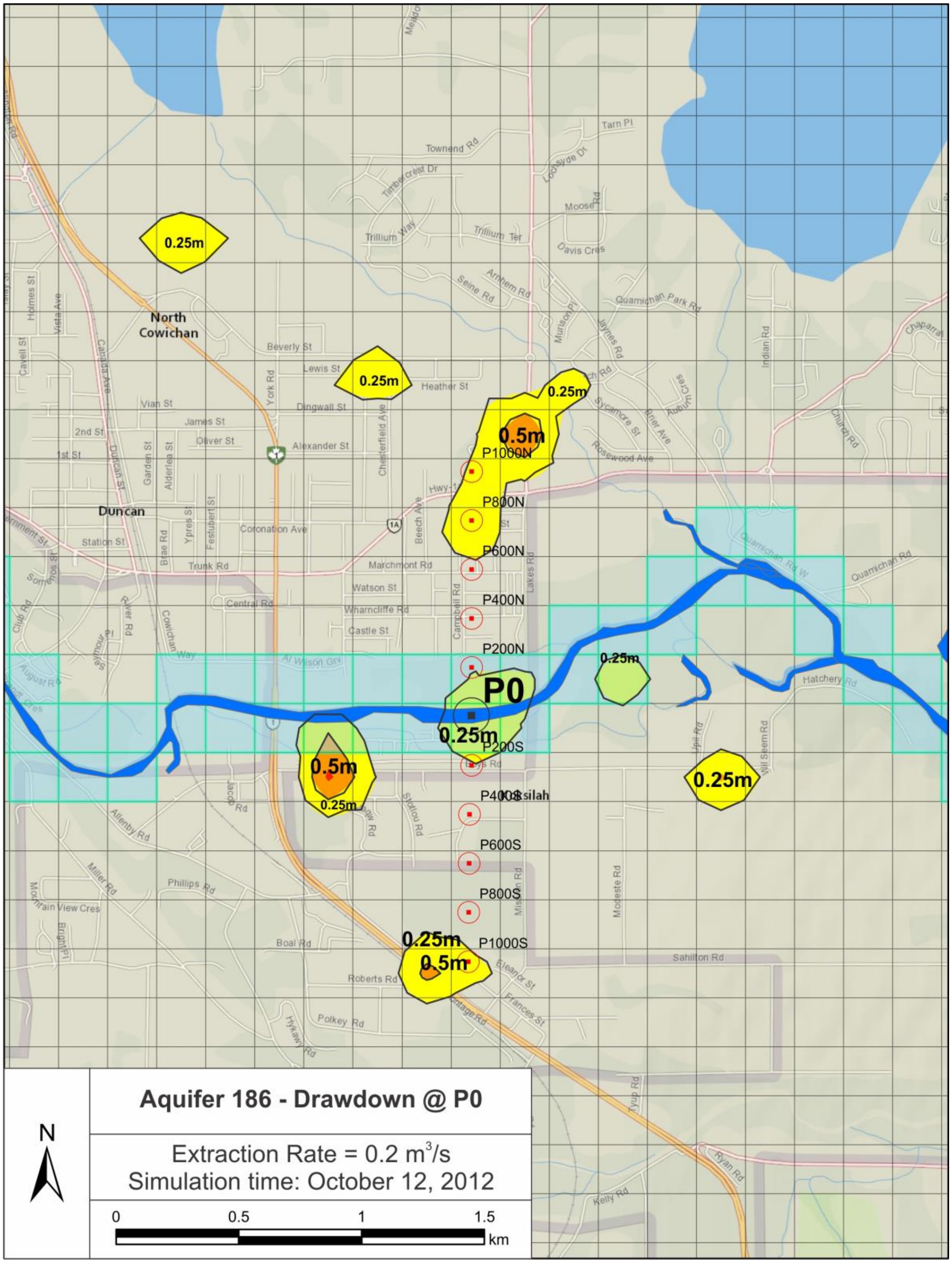

Figure 3.25. Drawdown during distance - sensitivity test. Pumping occurring at P0 location (0.2 m^3/s).

3.10. “Relief Well” Locations

An option to alleviate pressures from groundwater extraction on the surface water system during the summer low flow season could be to install “relief wells”, which are operated at times of the year when flows are low or during periods of drought. These relief wells would be located in areas that likely have minimal interaction with surface water bodies.

To evaluate whether or not a well will interact minimally with surface water bodies, a framework was developed and tested using the Cowichan Watershed Model. The framework consists of utilizing the existing aquifer vulnerability assessment results (Liggett and Gilchrist 2010), which uses the DRASTIC approach to evaluate the potential for surface contamination to reach the groundwater resource; the current (2015) cadastral Crown Land availability; and an initial physical buffer of 200 m from surface water features. The approach involves a GIS “union analysis” of several overlapping parameters. To meet the inclusion, an area must meet the following criteria: low aquifer vulnerability, crown land parcel, and not within a pre-defined (initial -200 m) buffer distance from a surface water body. The separation between groundwater wells and the surface water bodies is adjusted through this process, and is generally dependant on an aquifer’s hydraulic conductivity. This framework is illustrated in Figure 3.26. Note that this approach focuses on the horizontal separation between groundwater and surface water, as the vertical resolution between multiple layered aquifer systems is too fine to be modelled at this scale. However, the model is discretized into alluvium and bedrock, and therefore, wells placed within the bedrock system are a potential vertical separation. It is also important to note that the DRASTIC classification limits the number of available aquifers by essentially removing all of the unconsolidated aquifer class in the region due to their high vulnerability. Such high vulnerability aquifers are typically highly permeable and yield groundwater. Moreover, this method does not replace classical field-based water resource investigations (i.e. pumping tests), but rather is a desktop method for outlining potential areas. Possible interference with existing groundwater users in the vicinity was also not considered.

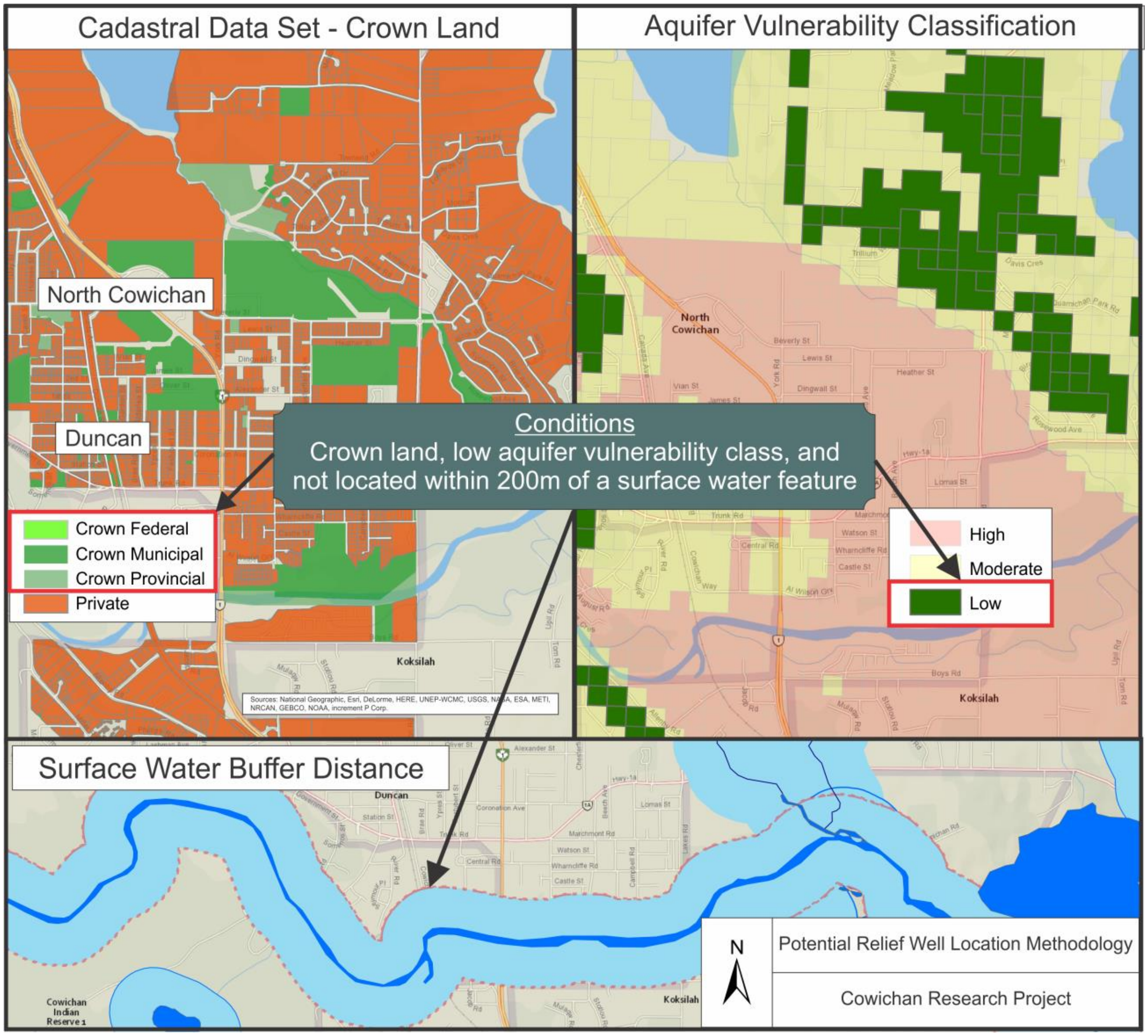

Figure 3.26. Proposed criteria for selecting alternative low flow "relief well" locations.

Areas that fit the criteria of the initial framework are illustrated in Figure 3.27. Only a small portion of the land fits these criteria. The model was then used to determine whether or not the areas could be targeted for installing "relief wells" by simulating water extraction. According to the results, the geological setting of potential relief well locations generally consists of a thin layer of alluvium directly overlying bedrock. Each of the simulated wells were completed in bedrock, with an overall screen length of 20 m, beginning approximately 20 m from ground surface.

