Groundwater and low flows: seasonality and trends in British Columbia

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ABSTRACT
The relationships between groundwater level, climate, and surface water within and between groups of well records from the two major hydro-climatic zones in BC are investigated in respect of potential connection to surface water, and their seasonality and trends particularly in relation to recharge from precipitation and surface water. To obtain a seasonal cycle comparable among the different wells, monthly groundwater levels were standardized and averaged over the period. The mean monthly levels were then used to manually classify the wells into rain- and snowmelt-dominated seasonal cycles. Temporal trends of groundwater levels and a simple recharge measure were used to determine whether a significant trend existed. Overall, summer groundwater levels seem to have lowered across the province, despite an increase in winter precipitation and recharge during the same time period. Due to the limited availability of long term records near gauged streams, the attribution of whether and how these changes have affected low flows proved difficult. This assessment was complicated by the varied nature of the climate in different parts of the province, which determines the hydrologic regime (pluvial, nival, glacierized, mixed), and natural climate variability phenomena. As well, the hydrogeologic character of the groundwater systems is a primary factor controlling the connection between groundwater and surface water systems.

RÉSUMÉ
Les rapports entre le niveau des eaux souterraines, le climat, et les eaux de surface dans deux zones hydro-climatiques principales en Colombie Britannique sont étudiés par rapport aux connexions potentielles aux eaux de surface, leur caractère saisonnier et leurs tendances notamment par rapport à la recharge par les précipitations et les eaux de surface. Pour obtenir un cycle saisonnier comparable parmi les différents puits, des niveaux mensuels d'eaux souterraines ont été normalisés et ramenés à une moyenne durant la période. Les niveaux mensuels moyens ont été ensuite utilisés pour classer manuellement les puits selon qu'ils se trouvent dans un régime de pluie ou un régime de fonte de neige. Des tendances temporelles des niveaux d'eaux souterraines et d'une mesure simple de la recharge ont été utilisées pour déterminer si une tendance significative a existé. De façon générale, les niveaux d'eaux souterraines d'été semblent s'être abaissés à travers la province malgré une augmentation des précipitations en hiver et de la recharge pendant la même période de temps. En raison de la disponibilité limitée de longues séries chronologiques, l'attribution de si et comment ces changements ont causé de plus les faibles écoulements souterrains est difficile à dire. Cette évaluation a été compliquée par la nature variée du climat dans différentes parties de la province, qui détermine le régime hydrologique (de pluie, de neige, des glaciers, et mélangé), et de phénomènes normaux de variabilité du climat. De même, l'hydrogéologie des systèmes d'eaux souterraines est un facteur principal contrôlant la connexion entre les eaux souterraines et les eaux de surface.

1 INTRODUCTION

Low flows in streams occur during periods of minimal rainfall or snowmelt inputs and are sustained by release of catchment storage in the forms of groundwater, glaciers, lakes and wetlands. During low flow periods, streamflow may be inadequate to meet needs for economic uses such as domestic consumption, hydroelectric generation, irrigation and effluent dilution, as well as ecological functions such as in-stream habitat. There is growing concern that climate change, associated with increases in air temperature and evapotranspiration, lower snow accumulation and earlier snowmelt, and possibly more extreme summer drought may result in more extreme low flows, particularly during the summer months. Therefore, to understand the potential impacts of climate change on the magnitude of low flows, more knowledge is required on how the climate changes will influence the magnitude and timing of storage releases. Of the main forms of catchment storage, our understanding is weakest for groundwater.

The aim of this study is to explore the relations between groundwater fluctuations and past climatic variations using available climate data, hydrometric data, and data from the recording well network in British Columbia (BC), Canada. The objective of the study is to gain insight on the mediating ability of groundwater to regulate summer low flows by examining the potential connection of groundwater to surface water, and the seasonality and trends in groundwater levels, particularly in relation to recharge from precipitation and surface water.

First, the relationships between groundwater level, climate, and surface water within and between groups of well records from the two major hydro-climatic zones (pluvial or rainfall regime, and nival or snowmelt regime) were investigated. Standardized seasonal cycles of all variables were used to manually classify the wells into rainfall- and snowmelt-dominated systems. Second, time series of monthly well records and a recharge measure derived the groundwater record were tested for trends during the common period used for comparison.

