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Groundwater level responses in temperate mountainous terrain: regime classification, and linkages to climate and streamflow

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Abstract:

Groundwater responses in temperate mountainous terrain are assessed using groundwater, hydrometric and climatic data from southern British Columbia, Canada. Well and stream hydrographs are analysed using a series of diagnostic tools including time series plots, hysteresis plots, and cross-correlation plots. Characterizing the seasonal timing of the response requires consideration of the hydroclimatology of the region: rainfall-dominated (pluvial), snowmelt-dominated (nival) or hybrid (mixture of rain and snow). The magnitude and timing of the recharge and discharge response of the groundwater system was shown to depend on the storage and permeability characteristics of the aquifer and whether the system is *stream-driven* or *recharge-driven*. These two dominant stream-aquifer system types were defined based on classifying different aquifer types found in the southwest portion of the province. The classification scheme and diagnostic tools have the potential to provide a framework for evaluating the responses of wells in other mountainous regions. Using this framework, the potential consequences of future climate change may then be better understood based on the interactions between the hydrogeological and hydroclimatic settings of these aquifers.

KEY WORDS groundwater levels; streamflow; groundwater–surface water interaction; climate; mountainous regions; aquifer characteristics

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INTRODUCTION

Mountainous watersheds or basins are unique high-relief environments that are important sources of water for local ecosystems and human population, as well as for connected downstream basins (Viviroli *et al*., 2003). As suggested by Wilson and Guan (2004), mountainous watersheds exhibit geological, landscape, climate, and other characteristics that are distinctive from other types of watersheds/basins. They may exhibit, for example, high relief, steep slopes, deeply incised valleys, variable bedrock and alluvium geological conditions, extreme spatial and temporal climate variability, complex and dynamic surface water drainage, significant areas of coniferous forest, and variable population concentrated in the valley bottom (relying on both surface water and groundwater resources). Commonalities of many of these characteristics are evident within and between mountainous watersheds.

Groundwater flow in mountains areas has been a topic of research for several decades, spanning regional flow characterization (Freeze and Witherspoon, 1967; Forster and Smith, 1988), interaction with mountain and valley bottom streams (Constantz, 1998; Winter *et al*., 1998, 2003; Kimball and Stolp, 2004; Wilson and Guan, 2004; Covino and McGlynn, 2007) and mountain block recharge (Manning and Solomon, 2003, 2005; Wilson and Guan, 2004). While much groundwater research has been done in arid mountainous regions of the southern United States (Manning and Solomon, 2003, 2005; Wahi *et al*., 2008), there has been comparatively little research in colder and more northern temperate mountainous regions.

The aim of this study is to explore the relationship between groundwater fluctuations and past climatic variations using available climate data, hydrometric data and data from the recording well network in British Columbia (BC). We consider data from nine aquifers across the southern portion of BC, Canada, where long-term monitoring data are available. This type of assessment is complicated due to the complexity of the groundwater system, which influences the nature of the connection between groundwater and recharge from precipitation or local streams, and to the varied nature of the climate in different parts of the province. To structure this assessment, the aquifers are first classified according to an *aquifer-stream system* type based on the dominant recharge mechanism for the six main categories of aquifers found in the province (Wei *et al*., 2007). Second, responses of these aquifers to local hydroclimatology are examined using data from selected observation wells and

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classified based upon the predominant recharge response mechanism (precipitation, snowmelt or local streamflow). This type of analysis enables defining those characteristics of the recharge and discharge, which separate the hydrogeologic effects of the site from those of hydroclimatology.

BACKGROUND

Physiography and climate

BC is characterized by several mountain ranges with elevations above 3000 m, vast plateau areas and deep valleys. Geology and geomorphology are highly variable; the mountains expose volcanic, plutonic and sedimentary bedrock (Holland, 1976; Back *et al*., 1988), and evidence of Pleistocene glacial, fluvioglacial and glaciolacustrine activity can be found almost anywhere in the region (Clague, 1977). Considerable Holocene alluvial deposits exist in the valleys of most large rivers (Clague, 1977). The region is also one of the most hydroclimatically complex regions in North America owing to its complex relief and proximity to the Pacific Ocean (Wade *et al*., 2001; Moore *et al*., 2008).