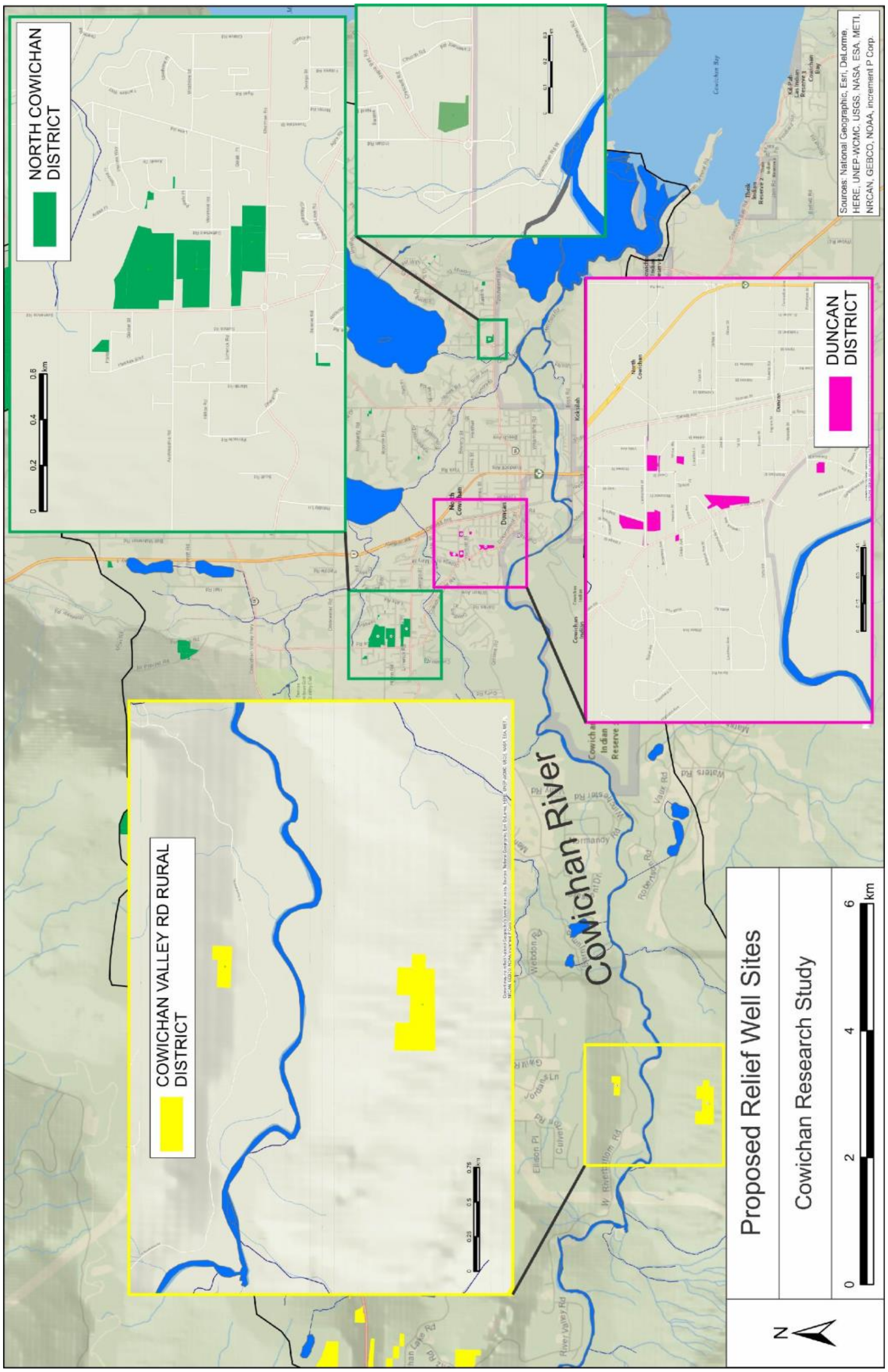

Figure 3.27. Results of the location selection criteria, grouped by location.

Results of the interaction simulations are shown in Figure 3.28. Due to the lower hydraulic conductivity of the bedrock for the model, wells were only able to be pumped at a maximum of approximately 0.01 m^3/s or 150 US gallons per minute (gal/min). Therefore, rather than testing each well individually, all wells were collectively pumped at their maximum yield. This of course assumes that such yields are possible. The Cowichan River was monitored for streamflow depletion; not for the direct interaction with the river, but for the potential of depressing the water table in the surficial aquifers in contact with the bedrock aquifers (indirectly influencing flows within the river). Figure 3.28 indicates that pumping from the bedrock relief wells causes no significant reduction in Cowichan River streamflow. Cones of depression were quite extensive, both horizontally (>1 km) and vertically (40 meters) as wells were being pumped at their maximum simulated capacity. Of course, significant infrastructure would be needed to connect a series of bedrock wells to a municipal water supply; however, water could be trucked from a centralized pumping station under emergency conditions.

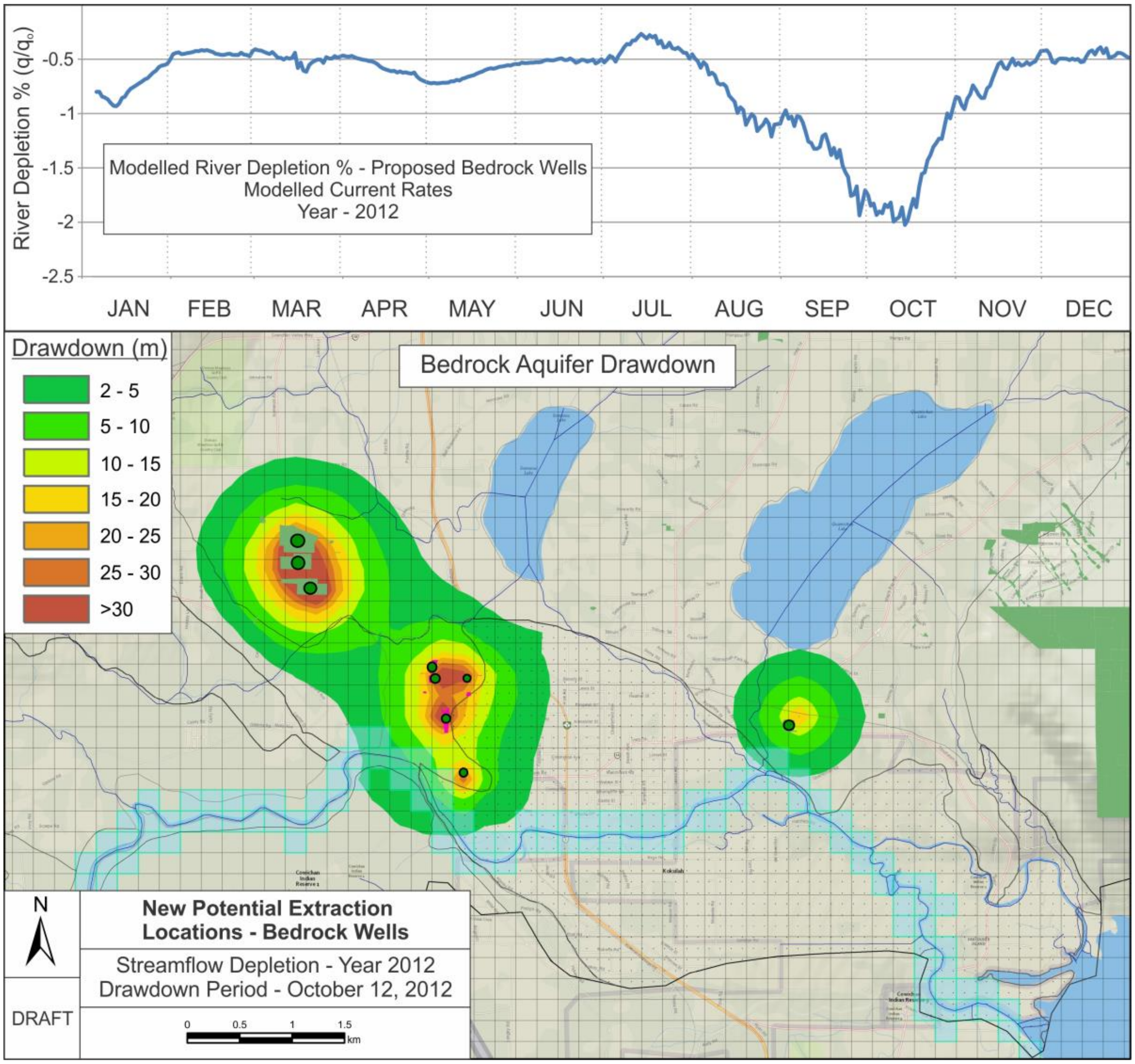

Figure 3.28. Stream flow depletion assessment and example of the drawdown assessment for the proposed "relief wells."

3.11. Climate Change Impacts

In order to assess how vulnerable the Cowichan Watershed may be to the potential impacts of climate change, future climate change data were used to force the MIKE SHE model. Two MIKE SHE simulations were run (one representing the 2050s and one the 2080s). The projected climate change impacts were assessed using the BC Regional Analysis Tool (Pacific Climate Impacts Consortium 2014). Specifically, the climate projections from the "TreeGen ensemble" were used (Cannon 2008, Stahl et al. 2008). The TreeGen downscaling tool was applied to an ensemble of global climate models (GCMs) and SRES AR4 emissions scenarios, with the results compiled for the Province of BC. The results from Canadian Global Coupled Model 3 (CGCM3)-A2 (five model runs) and the Max-Planck Institute for Meteorology (MPI) ECHAM5-A2 (one model run) were used in this study. The A2 emissions scenario was selected because it represents a "worst case" scenario in terms of emissions, CO_2 concentrations, and the resulting temperature increase (Nakicenovic 2000). Several datasets were extracted for the Cowichan area: absolute temperature change (max, min, mean, and medium) and percent change for precipitation and relative humidity for the time periods 2050s (2039–2069) and 2080s (2070–2099).

Figure 3.29 illustrates the absolute change in mean monthly temperature and relative change (as a percent) in monthly precipitation averaged across the study area. Temperature is expected to increase between 1 and 3°C during the period 2050, and by as much as 2–5°C for the 2080s time period (Figures 3.29a and 3.29c). The largest temperature differences are expected from July to August and from December to January. Figures 3.29b and 3.29d indicate that by the 2050s an increase in precipitation of 10–20% is expected for the winter months and a reduction by up to 20% in the summer months. This trend continues throughout the 2080s, increasing by up to 30% in the winter months, and decreasing by 40% in the summer months.

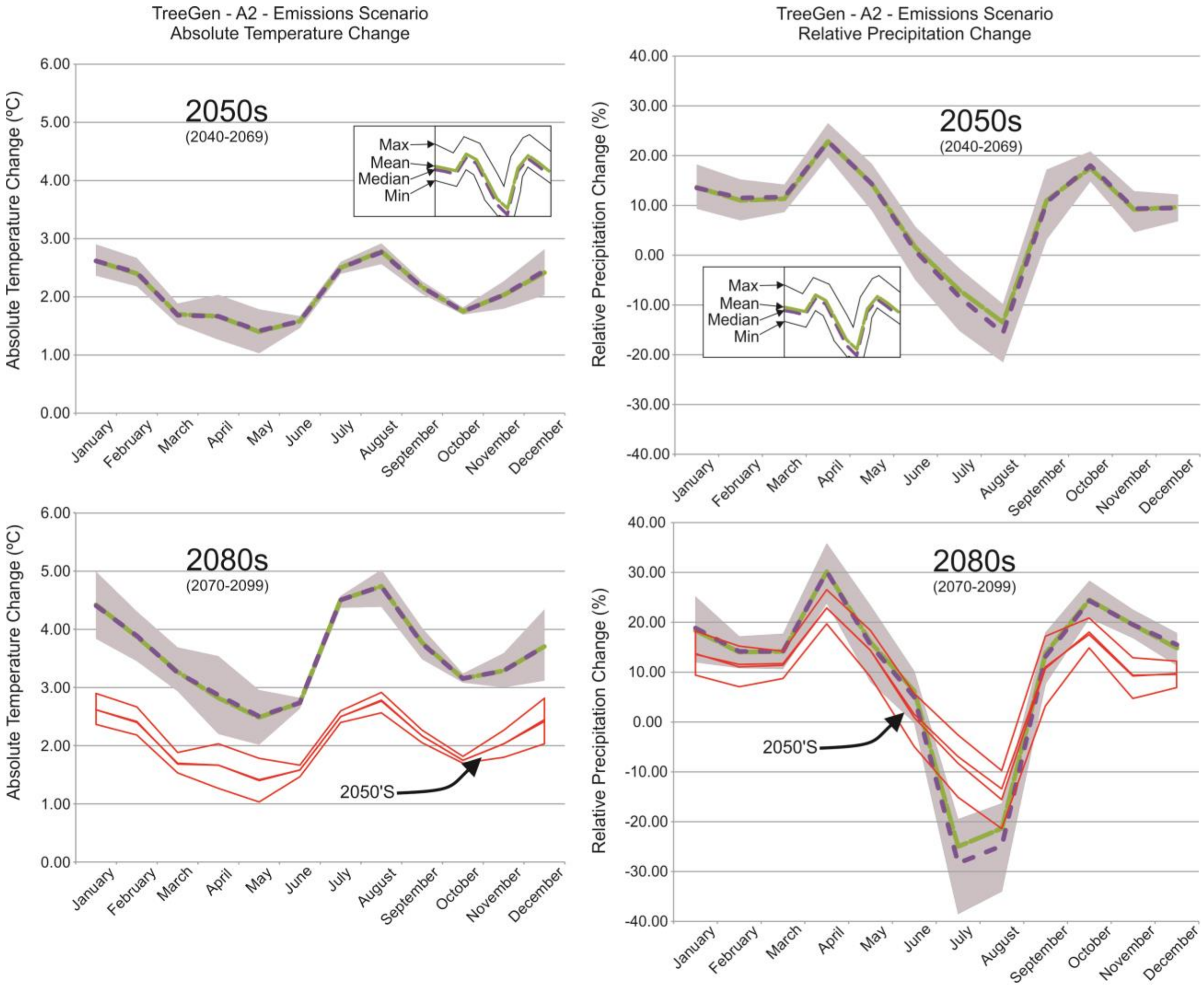

Figure 3.29. Projected climate shifts for the 2050s and 2080s for the Cowichan Region (TreeGen ensemble—A2 emissions scenario). Data from Pacific Climate Impacts Consortium (2014).