2 BACKGROUND

2.1 Climate and Hydrology of BC

British Columbia (BC) is one of the most hydro-climatically complex places in North America. It is provided with moisture and warmth by the Pacific Ocean and has steep terrain, which create strong precipitation and temperature gradients. Thus, the influence of climate variability and change is not homogeneous across the province (e.g., Whitfield and Cannon, 2000, Whitfield, 2001, Fleming et al., 2007, Kiffney et al., 2002, Regonda et al., 2005). The three predominant hydrologic regimes in BC are pluvial, nival, and hybrid (a mixture of pluvial and nival) (Whitfield et al., 2003). Some regions in BC have also been defined as nivally-supported pluvial because water is primarily supplied by rainfall, but is supplemented by snowmelt (Fleming et al., 2007). This melt water is not sufficient to augment low flows in summer as might be the case in a hybrid or nival regime. Other areas are influenced not only by snowmelt but also by glacier melt, which peaks later during the warmest months.

Over the longer term, climate change could have major regional effects on air temperature, precipitation, evapotranspiration and, ultimately, runoff (e.g., Whitfield et al., 2003). Whitfield and Taylor (1998) found that streams in coastal areas of BC respond to small variations in climate. In recent decades, decreases in stream discharge during early spring and late summer, and increases in winter runoff have been observed (Whitfield and Taylor, 1998). Lower and extended low flow periods during the late summer and early autumn are of particular concern as they threaten not only water supplies, but also reduce effluent dilution, increase the likelihood of algal blooms, and damage to wetlands and aquatic habitats. In addition, stream temperatures are moderated by groundwater, particularly during the summer months; therefore, reduced groundwater discharge could lead to increased stream temperatures.

With extended low flow periods, streams may be more strongly influenced by interaction with groundwater. Changes to the groundwater regime in respect of the timing and amount of natural recharge, greater groundwater use, and higher summer evapotranspiration could result in a lowering of groundwater levels in some areas. Therefore, low flows in the streams may be exacerbated by the decreasing groundwater levels.

Assessments concerning the future predicted impacts of climate change on groundwater have to-date largely been limited to modeling studies. Groundwater in the Grand Forks aquifer, in south central BC, was found to be tied closely to streamflow in the Kettle River (Scibek et al., 2006). This sand and gravel unconfined aquifer is situated in a valley bottom nestled in mountainous terrain through which the Kettle River meanders. Thus, the groundwater levels strongly respond to changes in river stage. This type of aquifer system is characteristic of many in valley bottom aquifers found in mountainous areas. In that study, changes in streamflow (river stage) and groundwater recharge from precipitation (snowmelt and rainfall) were modeled for future climate periods and used as boundary conditions within a three-dimensional groundwater flow model. Results suggest that variations in recharge to the aquifer under the different climate change scenarios (Scibek and Allen, 2006a) have a much smaller impact on the groundwater system than changes in the river stage elevation of the Kettle River. By the 2050s, the change in groundwater levels is less than 0.5 m away from floodplain, but can be greater than 0.5 m near the river.

Scibek and Allen (2006b) compared the results of the Grand Forks aquifer study to those for the Abbotsford-Sumas aquifer in the Lower Fraser Valley of BC and Washington State, USA. In contrast to the Grand Forks aquifer, this unconfined aquifer is an outwash deposit (sand and gravel) that is raised above the Fraser River floodplain. It receives recharge solely from precipitation (dominantly rain) and drains via small streams to lower elevation in the USA. Scibek and Allen (2006b) found that groundwater recharge to the Abbotsford-Sumas Aquifer, would decrease by 13-15% by the 2050s relative to historic values, and could result in a reduction in groundwater flow to the various streams that drain the aquifer.

The varied responses of these two aquifer systems points to the complexity of the climate – groundwater – surface water interconnections, and how these might be variably influenced not only by the climate of different regions, but also the geologic character of the aquifer which influences its potential connection with surface water. Thus, to be able to characterize the hydraulic response of a system in response to climate forcing, it is important to first characterize the aquifer in respect of its dominant recharge mechanism (i.e., dominantly direct recharge from precipitation, or dominantly indirect recharge via streams and rivers).

2.2 Aquifer-Stream System Types

Wei et al. (2007) identified six main aquifer types (four with sub-categories) within the Cordillera Hydrogeologic Region of Canada based on each aquifer's unique hydrogeologic characteristics, such as the nature of its origin, size and location, typical well depths, well yields, permeability, vulnerability, and potential connection to surface water. Each aquifer type and sub-types can be expected to interact to varying degrees with streams that flow through them. Fluvial (Type 1), deltaic (Type 2), and alluvial/colluvial (Type 3) aquifers are most likely to have a hydraulic connection to surface waters due to their high permeability and geomorphic setting. Sand and gravel aquifers of glacial or pre-glacial origin (Type 4) have the potential to be in connection with surface waters, depending on local context. Sedimentary rock (Type 5) and crystalline rock aquifers (Type 6) are least likely to be connected to surface waters due to their low permeability.