BC can be divided into five physiographic regions that have distinct macroclimatic regimes (Chilton, 1981; Moore *et al*., 2008). The numerous parallel mountain ranges and extensive plateaus, plains and basins produce a range of climatic regimes that are reflected in 14 vegetation zones named from the dominant tree species of that zone (Moore *et al*., 2008). Precipitation generally ranges from greater than 4000 mm/year in the west to less than 200 mm/year in a series of rain belts and rain shadows (Moore *et al*., 2008). During the winter months, frontal weather systems formed in the Pacific Ocean bring moisture into the region resulting in high amounts of precipitation falling onto the western slopes of the mountain ranges. Conversely, the eastern slopes and the valleys in the lee of the mountains are drier. Except at low elevations along the coast, winter precipitation falls predominantly as snow. Summers are relatively dry throughout the region and considerable climatic moisture deficits develop, particularly in parts of the southern interior where summer temperatures are highest.

Within the Cordillera, streams are broadly classified as rain-dominated, snow-dominated, hybrid (rain and snow) and glacierized, with each having distinct summer low-flow seasons. During summer, after a prolonged period with a climatic moisture deficit, streamflow in interior snow-dominated regimes is sustained either by late-lying snow or glacier melt, or by the release of stored water from groundwater, lakes and wetlands (Moore *et al*., 2007). During these summer low-flow conditions, it can be expected that streamflows in unglacierized basins are mainly fed by groundwater. In glacierized basins, increased ice melt contributions during the warm season maintain streamflows after the snowmelt period (Stahl and Moore, 2006). In the western portion of this region, near the coast, and particularly at low elevation, pluvial systems are predominant and low streamflows occur during summer (Wade *et al*., 2001). Hybrid systems (a mixture of pluvial and nival) are also present (Wade *et al*., 2001; Fleming *et al*., 2007).

Variations in temperature and precipitation associated with the effects of ENSO (El Niño Southern Oscillation) (Shabbar and Khandekar, 1996; Shabbar *et al*., 1997) and PDO (Pacific Decadal Oscillation) (Mantua *et al*., 1997; Fleming and Whitfield, submitted; Whitfield *et al*., 2010) influence the amount and form of water that both drives streamflow (Redmond and Koch, 1991; Wang *et al*., 2006; Fleming *et al*., 2007; Rodenhuis *et al*., 2007; Moore *et al*., 2009) and recharges groundwater (Fleming and Quilty, 2006). This strong connection to the climate system at sub-decadal to multi-decadal timescales suggests that longer term climate changes could have important effects on hydroclimate, streamflow and, ultimately, groundwater levels and the interaction of groundwater with surface water. For example, while the warmer winters of recent decades have increased the number of mid-winter melt events and, therefore, have directly increased winter low flows in hybrid (pluvial-nival) regimes, summer low flows have mainly decreased (Whitfield and Cannon, 2000). This recent decrease in summer low flows was interpreted as the result of an extended summer recession period due to lower snowpacks and earlier snowmelt, which was similarly demonstrated through modelling (Whitfield *et al*., 2003).

With extended low-flow periods, caused by lower snowpack, earlier snowmelt and glacier loss, streams may be more strongly influenced by interaction with groundwater. Changes to the groundwater regime via the timing and amount of natural recharge (Scibek and Allen, 2006) as a consequence of shifts in precipitation and higher summer evapotranspiration, as well as greater groundwater use, could result in lower groundwater levels in some areas. Therefore, summer low flows in streams may be exacerbated by decreasing groundwater levels, and streamflow may become inadequate to meet economic needs such as domestic consumption, as well as ecological functions such as in-stream habitat for fish and other aquatic species (Moore *et al*., 2007). Hence, it is important to understand the interactions of the groundwater regime with both local streamflow and the climate system.