The mean monthly climate shift factors (from the selected models in the ensemble) for each future time period were applied to historical data (1998–2012) from the Cowichan Lake Forestry Research Climate Station and the Kelvin Creek Climate Station. Specifically, the mean monthly climate shifts were applied directly (subtraction or addition to the mean daily temperatures or % increase/decrease to the precipitation rates) to the temporal climate datasets in MIKE SHE. The model was rerun for two 14 year period (representing a shift in the 1998–2012 climate data to each of the 2050s and 2080s climate).

PET was also adjusted for the climate change simulations. The projected minimum, maximum, and mean temperatures, as well as the projected changes in relative humidity were used to calculate new PET values to reflect the projected climate. The AWSET program (Cranfield 2002) was utilized to generate daily PET using the Penman-Monteith equation (Penman 1948). The shifts to the temperature and humidity were added to the AWSET program by subtracting or adding the absolute temperature change to the minimum, maximum, and mean historical daily values, as well as the relative percent change to the historical relative humidity daily values. Modeled solar insolation and wind speed remained the same. By the 2050s, PET is expected to increase by 6.4 to 12.1% and by the 2080s by 11.9 to 21.2%. The relative shifts in PET closely reflect the projected shifts in temperature. The same relative change in PET (% change) was applied to all climate zones represented in the model (see Foster 2014).

The climate change results were analyzed over the last 10 years of the full 14 year simulation period to avoid the model spin-up time. The results represent a ten year time span during each of the 2050s and 2080s (numbered WY 1 through 10). The results focus on verifying projected increased atmospheric evaporative demand, altered groundwater storage or recharge, decreased snow accumulation and accelerated melt, and altered timing and magnitude of streamflow (peak flows, low flow) as suggested by Pike et al. (2010) for BC as a whole. The evaporative demand and changes to groundwater storage and recharge were assessed using the MIKE SHE water balance tool. The yearly results for the 2050s and 2080s are shown in Tables 3.6 and 3.7, respectively.

Compared to the water balance values for the baseline model (Table 3.2), the following trends are observed over time (baseline to 2050s to 2080s):

- Precipitation increases, with subsequent increases in runoff (overland flow) to the Cowichan River;
- Evapotranspiration increases;
- All other aspects of the water balance remain fairly constant, including recharge, which is shown to increase only slightly. The estimated changes in recharge are within the uncertainty (error) range in the model.

These results are consistent with results of future recharge modelling carried out in other areas of BC for the 2050s and 2080s (e.g. for the Grand Forks aquifer - Scibek and Allen 2006a; the Lower Fraser Valley – Scibek and Allen 2006b, Allen et al. 2010; the Oliver region of the Okanagan - Toews and Allen 2009; and the Gulf Islands – Appaih-Adjei and Allen 2009).

Table 3.6. Simulated total water balance results for the 2050s for each water year (WY) (mm/a).

2050s Year	P	ET	Snow-Storage Change	OL-Flow to River	OL Storage change	OL-BF	Base-flow to River	River to Base-flow	SZ-Storage change	SZ-BF	Pump	Total Error	R
WY-1	2877	-1149	0	-1608	-2	-208	-57	59	79	0	-24	100	439
WY-2	3134	-1278	0	-1735	-3	-214	-60	59	-38	0	-24	-28	607
WY-3	2798	-1306	0	-1561	0	-207	-56	59	114	0	-24	-53	475
WY-4	2925	-1241	0	-1742	-1	-217	-56	60	130	0	-24	-32	460
WY-5	3873	-1265	0	-2357	-14	-245	-69	63	-74	0	-24	21	656
WY-6	2651	-1225	0	-1575	12	-208	-62	60	197	0	-24	-40	397
WY-7	1681	-1160	0	-607	2	-164	-46	50	89	0	-24	-52	339
WY-8	3318	-1233	0	-1870	-8	-228	-67	58	-66	0	-24	16	591
WY-9	3139	-1182	0	-1892	2	-230	-65	59	65	0	-24	4	456
WY-10	2634	-1089	0	-1647	3	-214	--63	59	206	0	-24	0	380
Avg.	2903	-1212	0	-1659	-1	-213	-61	59	70	0	-24	-7	480
Water Bal. (%)	100	-42	0	-57	0	-7	-2	2	2	0	-1	-1	17

Table 3.7. Simulated total water balance results for the 2080s for each water year (WY) (mm/a).

2080s Year	P	ET	Snow-Storage Change	OL - Flow to River	OL Storage change	OL-BF	Base-flow to River	River to Base-flow	SZ-Storage change	SZ-BF	Pump	Total Error	R
WY-1	3006	-1202	0	-1684	-2	-212	-57	59	80	0	-24	97	454
WY-2	3262	-1343	0	-1798	-8	-218	-60	59	-39	0	-24	-35	632
WY-3	2908	-1366	0	-1623	2	-210	-56	59	113	0	-24	-65	492
WY-4	3048	-1302	0	-1806	-1	-219	-56	60	127	0	-24	-38	486
WY-5	4054	-1330	0	-2501	-12	-250	-69	63	-68	0	-24	-1	657
WY-6	2763	-1286	0	-1648	10	-210	-62	60	197	0	-24	-65	431
WY-7	1753	-1221	0	-633	2	-164	-46	50	82	0	-24	-75	389
WY-8	3483	-1302	0	-1980	-9	-233	-67	58	-67	0	-24	-3	620
WY-9	3264	-1245	0	-1977	2	-232	-65	59	65	0	-24	-20	481
WY-10	2752	-1148	0	-1717	3	-216	--63	59	209	0	-24	-10	397
Avg.	3029	-1274	0	-1737	-1	-216	-61	59	70	0	-24	-21	504
Water Bal (%)	100	-42	0	-57	0	-7	-2	2	2	0	-1	-1	17

To further assess the expected effects of climate change, the results were examined monthly (Tables 3.8 and 3.9). Table 3.10 combines the results for precipitation (P), evapotranspiration (ET), and recharge. The following summarizes key observations:

- Precipitation: precipitation rates increase (relative to baseline) from September through to June, with the greatest increases in October, November, and January (>50 mm/month by the 2080s);
- Evapotranspiration (ET): ET rates increase (relative to baseline) throughout the entirety of the year, with the greatest increases from April to June;
- Recharge: recharge rates increase (relative to baseline) for all months except July. The greatest increases occur in October and November.

Table 3.8. Simulated mean monthly water balance results for the 2050s (mm/month).

2050s Mean Monthly	P	ET	Snow-Storage Change	OL - Flow to River	OL Storage change	OL-BF-out	Base-flow to River	River to Base-flow	SZ-Storage change	SZ-BF	Pump	Total Error	R
Jan	528	-69	5	-396	-8	-30	-7	7	-16	0	-2	24	62
Feb	246	-79	0	-175	9	-21	-7	5	23	0	-2	10	28
Mar	344	-93	4	-231	-1	-22	-7	6	-1	0	-2	7	56
Apr	190	-118	1	-108	5	-17	-6	5	35	0	-2	-5	23
May	112	-147	0	-31	4	-14	-6	4	56	0	-2	-13	24
Jun	56	-155	0	-3	5	-12	-5	4	87	0	-2	-15	-7
Jul	33	-146	0	6	5	-12	-4	3	91	0	-2	-17	-29
Aug	37	-111	0	5	3	-12	-4	3	56	0	-2	-13	-22
Sep	102	-85	0	-5	-1	-11	-3	3	-14	0	-2	-6	12
Oct	298	-71	0	-85	-10	-14	-3	4	-119	0	-2	8	120
Nov	500	-60	-7	-284	-10	-21	-3	7	-101	0	-2	32	132
Dec	460	-60	-5	-329	-4	-26	-6	7	-28	0	-2	20	68

Table 3.9. Simulated mean monthly water balance results for the 2080s (mm/month).

2080s Mean Monthly	P	ET	Snow-Storage Change	OL - Flow to River	OL Storage change	OL-BF-out	Base-flow to River	River to Base-flow	SZ-Storage change	SZ-BF	Pump	Total Error	R
Jan	549	-74	5	-411	-7	-30	-7	7	-15	0	-2	27	61
Feb	252	-85	-1	-175	8	-21	-7	5	24	0	-2	11	29
Mar	352	-100	1	-231	0	-22	-7	6	-1	0	-2	7	57
Apr	200	-124	0	-113	5	-17	-6	5	36	0	-2	-6	27
May	114	-154	0	-30	5	-14	-6	4	58	0	-2	-15	26
Jun	59	-161	0	-3	5	-12	-5	4	86	0	-2	-18	-4
Jul	27	-152	0	8	5	-12	-4	3	95	0	-2	-21	-31
Aug	34	-113	0	7	4	-12	-4	3	55	0	-2	-17	-19
Sep	104	-87	0	-4	-1	-11	-3	3	-16	0	-2	-7	13
Oct	315	-75	0	-88	-11	-14	-3	4	-125	0	-2	12	124
Nov	545	-63	-3	-317	-12	-21	-3	7	-105	0	-2	37	136
Dec	481	-64	-2	-348	-4	-27	-6	7	-27	0	-2	22	68

Table 3.10. Comparison of mean monthly water balance results for the baseline, 2050s, and 2080s for the Cowichan watershed (mm/month).

Parameter	Precipitation			ET			Recharge		
Scenario	Baseline	2050s	2080s	Baseline	2050s	2080s	Baseline	2050s	2080s
Jan	464	528	549	-60	-69	-74	61	62	61
Feb	221	246	252	-70	-79	-85	24	28	29
Mar	309	344	352	-86	-93	-100	56	56	57
Apr	154	190	200	-110	-118	-124	20	23	27
May	98	112	114	-138	-147	-154	20	24	26
Jun	55	56	59	-146	-155	-161	-7	-7	-4
Jul	35	33	27	-138	-146	-152	-28	-29	-31
Aug	43	37	34	-108	-111	-113	-26	-22	-19
Sep	92	102	104	-81	-85	-87	13	12	13
Oct	253	298	315	-66	-71	-75	107	120	124
Nov	456	500	545	-54	-60	-63	131	132	136
Dec	418	460	481	-53	-60	-64	67	68	68

The most noticeable effects of climate change within the Cowichan Watershed are related to snow. The continued increases in temperature consistently decrease the amount of snow accumulation (water storage), and alter the melt timing (earlier melt) as projected for other regions of BC and the Pacific Northwest (Mote et al. 2003, Rodenhuis et al. 2007, Casola et al. 2009). Snow accumulation within the Cowichan is especially sensitive to climate change due to the dependancy of altitude for snow accumulation (currently simulated at above the 200 masl snow line). Snow accumulation near the snow line undergoes rapid melting due to temperature effects. A warmer climate means that rain, as opposed to snow, will fall at progressively higher elevations during the winter months, and elevations where snow accumulation is currently limited may have less winter snowpack, and that snowpack will melt rapidly. The snow line represents a “mixed regime,” where the boundary between rainfall and snowfall precipitation exists.

Figure 3.30 illustrates an example of the simulated spatial snowpack for the Cowichan region under the current climate condition, the 2050s, and the 2080s. A drastic decrease in snow accumulation is projected for the 2050s and 2080s. The snowpack becomes increasingly restricted to higher elevations, controlled largely by the temperature lapse rates, as temperatures within the valley are largely above 0°C. Both the spatial extent of the snowpack and the amount of accumulation within snowpack areas are greatly reduced.