These six different aquifers types were then classified by Moore et al. (2007) into two main *Aquifer-Stream System types* based on the anticipated responses to streamflow. Two main aquifer-stream system types or end-members were proposed:

- *Stream-Driven Systems* - in which groundwater flow to and from streams is bi-directional, and varies seasonally depending on the magnitude of the streamflow and precipitation. These include valley bottom unconfined fluvial or glaciofluvial aquifers that are found in association with major streams/rivers (e.g., Grand Forks aquifer), and aquifers that are found at a break in slope, such as a valley bottom or a coastal plain, in which streams flow variably across the top or possibly "disappear" into the sediments (e.g., Okanagan Valley alluvial fan aquifers).
- *Recharge-Driven Systems* - in which the aquifer is raised above the surrounding land surface and which drains to lower elevation. In this type of system, groundwater is recharged solely by precipitation and dominantly discharges to streams during periods of low flow (e.g., Abbotsford-Sumas aquifer).

The magnitude and timing of the response of the groundwater system, as reflected in changes in groundwater levels, will depend on the nature of the driving force, that is, whether the system is stream-driven or recharge-driven, and also on the climatology of the region. Thus, an overall classification system was proposed (Moore et al., 2007) for hydrogeologic systems in mountainous regions according to Figure 1:

1. the hydro-climatic regime (pluvial, nival, mixed); and
2. whether the response is indicative of hydraulic connection with surface water as predicted by the aquifer-stream system types defined previously.

To test whether this classification scheme was applicable to aquifers in BC, Moore et al. (2007) conducted a preliminary examination of provincial observation well records.

As of September 2006, there were 158 active observation wells in the network covering major groundwater areas of the province. Each well is identified with a unique observation well number. A select few of these wells monitor aquifers in pristine areas that reflect natural variability; others have been influenced by human activity making them less representative. Most long observation well records in BC consist of end-of-month manual readings. Some provincial observation wells are equipped with Stevens recorders (end-of-month readings only), but several were recently equipped with data loggers that record hourly or daily groundwater levels. The periods of record for these observation wells vary.

The earliest records date back to 1962, and a few are still being monitored. As groundwater development increased over time, new observation wells were installed in other regions, hence their periods of record are shorter.

Of the 158 active observation wells (BC Ministry of Environment, 2006a), only nine had records that were considered suitable for detailed analysis based on whether daily time series data were available and whether the record was of sufficient length. The nine wells are located across southern BC; they span from the western coastal area encompassing Vancouver Island, the Gulf Islands, and the Lower Fraser Valley, and eastward as far as Golden. Meteorological and hydrological stations were selected based on their close proximity to these wells (see Moore et al., 2007 for listing of wells and aquifer characteristics for each).

Moore et al. (2007) divided the well responses based on their hydro-climatic regime; namely rainfall-dominated (pluvial) and snowmelt-dominated (nival). Mixed regimes were also identified in two wells. Then, each well response was classified within the context of aquifer-stream system type. The results of this preliminary analysis of high quality well records confirmed the overall classification scheme, as detailed by Moore et al. (2007), and led to an overall framework for evaluating the responses of other lower quality well records as discussed in the following section.

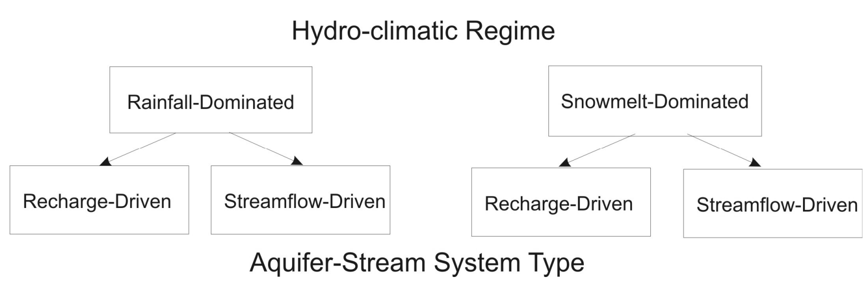

Figure 1. Classification system for hydrogeologic systems in mountainous regions.