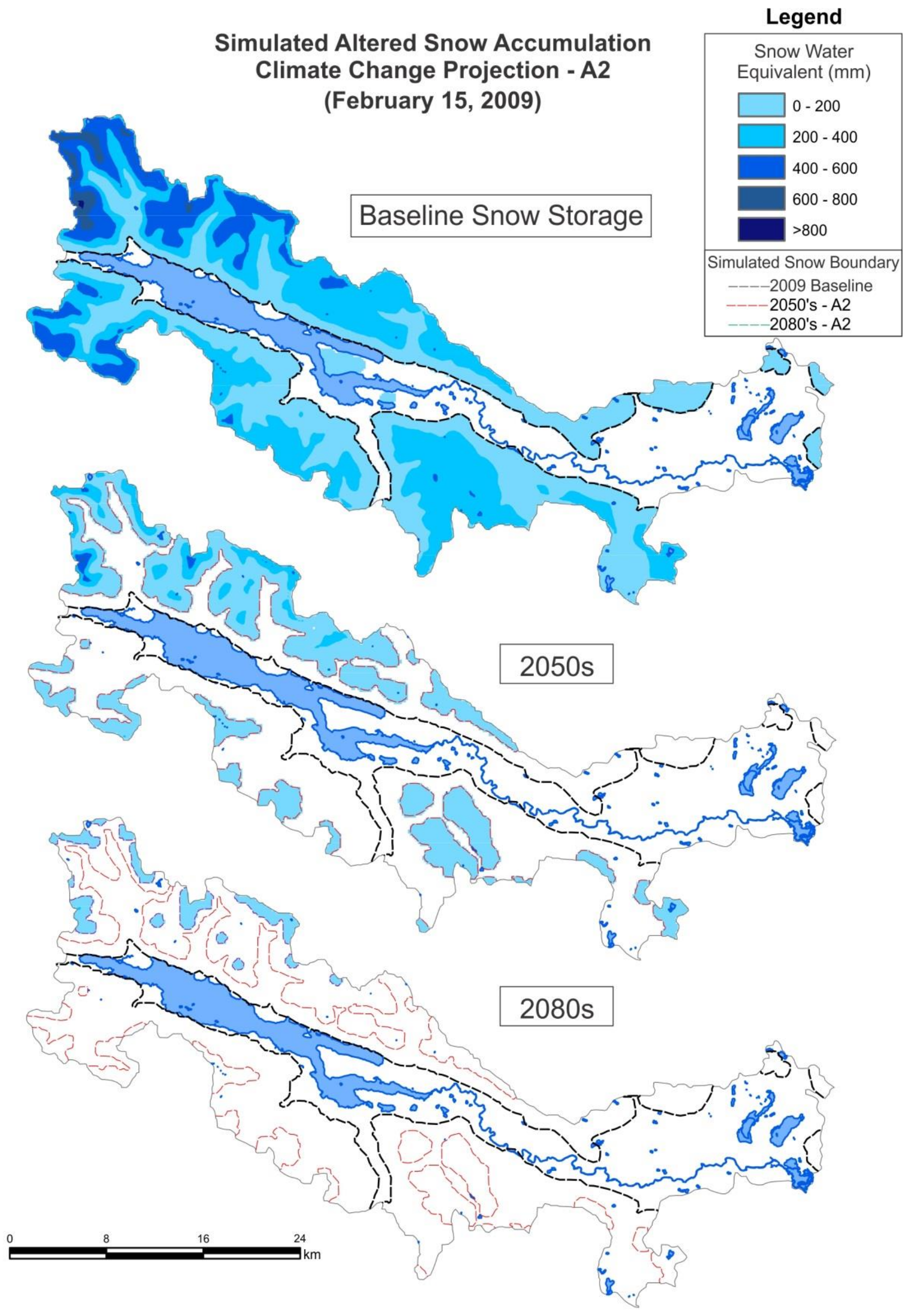

Figure 3.30. Simulated spatial snowpack SWE (mm) for baseline, 2050s and 2080s (from Foster and Allen 2015).

Figure 3.31 shows the simulated variation in the SWE (mm) at the Jump Creek Snow Pillow Station for the historical and climate change scenarios. By the 2050s, in most years, the onset of snow accumulation occurs later than historically, the total accumulation is much less, and the melt occurs much earlier. By the 2080s, only a small snowpack accumulates, as the snow often melts quickly (days) after accumulation. The simulation produces a "flashy" accumulation and melt pattern, which, as discussed below translates into shifts in the hydrologic regime.

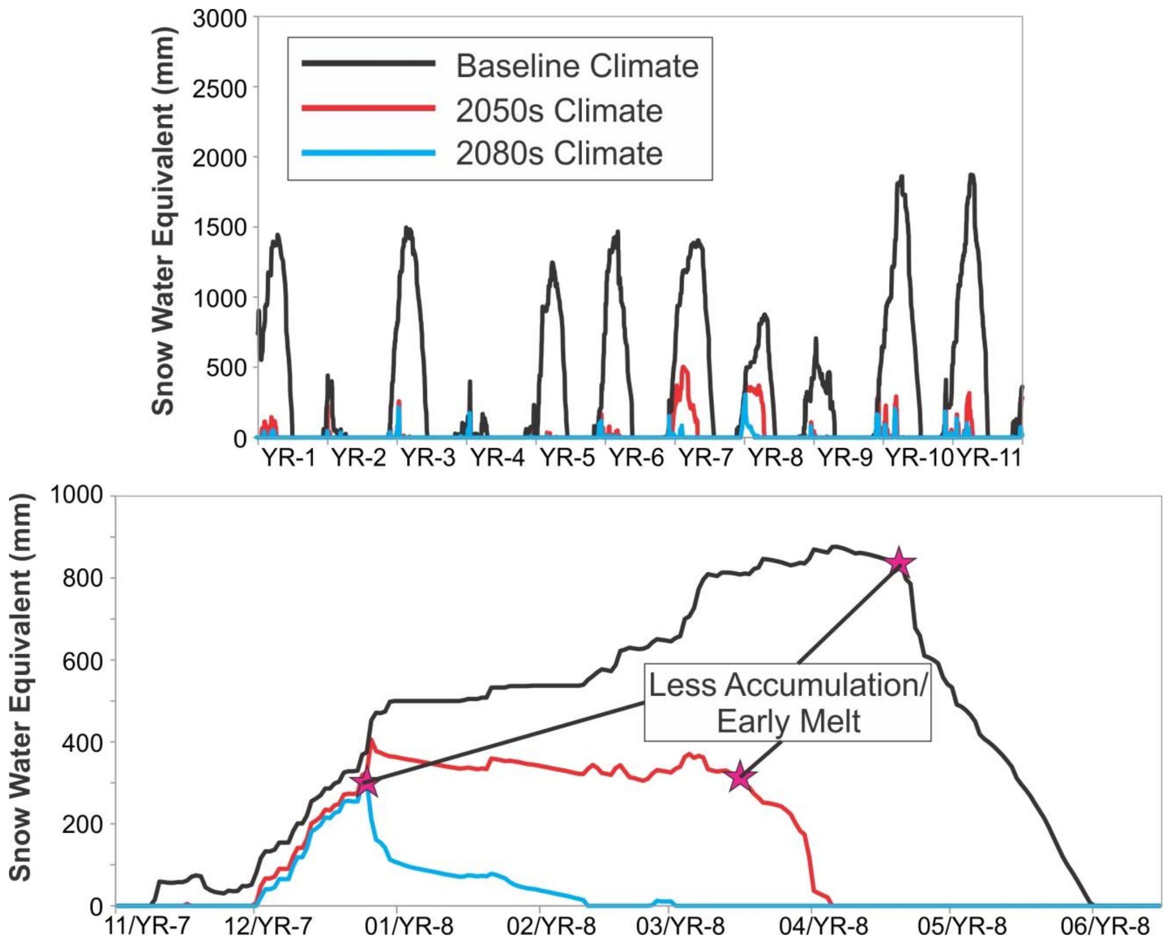

Figure 3.31. Simulated SWE (mm) at the Jump Creek Snow Pillow Station for the baseline, 2050s and 2080s.

Figure 3.32 shows the changes in base elevation of the snowpack. Historically, the simulated snowpack is sustained throughout the winter and early spring at the 200 masl elevation (for February 15, 2009). For the same date in future climate periods, the simulation results suggest that the snowpack will increase to 600 masl and 900 masl for the 2050s and 2080 time periods, respectively.

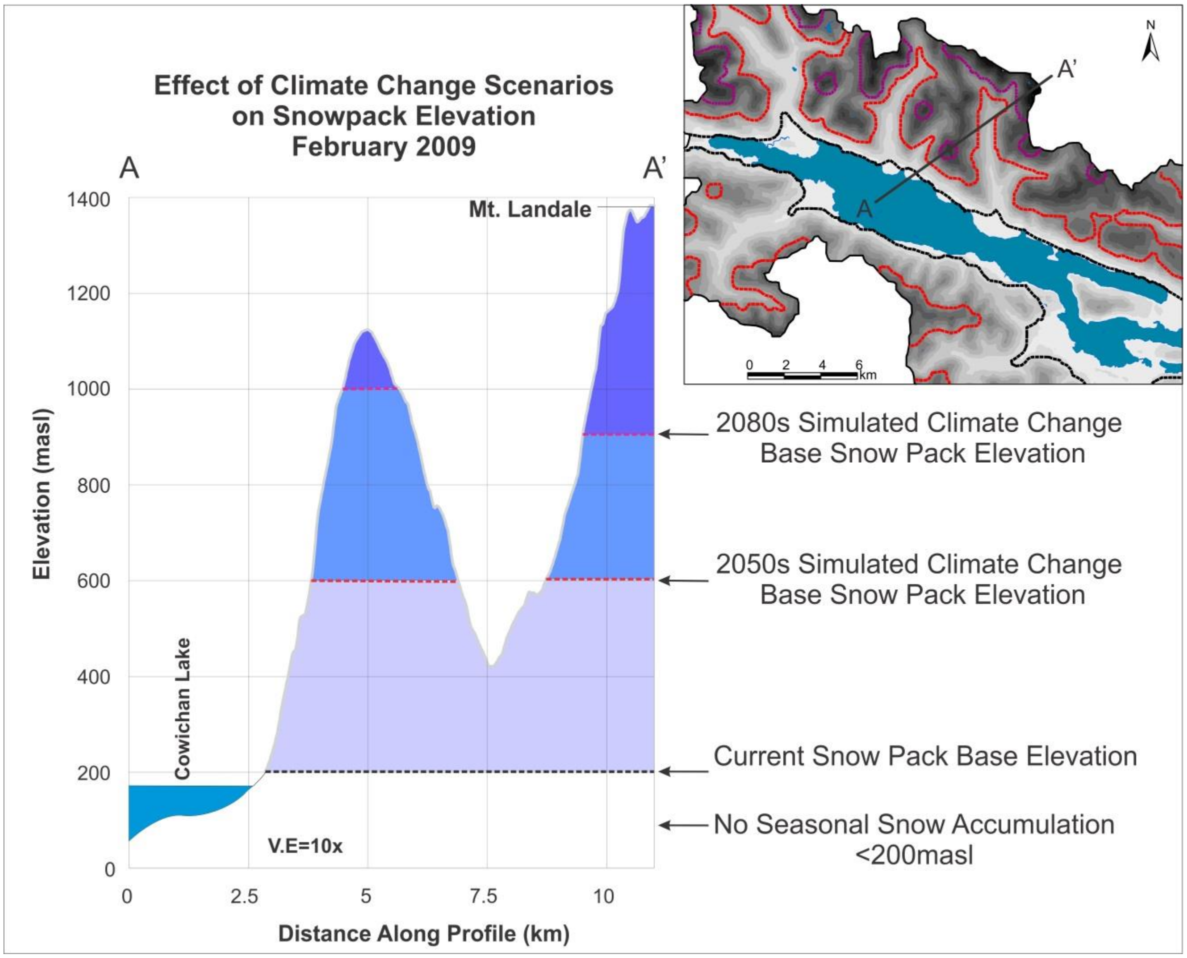

Figure 3.32. Simulated representation of the base elevation of the snowpack on February 15 under current climate conditions, the 2050s and the 2080s.