3 METHODOLOGY

For the trend analysis presented in this section all available records that cover the time period from 1980 or earlier until at least the year 2002 were extracted from the observation well database (BC Ministry of Environment, 2006a), including end-of-month only series, and series that have mixed end-of-month and (later) daily records. For mixed series, the daily part of the record was aggregated to end-of-month values to obtain longer time series (see Moore et al., 2007; Appendix 1). Records with more than 20% missing data were excluded. The time series were plotted and visually inspected for inhomogeneities, such as jumps, changes in annual amplitude, etc. Finally, 36 observation well records remained (see Moore et al., 2007 for a listing of all wells). Aquifer information and distance to the closest stream were determined for all wells from the information available in the Water Resources Atlas (BC Ministry of Environment, 2006b) and the WELLS database (BC Ministry of Environment, 2006c).

For the 36 monthly records, a common period from 1976 to 1996 was chosen for the analyses. Where records started later, the earliest year after 1976 was selected as the starting date. This period was chosen because of the best overlap with the streamflow and climate records. The starting year coincides with the shift to the positive PDO phase, a situation that is predicted to become more dominant in the future climate.

To obtain a seasonal cycle comparable among the different wells and different variables, monthly temperature, precipitation totals, streamfllow, and groundwater levels were standardized and averaged over the period. The mean monthly variables were then used to manually classify the wells into rain- and snowmelt-dominated seasonal cycles and their recharge mechanism (driven by recharge from precipitation only or additionally through a stream)..

Then, temporal trends of groundwater levels and a simple recharge measure were calculated using the non-parametric Spearman's rank correlation coefficient, *rs*, and a p-value of <0.05 to determine whether the trend was significant. Trends for the observation well levels were calculated for annual series of each individual calendar month. To determine trends in the annual recharge, series of differences between the annual minimum and maximum levels were derived. This technique is similar to water table fluctuation methods for determining groundwater recharge (e.g., Healy and Cook, 2002) except that aquifer storage properties are not taken into account. This is a reasonable approach given that for trend analysis the aquifer properties would remain constant. Specifically, for rain-dominated basins, the minimum level during summer was deducted from the maximum level in the following winter. For snow-dominated systems, the minimum level during winter was deducted from the maximum of the following spring/summer season. Larger values of the differences in water level likely indicative of more recharge, but could falsely represent changes in total recharge because shifts in cumulative amounts (area under the curve) are not considered.

4 RESULTS

4.1 Seasonality

Figure 2 shows the final dataset of observation wells and the primary classification into rain- or snowmelt-dominated seasonality of the recharge. Rain-dominated groundwater systems are found on Vancouver Island or along the coast, while all wells in the interior reflect the winter snow storage and recharge by spring snowmelt. Unfortunately, there are no long records available in the central and northern parts of the province.

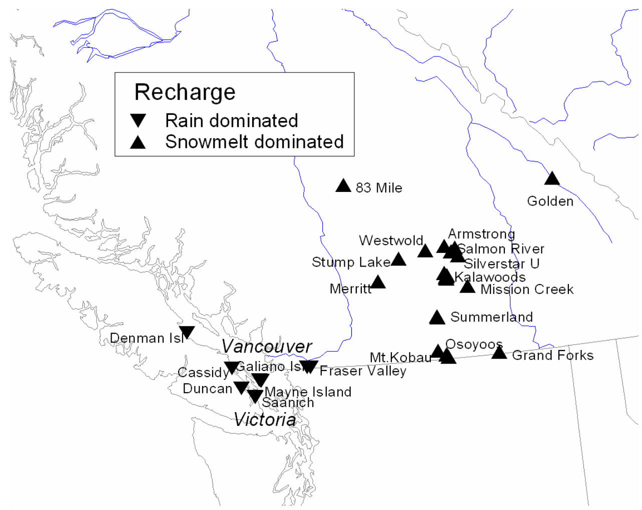

Figure 2. Map of final dataset of observation wells with location names and dominant recharge mechanism. Rain dominated recharge is indicated by inverted triangles, and snowmelt dominated recharge is indicated by upright triangles.

Figure 3 shows the seasonality of the groundwater level fluctuations for selected wells in the rain-dominated region. These encompass wells on the Gulf Islands, southwest Vancouver Island, and the Fraser Valley. Most follow very similar annual cycles with maximum levels in January, and minimum levels in September. The fluctuations in the Fraser Valley #002 and Saanich #060 lag behind, with a maximum level in March and minimum level in October.

Of the wells shown in Figure 3, three wells (#002 in Fraser Valley, #060 in Saanich, and #228 in Cassidy) are completed in alluvial aquifers. The remaining four wells are completed in bedrock. As already discussed, there is variability in the seasonality because the response of the aquifers depends on the local aquifer characteristics and its potential connection to surface water. With the exception of the Cassidy well, none are situated close to a stream, thus, these are all recharge-driven systems and should show close resemblance to precipitation seasonality. The hydrograph for the Cassidy well is distinctly different in shape to that of the others, which may suggest connection to the stream.

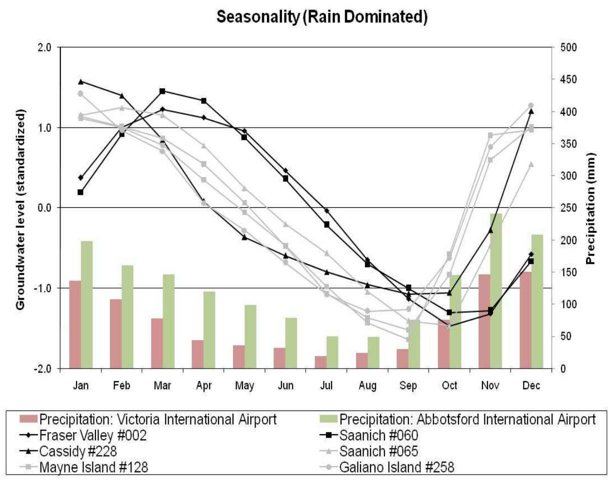

Figure 3. Seasonality of selected groundwater observation wells with rain-dominated seasonality and mean monthly precipitation for two coastal climate stations.

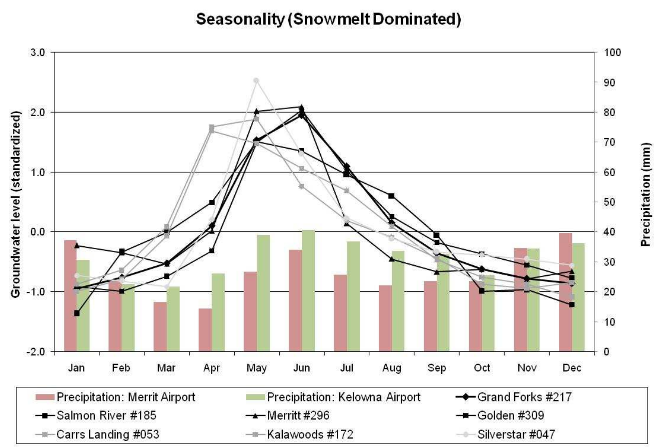

Figure 4. Seasonality of selected groundwater observation wells with snowmelt-dominated seasonality and mean monthly precipitation for two interior climate stations

Among the snow-dominated systems there is also considerable variability (Figure 4). Recharge depends on the timing of the snowmelt, which depends on elevation, topography, etc. and on aquifer characteristics. The early response at Kalawoods (#172) and Carr's Landing (#53/54) suggest a rapid response to snowmelt. Both of these wells are situated in Okanagan Valley at low elevation, but not nearby any stream, thus their response can be directly linked to snowmelt and rainfall inputs (although evaporation is generally quite high in the Okanagan and limits rainfall infiltration during the summer months). Silverstar (#047) is also situated in Okanagan Valley, but at high elevation. Its response is somewhat delayed relative to the other Okanagan wells, and a prominent peak is observed. This well is not connected to a stream and is driven primarily by snowmelt in the spring and possibly limited summer rainfall. All wells are completed in alluvial material. The wells in Grand Forks (#217), Salmon River (#185), Merritt (#296) and Golden (#309) are in alluvial gravel aquifers and are relatively close to streams. With their fast rise, the groundwater level series closely resembles the streamflow hydrographs. The groundwater level in Merritt drops first after snowmelt among those four sites, possibly reflecting the earlier and faster spring snowmelt in this dry area with comparably low elevation differences, and/or a very direct hydraulic connection to the stream.

4.2 Trends

Trends in groundwater well levels were found to be highly variable. However, negative trends, i.e. decreasing groundwater levels, dominate the records. Among the rain dominated systems (Figure 5), two observation wells show increasing groundwater levels over the majority of the year, particularly in the summer. These include Saanich #065 and Cassidy (#228) on Vancouver Island. A detailed discussion of trends observed in precipitation, streamflow and groundwater levels is given in the following section for selected wells.

Negative trends also dominate the snowmelt driven systems (Figure 6). One exception within this subset is the groundwater level at Grand Forks, which has increased, particularly in winter. This trend is discussed in more detail later. There is no common seasonal pattern in the trends.