As larger portions of winter precipitation fall as rain in future, the amount of water stored as snowpack decreases significantly, which greatly alters river flow dynamics throughout the year (Pike et al. 2010). In general, in the Cowichan, the freshet will occur approximately 44 days earlier by the 2050s, and >100 days earlier by the 2080s. The simulated earlier freshet season results in increased peak flows during the winter months, and lower flows during the summer and fall. Figure 3.33 shows the Cowichan River discharge (at the 08HA011 hydrometric station) near Duncan throughout the simulation for the baseline and climate change simulations. The higher resolution time series (bottom) shows that the peak flows in the winter increase by as much as 100 m^3/s; while snowmelt-driven flows are no longer observed and summer flows are more than 50% less. These trends are fairly consistent for all model years. The hydrologic results are consistent with results of studies by Loukas et al. (2002) and Merritt et al. (2006) for other areas of BC.

For the Cowichan, the effect of these river discharge changes may be mitigated by the operation of the weir, which can provide a means to store additional water within Lake Cowichan. However, typically during the winter, the lake stage is at a level such that water directly flows over the weir, and therefore, the ability to store additional water in the future may be similar to today. The key will be the adjustment of the operating rules to maximize storage potential and release rates during the early spring to mitigate future extreme low flow situations. The simulation results suggest that the decreased summer flows may put additional stress on already sensitive aquatic habitat.

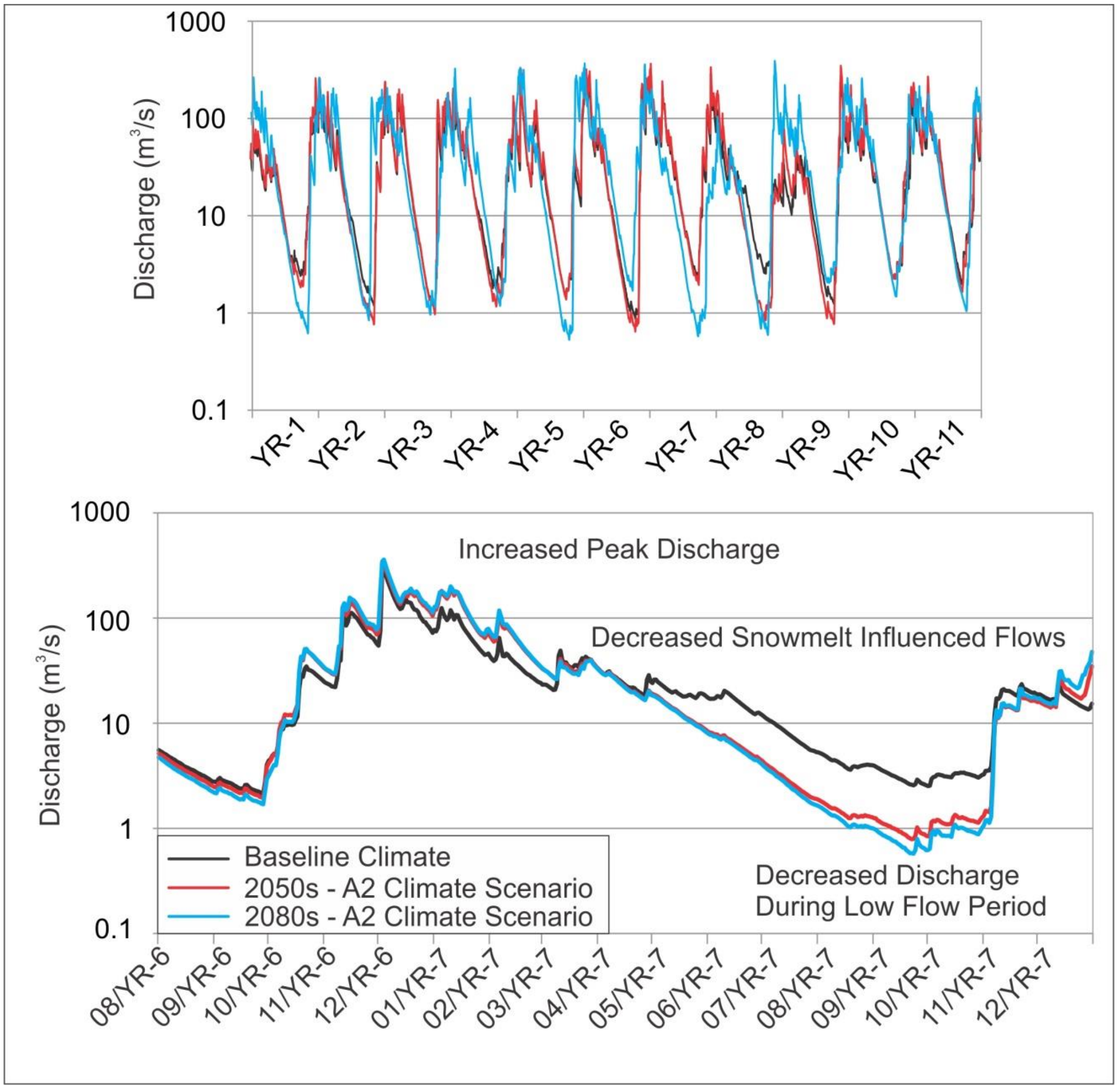

Figure 3.33. Simulated Cowichan River flows under baseline and climate change conditions (from Foster and Allen 2015).

4. Conclusions

4.1. MIKE SHE Modelling Study - GW-SW Interactions

MIKE SHE (DHI 2007) was used to model groundwater – surface water interactions within the Cowichan watershed, estimate a water balance, simulate capture zones for wells and the Cowichan River, estimate the effects of pumping from groundwater extraction wells, and project how climate change may influence the hydrology of the watershed. Conclusions stemming from the modelling work are described below:

- The Cowichan River is dominantly gaining in the upper reaches except at a few isolated locations. At lower elevation, the river becomes dominantly losing;
- The aquifer hydraulic properties appear to be the main control on the magnitude of exchange that occurs, as most exchange occurs through the aquifers with the higher hydraulic conductivities;
- Evapotranspiration ranges from 0.5 to 10 mm daily, and is estimated at 1126 mm annually (44% of the annual precipitation);
- Groundwater recharge over the extent of the watershed was found to range from approximately 253 to 630 mm annually, with the mean amount being 438 mm. This average corresponds to 17% of the annual precipitation;
- Recharge varies significantly throughout the year. The highest recharge occurs in October and November (> 100 mm/month), while a recharge deficit (P-ET) is indicated in the months of June, July and August, largely reflecting precipitation patterns;
- Simulated groundwater discharge locations coincide with mapped springs and wetland areas;
- The water balance for year 2012 (extended low flow conditions in the Cowichan River) shows significantly lower amounts of recharge and precipitation, with increased evapotranspiration, when compared to average conditions;
- Groundwater pumping noticeably affects exchanges between the Cowichan River and the aquifer within the lower valley (near Duncan). Exchange conditions at some locations change from gaining (no pumping included in the model) to losing (pumping included). Within the losing segments of the river, the large negative peaks in losses are lessened with no pumping;

- The particle tracking module in MIKE SHE illustrates the capture zones of the major wells within the lower valley. The following wells had capture zones that intercepted the Cowichan River: the North Cowichan municipal well, the Marine Harvest Hatchery well, the City of Duncan south well, and possibly the Cowichan River Hatchery;
- At current modelled discharge rates, individual modelled wells generally resulted in streamflow reductions of nil to 5% during the low flow seasons
- Overall pumping resulted in a 20% reduction in streamflow during the peak low flow period in the model;
- Both the discharge rate and the proximity of a well pumping an aquifer near a surface water result in streamflow depletion;
- Modelled drawdown and capture zone analysis can be used as a tool to predict future groundwater-surface interactions; and
- Modelled bedrock groundwater extraction “relief wells” resulted in negligible streamflow depletions.
- Climate change is expected to influence the Cowichan Watershed in the following ways: precipitation and subsequent runoff increases; evapotranspiration increases; while all other aspects of the water balance remain fairly constant, including recharge, which is shown to increase only slightly;
- Climate change simulations show significant alteration to the accumulation of snow within alpine regions, as the snowpack in the 2080s simulation become increasingly limited to higher elevations;

4.2. Limitations of the Study and Future Opportunities

The MIKE SHE model developed for the Cowichan Watershed required simplification of the hydrogeological and river model in order to simulate processes at this large scale. Consequently, the model’s ability to simulate local conditions is limited. This has implications for future use of the model as well as for data collection that can be used to improve the model. For example, the model should not be used to simulate local exchange conditions within a river reach, although it can be used to set a regional context for measuring such interactions. Future in-stream studies can potentially target the key gaining sections of the Cowichan River, and additional monitoring/investigations can be carried out to confirm the modelling results.

The capture zones, pumping sensitivity analysis, and drawdown extents simulated for the wells and the river should be viewed with caution, but can serve as a preliminary tool for more detailed analysis. Capture zones delineated by particle tracking methods only consider advective transport; diffusive and dispersive transport mechanisms are not simulated. Therefore, the actual extent of the capture zones from the perspective of contaminant transport may be larger. More rigorous capture zone analysis is warranted, but this would require a suitable mass transport code. As stated in the report, the cell size used for the model (200 m) is relatively large for making local approximations, and refinements can be made with smaller horizontal and vertical cell discretization. A more proper approach to illustrate the effects of groundwater extraction on the conditions of the river would be to use a small scale model of a specific region. Such a small scale model should incorporate a higher degree of resolution in the representation of groundwater levels, aquifer conditions, land surface elevations (if modelling unsaturated zone flow), and incorporate the schedule of the extraction of each groundwater well. Estimates of recharge, AET, and groundwater levels may be obtained from the current model to use as boundary conditions for a smaller scale model.

The model was highly parameterized and required estimation of numerous properties for which data were lacking. Specifically, the hydraulic properties were not available for several aquifers and had to be estimated from the literature. Additional work could focus on conducting aquifer tests in a broader range of aquifers. The hydraulic properties of sediment forming the river bed should also be estimated to refine the leakage properties.

Also, the model did not include the weir, which is used to control discharge in the Cowichan River, and thus affects measured values. The exclusion of the weir is a simplification of the model, and could be overcome by further developing the Cowichan Lake calibration and the additional use of the structures MIKE SHE module. The model could be adapted and used as a decision making tool in terms of the release schedule of the weir, as simulations regarding the availability of water under several climatic conditions could be assessed.

The effects of other stressors to the watershed could also be modelled. For example, the impacts of land use change on overland flow dynamics.