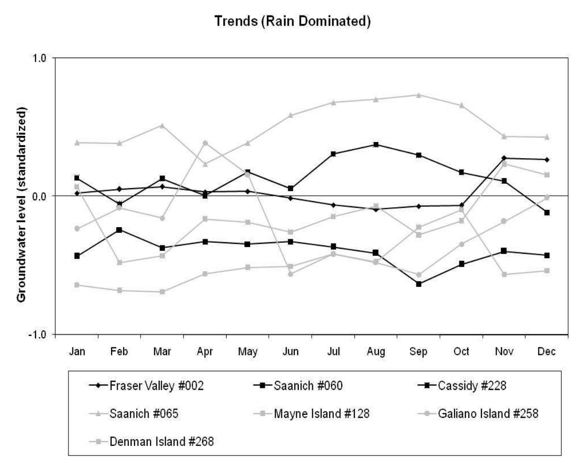

Figure 5. Monthly trends for selected groundwater observation wells with rain-dominated seasonality.

The spatial distribution of trends found for late summer (September), which is the time when groundwater most likely feeds streamflow in BC, is mapped in Figure 7. August trends (not shown) are similar. The map also shows a predominance of negative trends many of which are significant, but there are exceptions that do not appear to have any spatial pattern. In general, the dominance of negative trends could suggest that the negative streamflow trends seen during these months (see Moore et al., 2007) may be linked to groundwater decrease.

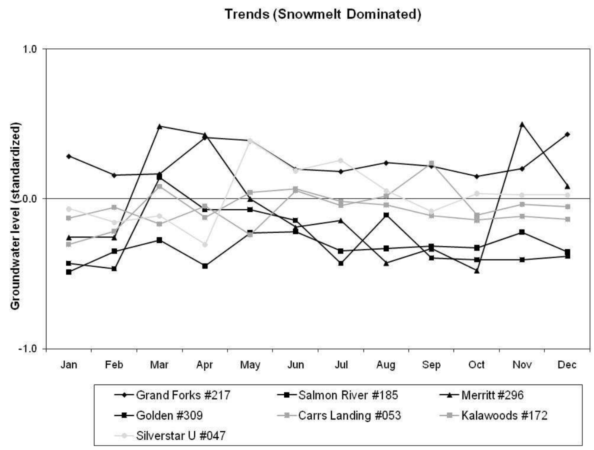

Figure 6. Monthly trends in selected groundwater observation wells with snowmelt-dominated seasonality.

Trends in the estimated recharge are more variable (Figure 8). Positive trends indicate an increase in the difference between the lowest and the following highest groundwater level; negative trends indicate a decrease. There are more positive trends; however, these trends in recharge were not significant, which suggests a large range of variability. Moore et al. (2007) also undertook a similar trend analysis on recharge-season precipitation as well as April 1st snow water equivalent (SWE) records at provincial snow course sites over the period 1976-2002. Precipitation amounts from October to March have increased. April 1st SWE has increased at some sites and decreased at other sites with only a few significant increasing trends. These results are supported by positive trends in recharge. These are interesting results, which suggest that while groundwater levels have declined, on average, throughout the province, precipitation and snow water equivalent during the recharge season and the aquifer responses themselves have positive trends.

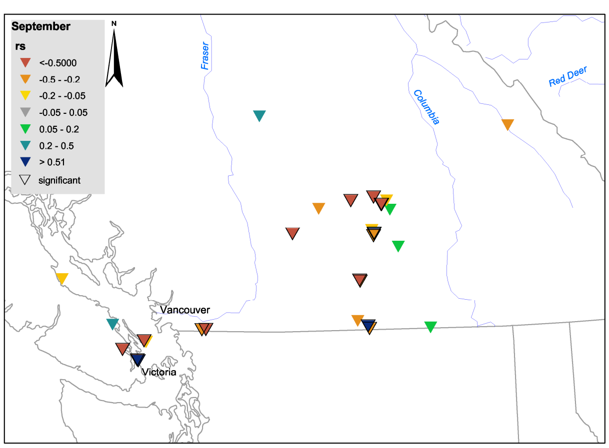

Figure 7. Trends in groundwater well levels in September. Spearman's rank correlation coefficient, rs, is shown for sites. The trend was significant (symbol is outlined in black) when p-value <0.05.

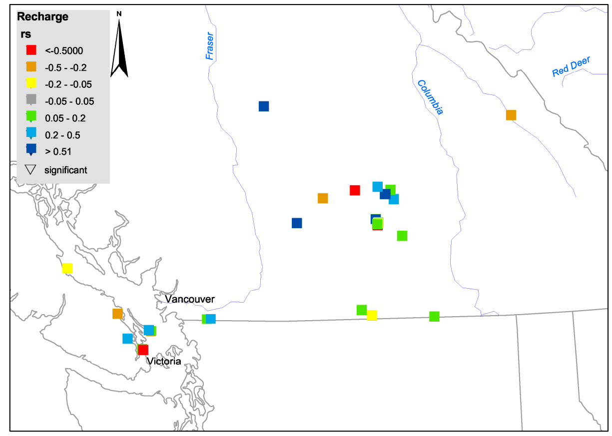

Figure 8. Trends in groundwater recharge estimated from annual minimum and maximum groundwater levels. Spearman's rank correlation coefficient, rs, is shown for sites. The trend was significant when p-value <0.05. None were significant.