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Appendix 1: Results of Simulations of Extraction Well Pumping Rate vs. Streamflow Depletion

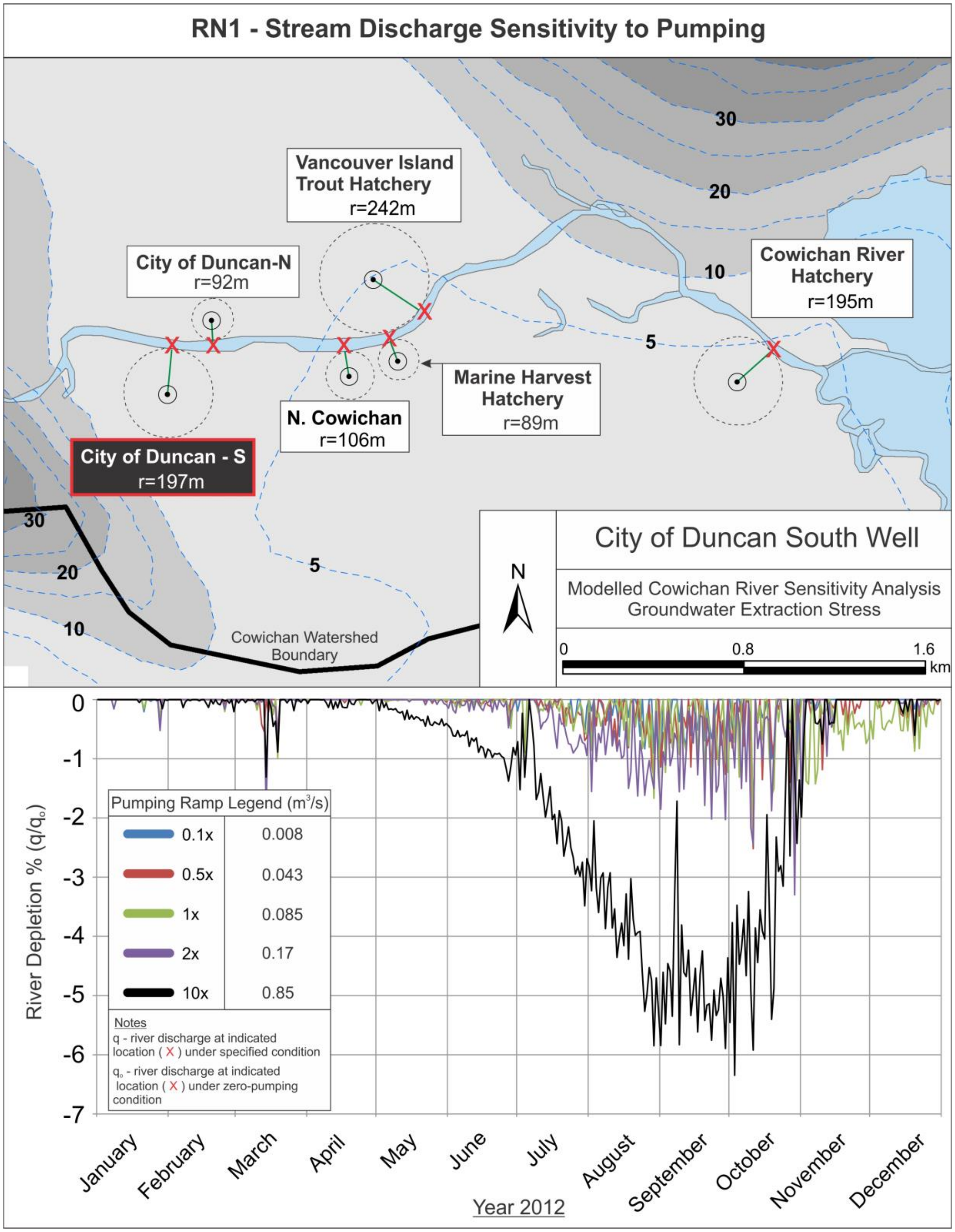

Figure A1.1. Cowichan River depletion assessment - variable pumping rates for the City of Duncan S well.

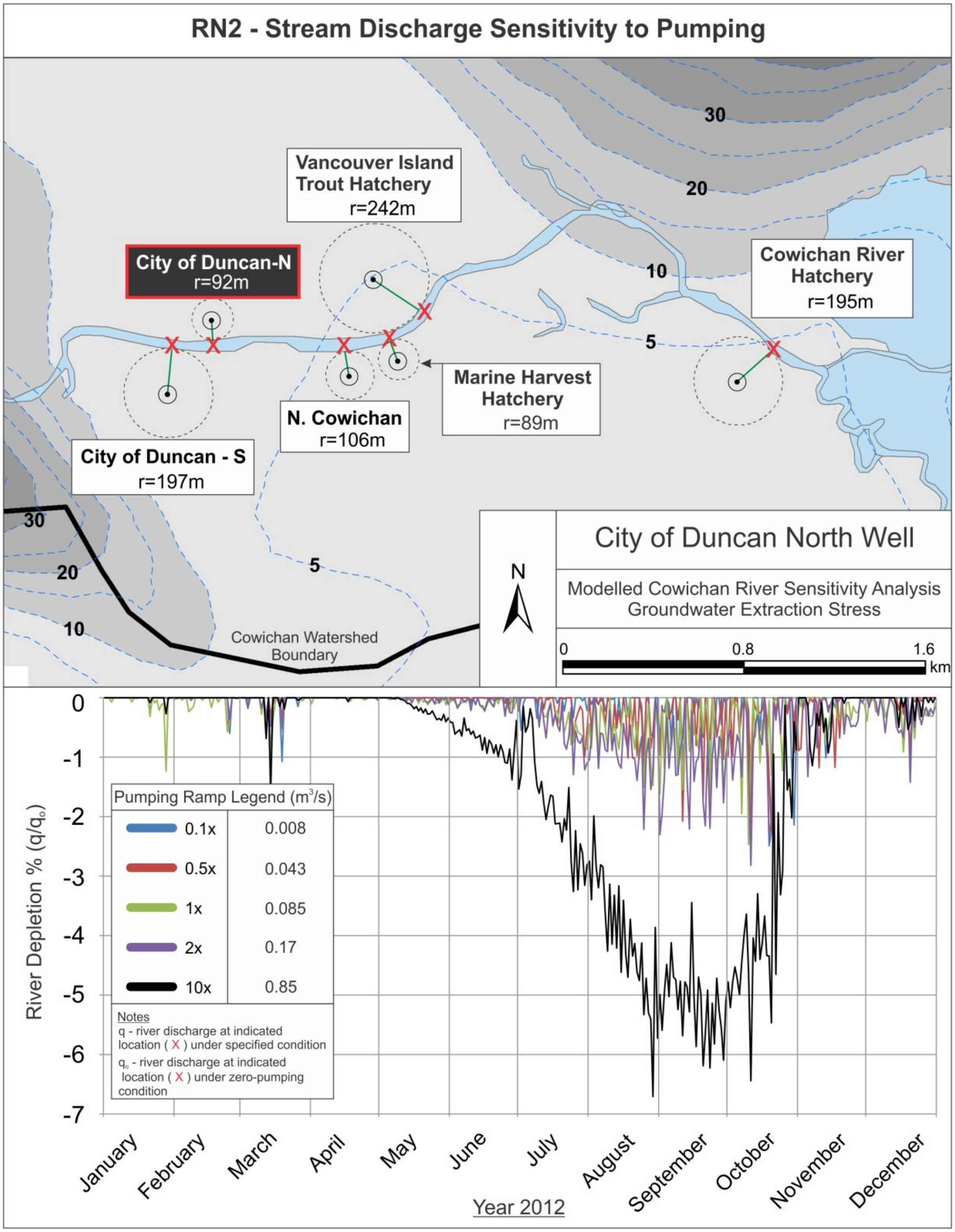

Figure A1.2. Cowichan River depletion assessment - variable pumping rates for the City of Duncan N well.

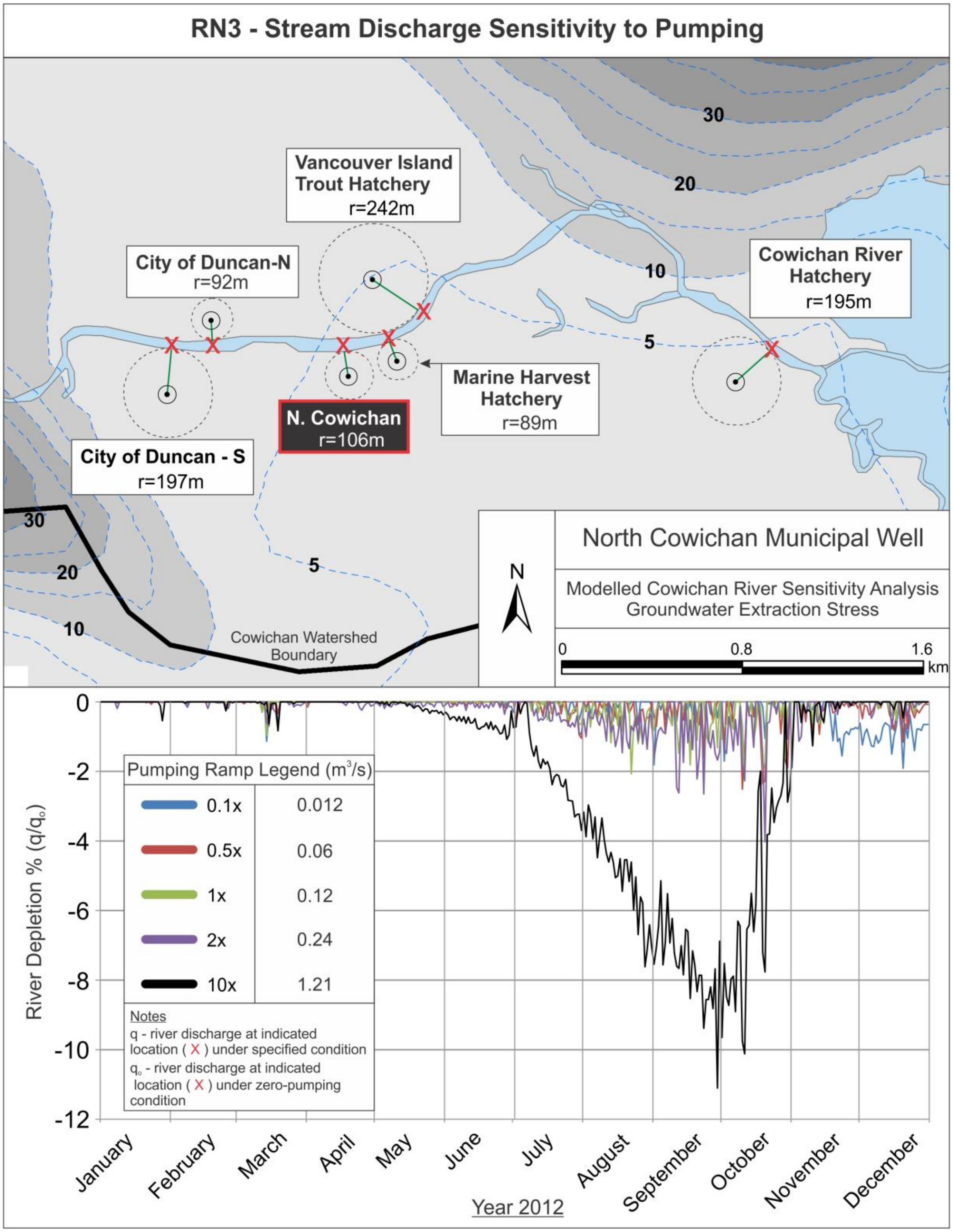

Figure A1.3. Cowichan River depletion assessment - variable pumping rates for the municipality of North Cowichan well.

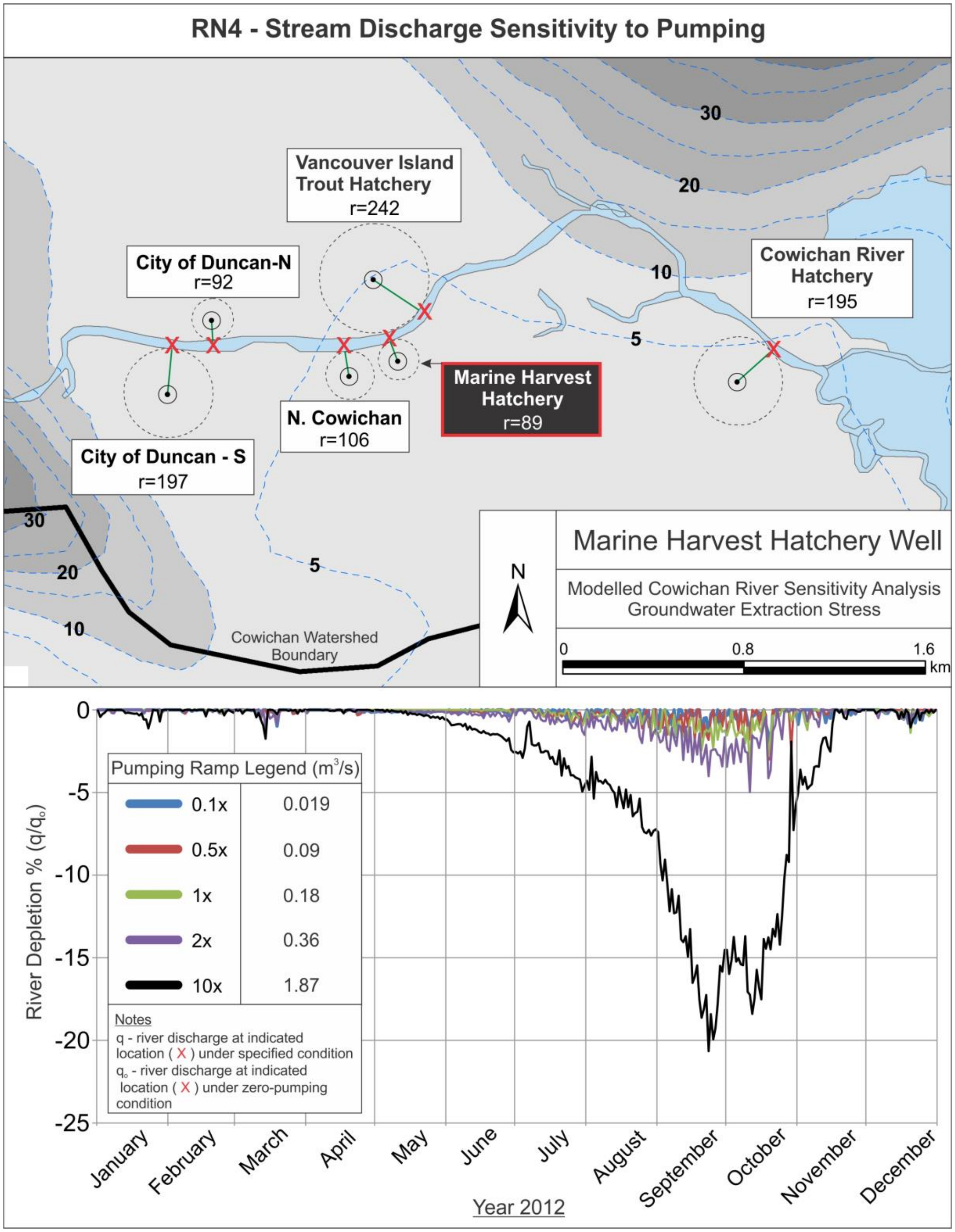

Figure A1.4. Cowichan River depletion assessment - variable pumping rates for the Marine Harvest Hatchery well.

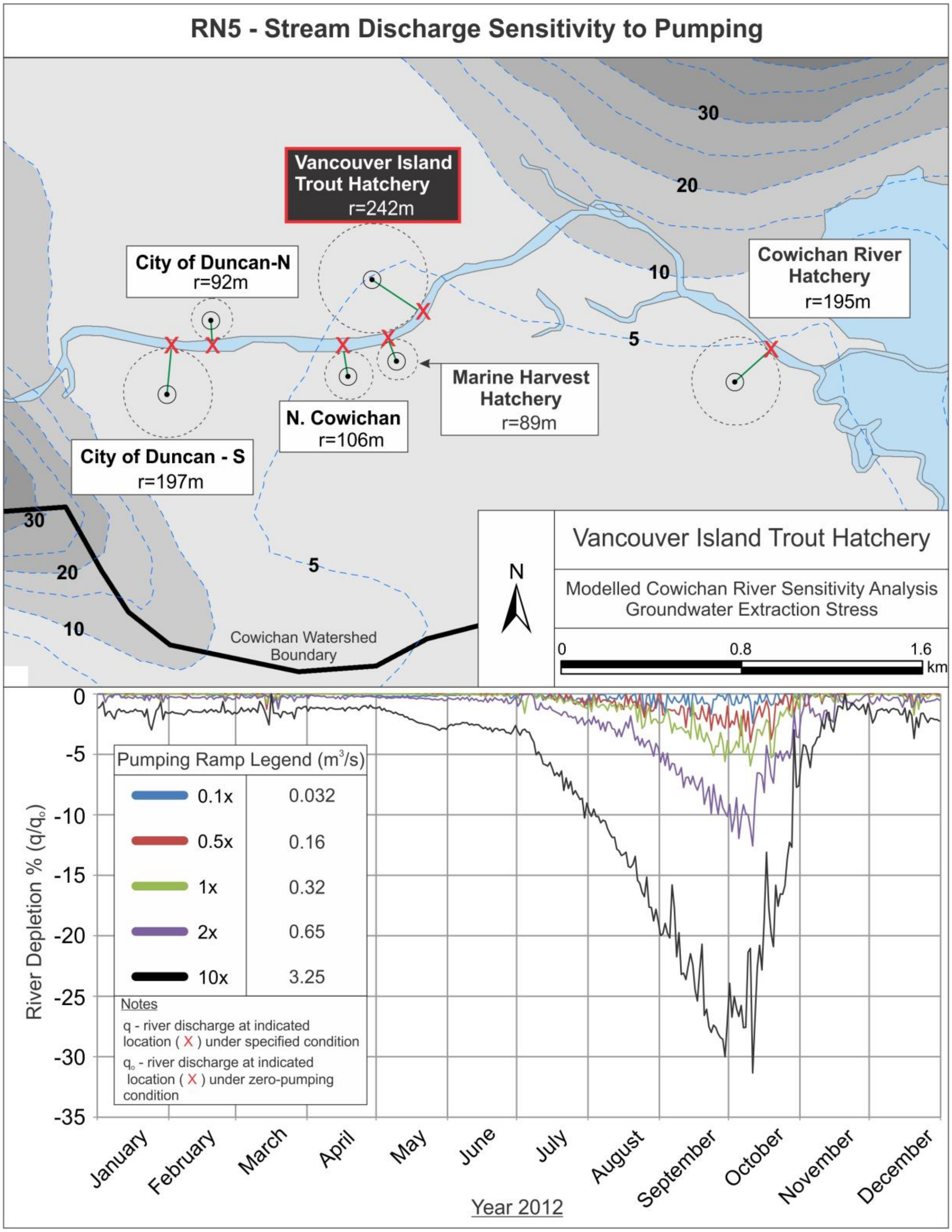

Figure A1.5. Cowichan River depletion assessment - variable pumping rates for the Vancouver Island Trout Hatchery well.

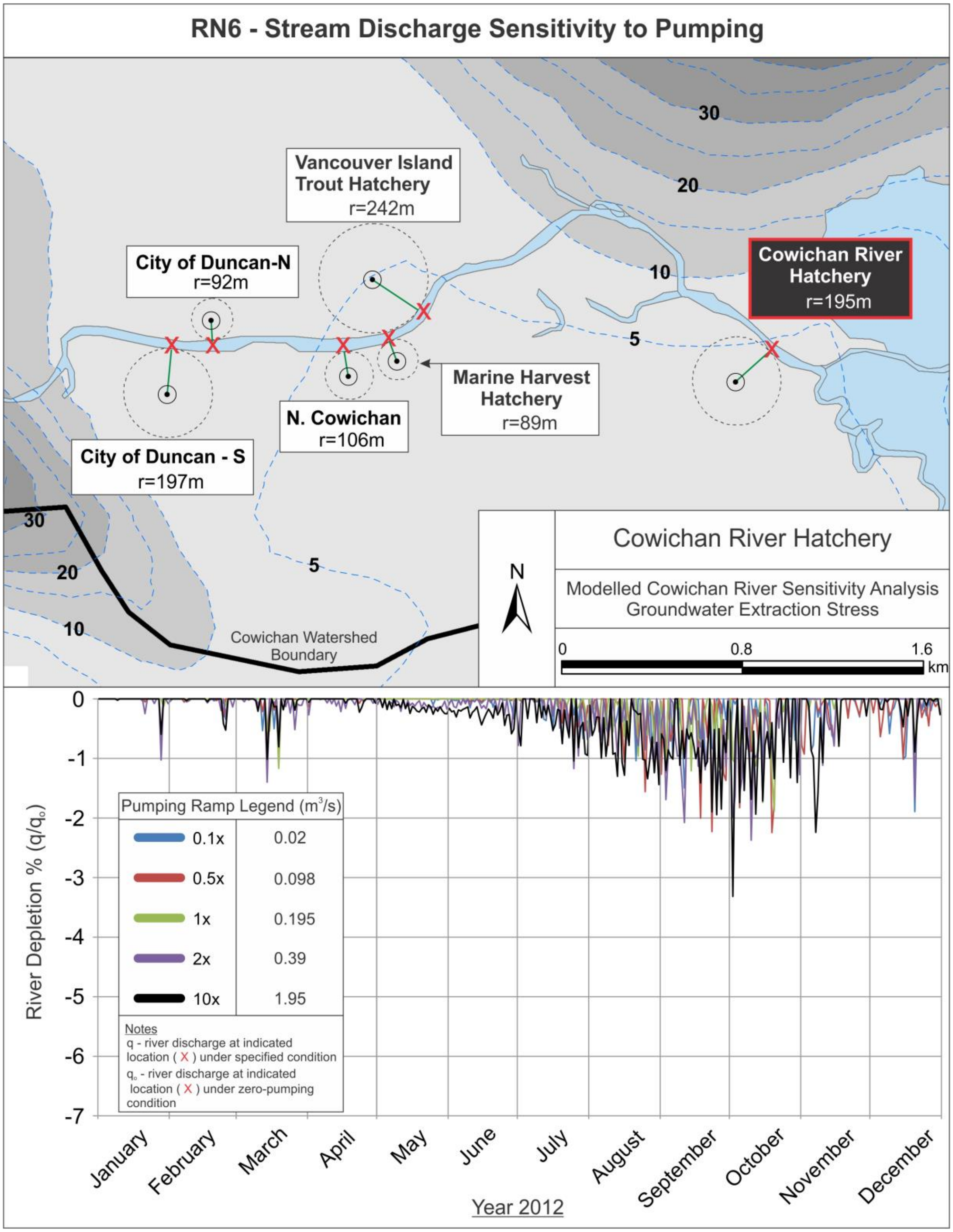

Figure A1.6. Modelled Cowichan River depletion assessment - variable pumping rates for the Cowichan River Hatchery well.

Appendix 2: Results of Well Distance vs. Streamflow Depletion Simulations for Aquifer 179

Aquifer 179 is an unconfined aquifer, 9 km^2 in area, located at the west end of Sahtlam, and bounded by the Cowichan River floodplain. It is comprised of valley alluvium and colluvium, Salish Sediments including gravel, sand, and some silt and clay originating from channel deposits. Vulnerability is high as there is no confining layer and the water table is shallow. Transmissivity and specific capacity have not been determined for this aquifer; therefore, values of hydraulic conductivity were based on literature values for sand and gravel (Freeze and Cherry 1979). Probable direction of groundwater flow is towards the Cowichan River and towards the east. Recharge is likely from precipitation and from the Cowichan River (Lapcevic 2014). The aquifer is less extensive than Aquifer 186, and therefore only wells located up to a distance of 400 metres from the river were simulated. Throughout this aquifer, the river is highly meandering, and therefore the distances are not accurate as the cones of depressions created by the simulated pumping wells interact highly with the upstream and downstream river bends. Figure A2.1 shows the modelling setup (bottom), and two graphs showing the amount of streamflow depletion occurring north and south of the Cowichan River. Figures A2.2 and A2.3 illustrate the degree of drawdown simulated for wells pumped at 0.2 m^3/s (P400N and P400S locations, respectively.