One possible explanation is a shift in the timing of recharge. Multiple studies have found that the timing of snowmelt has advanced, which has resulted in early peak flows in snow-dominated streams (Leith and Whitfield, 1998; Whitfield and Cannon, 2000; Stewart et al., 2005). As a result of earlier snowmelt, streamflow has been depleted sooner and this has reduced magnitude of summer low-flows and extended the low-flow period. Similar responses could be expected in groundwater. Investigation into the change in timing of recharge should be pursued. Unfortunately, in many cases data is not available at the temporal resolution to facilitate this work.

5 DISCUSSION

The assessment undertaken in this study is complicated due to the varied nature of the climate in different parts of the province, which determines the hydrologic regime (pluvial, nival, glacierized, mixed), natural climate variability phenomena.Natural cycles of variability acting on the region are the El Nino Southern Oscillation (ENSO) (Shabbar et al., 1997; Cayan et al., 2001), the Pacific Decadal Oscillation (PDO), and the Pacific North American pattern (PNA) (Stahl et al., 2005). Cycles in PDO are thought to last for 20-30 years (Mantua et al., 1997) and those of ENSO are in the range of 2-5 years. A warm phase of the PDO started in the mid 1970s (Mantua et al., 1997). Previous to that was a cool phase that started in the 1940s. Consensus on the phase of the PDO presently affecting BC has not been reached. In BC, variations in temperature and precipitation associated with ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation) affect the amount and form of water that drives streamflow (e.g., Redmond and Koch, 1991) and groundwater recharge. Fleming and Quilty (2006) used climatological composite analysis to investigate ENSO signals in long-term groundwater level observations from four wells in the lower Fraser Valley of BC. ENSO precipitation impacts were largely limited to winter and spring, with higher and lower rainfall occurring, respectively, under cold-phase and warm-phase episodes. Relative to the surface hydrologic systems considered in that study, the aquifers were seen to retain a strong memory of seasonal ENSO-related precipitation anomalies. Changes were potentially extended through to the following summer.

Perhaps more importantly is the complexity of groundwater system, which influences the nature of the connection between groundwater and surface water. Unfortunately, the majority of the well hydrographs start in the late 70s or 80s, providing only 20 to 30 years of record at most. Only a few of these wells monitor aquifers in “pristine” areas that reflect natural variability; the others have been influenced by human activity. Although, the relationship between climate variability and change, and trends in precipitation, temperature, and streamflow have been tested, the limited record length of groundwater wells has largely prevented relationships between natural climate variability and groundwater levels to be rigorously tested for trends.

6 CONCLUSIONS

The relationships between groundwater level, climate, and surface water within and between groups of well records from the two major hydro-climatic zones in BC are investigated in respect to potential connection to surface water, and their seasonality and trends, particularly in relation to recharge from precipitation and surface water. Two distinct end-member aquifer-system types were identified; recharge-driven and stream-driven, and each may be found within either climate regime. Thus, there are many possible combinations of potential responses of wells.

Overall, summer groundwater levels seem to have lowered across the province, despite an increase in winter precipitation and recharge during the same time period. Due to the limited availability of long well records near gauged streams, the attribution of whether and how these changes have affected low flows proves difficult. The available groundwater observation wells are quite different in terms of surrounding aquifer properties and the hydraulic connection of the aquifer to rivers and, for many, we suspect the natural records may be altered by changes in the abstraction patterns despite an attempt to eliminate such records from analysis.

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REFERENCES

Allen, D.M., Mackie, D.C. *and* Wei, M. 2004. Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada, *Hydrogeology Journal*, 12:270-290.

British Columbia Ministry of Environment. 2006a. Observation well network http://srmapps.gov.bc.ca/apps/gwl/disclaimerInit.do

British Columbia Ministry of Environment. 2006b. Water Resources Atlas http://www.env.gov.bc.ca/wsd/ data_searches/wrbc/index.html

British Columbia Ministry of Environment. 2006c. WELLS database http://aardvark.gov.bc.ca/apps/wells/

Cayan, D.R., Kammerdiener, S.A., Dettinger, M.D., Caprio, J.M. and Peterson, D.H. 2001. Changes in the onset of spring in the western United States. *Bulletin Amer. Met. Soc.,* 82(3):399-416.