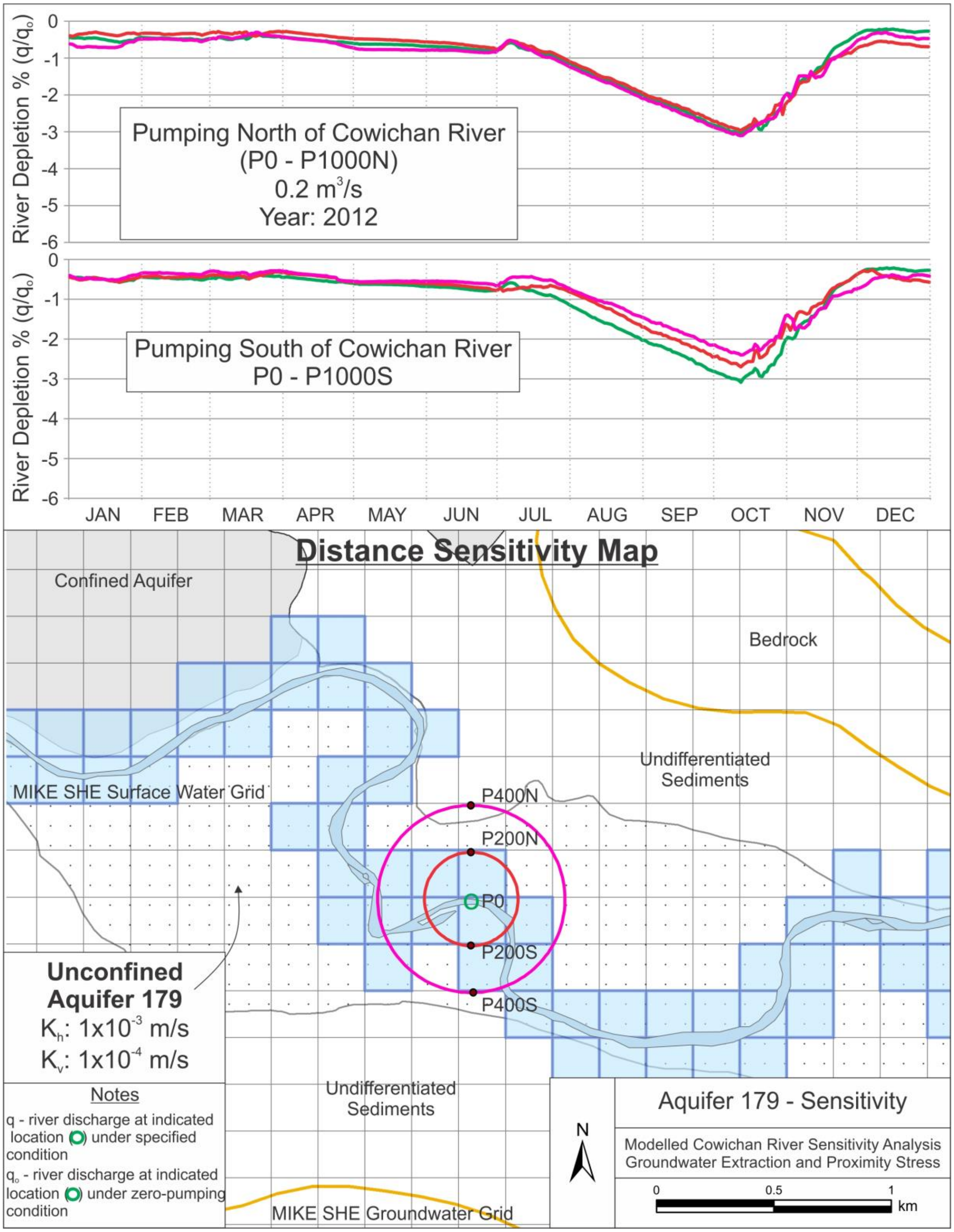

Figure A2.1. Modelled Cowichan River distance - sensitivity assessment for Aquifer 179 (0.2 m^3/s pumping rate).

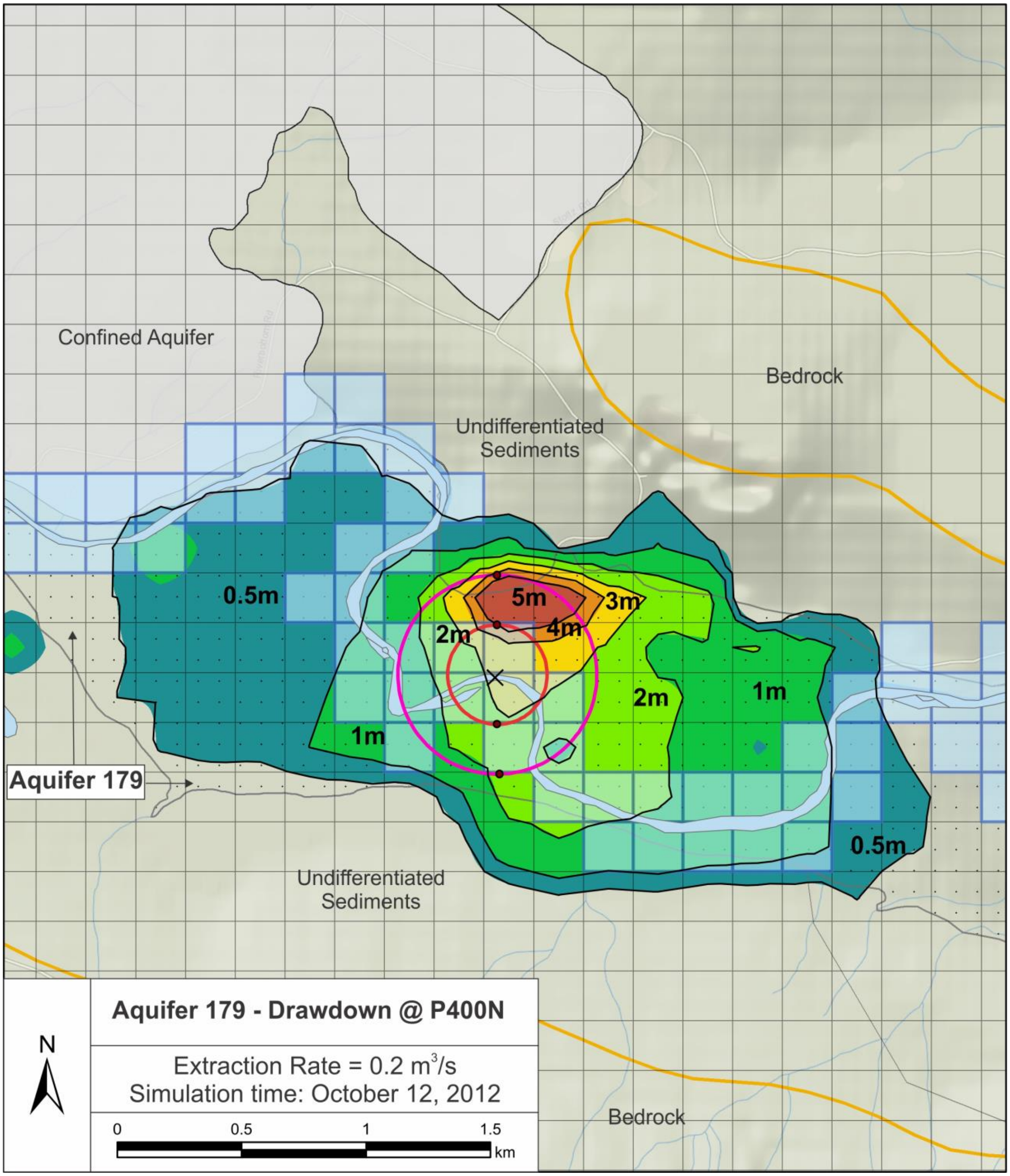

Figure A2.2. **Drawdown during distance - sensitivity test. Pumping occurring at P400N location (0.2 m^3/s).**

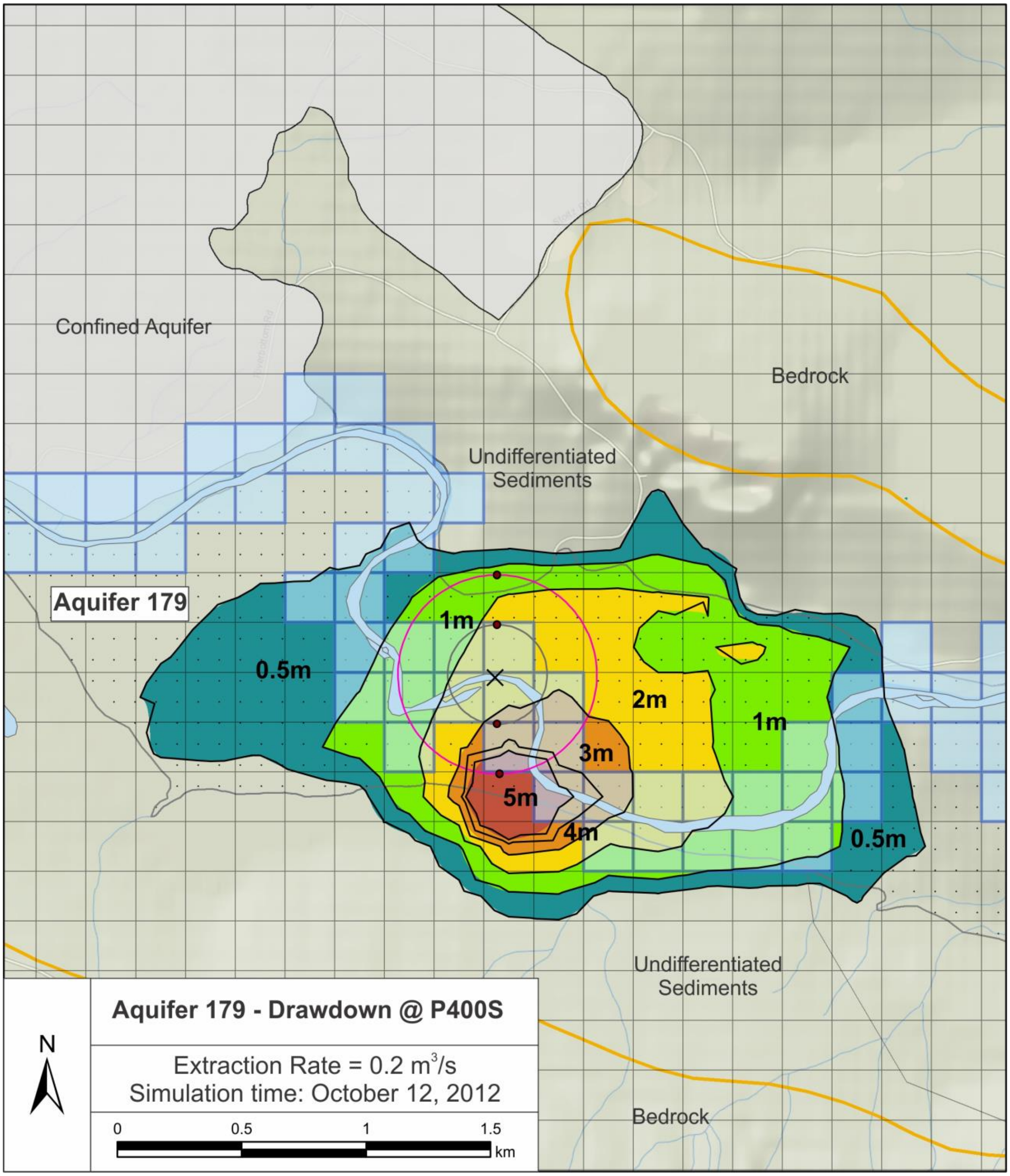

Figure A2.3. Drawdown during distance - sensitivity test. Pumping occurring at P400S location (0.2 m^3/s).