Environment Canada. 2002. Canadian Climate Normals Online, CDCD West CD. Accessed November 2005. http://www.climate.weatheroffice.ec.gc.ca/prods_servs/cdcd_iso_e.html

Environment Canada. 2004. Water Survey of Canada Archived Hydrometric Data Online. Accessed October 2005. http://www.wsc.ec.gc.ca/hydat/H2O/

Fleming, S.W. and Quilty, E.J. 2006. Aquifer responses to el niño-southern oscillation, southwest British Columbia. *Ground Water,* 44: 494-499.

Fleming, S.W., Whitfield, P.H. Moore, R.D. and Quilty, E.J. 2007. Sensitivity of distinct streamflow regimes across the Georgia-Puget transboundary ecoregion to Pacific ocean-atmosphere circulation. *Hydrological Processes*, Published Online: 8 May 2007, DOI: 10.1002/hyp.6544

Healy, R.W. and Cook, P.G. 2002. Using groundwater levels to estimate recharge, *Hydrogeology Journal*, 10(10):91-109.

Kiffney, P.M., Bull, J.P. and Feller, M.C. 2002. Climatic and hydrologic variability in a coastal watershed of southwestern British Columbia, *Journal of the American Water Resource Association*, 38: 1437-1451.

Leith, R.M. and Whitfield, P.H., 1998. Evidence of climate change effects on the hydrology of streams in South-Central BC, *Canadian Water Resources Journal*, 23: 219-230.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J. M., & Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production, *Bulletin of the American Meteorological Society,* 78: 1069–1079.

Moore, R.D., Allen, D.M. and Stahl, K. 2007. Climate Change and Low Flows: Influences of Groundwater and Glaciers. Final Report for Climate Change Action Fund Project A875, 211 pp.

Redmond, K.T. and Koch, R.W. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research*, 27: 2381-2399.

Regonda, S.K., Rajagopalan, B., Clark, M. and Pitlick, J. 2005. Seasonal cycle shifts in hydroclimatology over the western United States, *Journal of Climate,* 18: 372-384.

Scibek, J. and Allen, D.M. 2006a. Modeled impacts of predicted climate change on recharge and groundwater levels, *Water Resources Research*, 42, doi:10.1029/2005WR004742

Scibek, J. and Allen, D.M. 2006b. Comparing the responses of two high permeability, unconfined aquifers to predicted climate change, *Global and Planetary Change*, 50: 50-62.

Scibek, J., Allen, D.M., Cannon A.and Whitfield, P.H. 2007. Groundwater-surface water interaction under scenarios of climate change using a high-resolution transient groundwater model, *Journal of Hydrology*, doi:10.1016/j.jhydrol.2006.08.005

Shabbar, A. Bonsal, B. and Khandekar, M. 1997. Canadian precipitation patterns associated with the Southern Oscillation, *Journal of Climate,* 10: 3016-3027.

Stahl, K., Moore, R.D. and McKendry, I.G. 2005. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada, *International Journal of Climatology*, DOI: 10.1002/joc.1268

Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2005. Changes toward earlier streamflow timing across Western North America, *Journal of Climate*, 18: 1136-1155.

Wei, M., Ronneseth, K, Allen, D., Kohut, A.P., Turner, B., and Grasby, S. 2007. Types and general characteristics of aquifers in the Canadian Cordillera Hydrogeologic Region. In: Proceedings 8th Annual CGS-IAH Joint Conference, OttawaGeo2007, Ottawa, October 21-24, 2007.

Whitfield, P.H. 2001. Linked hydrologic and climate variations in British Columbia and Yukon, *Environmental Monitoring and Assessment*, 67: 217-238.

Whitfield, P.H. and A.J. Cannon, 2000. Recent Variations in Climate and Hydrology in Canada. *Canadian Water Resource Journal*, 25 (1):

Whitfield, P.H., and Taylor, E. 1998. Apparent Recent Changes in Hydrology and Climate of Coastal British Columbia. In: Alila, Y. ed., Mountains to Sea: Human interactions with the Hydrologic Cycle. Proceedings of the 51st Canadian Water Resources Association Conference: 22-29.

Whitfield, P.H., Wang, J.Y. and Cannon, A.J. 2003. Modelling future streamflow extremes — floods and low flows in Georgia Basin, British Columbia, *Canadian Water Resources Journal*. 28: 633-656.