Hydrogeological setting

There are two main hydrogeological factors that affect the response of an aquifer to changes in water input/output. By response, we mean the magnitude (amplitude) and timing of changes in groundwater level, commonly recorded on a well hydrograph. The first determinant is the driving mechanisms for flow. These driving mechanisms include primarily recharge mechanisms, but also conditions that moderate the flow in discharge zones. Water can enter the ground either directly from rainfall and snowmelt (*direct recharge*) or indirectly

Table I. Aquifer type in mountainous regions and key hydrogeological characteristics

Aquifer type[a]	Expected recharge mechanisms	Connection with surface water	Confined–unconfined
1. Fluvial or glaciouvial aquifers along river valley bottoms			Variable
a. Aquifers along low gradient, higher order rivers	a. Throughflow from upstream, indirect from river, infiltration of precipitation	a. Possible direct connection	a. Partially confined
b. Aquifers along generally higher gradient, moderate order rivers	b. Throughflow from upstream, indirect from river, infiltration of precipitation	b. Direct connection	b. Unconfined
c. Aquifers along lower order streams in confined valleys; limited aquifer thickness and lateral extent	c. Infiltration of precipitation, indirect from river, runoff from valley sides	c. Possible direct connection	c. Partially confined
2. Deltaic (sand and gravel) aquifers	Infiltration of precipitation and runoff from uplands	Direct connection	Unconfined
3. Alluvial, colluvial (sand and gravel) fan aquifers	Induced from river, infiltration of precipitation	Direct connection	Unconfined
4. Glaciofluvial aquifers			Variable
a. Unconfined outwash and ice-contact sand and gravel aquifers	a. Infiltration of precipitation	a. Drained by local creeks	a. Unconfined
b. Confined aquifers of glacial or pre-glacial origin	b. Infiltration of precipitation	b. Possible connection	b. Mostly confined
c. Confined aquifers of glaciomarine origin	c. Infiltration of precipitation, infiltration from overlying aquifers	c. Connection unlikely	c. Confined
5. Sedimentary rock aquifers			Variable
a. Fractured sedimentary rock aquifers	a. Limited in ltra tion of precipitation	a. Drained by local creeks	a. Unconfined
b. Karstic limestone aquifers	b. Unknown, but likely in ltration of precipitation	b. Unknown	b. Unknown
6. Crystalline rock aquifers			Partially confined
a. Flat-lying or gently dipping volcanic ow aquifers	a. Limited infiltration of precipitation	a. Drained by local creeks	a. Partially confined
b. Fractured igneous intrusive, metamorphic, fractured volcanic or metavolcanic aquifers	b. Limited infiltration of precipitation	b. Drained by local creeks	b. Partially confined

[a] Aquifer type based on Wei *et al*. (2007).

through influent streams and rivers (*indirect recharge*). Lerner *et al*. (1990) also identified localized recharge as a third mechanism, in which recharge is derived from a concentrated source resulting from the horizontal surface or near-surface flow of water in the absence of well-defined channels. Recharge may also occur to confined aquifers through semi-confining layers where they are not in direct connection with the atmosphere. Considering the first two mechanisms, which are the predominant ones, the replenishment of stored water, and hence the response of a groundwater level hydrograph, will be closely tied to the climate, the surface hydrology of the area and the nature of land–atmosphere interactions that control water–energy budgets.

The geological characteristics of aquifers are the second important determinant of the magnitude and timing of the hydrological response in the aquifer. In equivalent physiographic settings, more permeable aquifers (e.g. sand and gravel aquifers) will respond quickly to hydrological stresses, but the overall amplitude of the response will be dampened due to the moderate to high storage capacity of these aquifers. In contrast, low-permeability aquifers with low storage capacity (e.g. unfractured bedrock aquifers) will show delayed responses with large amplitude responses.

The different aquifer types found in the Cordillera Region of Canada have recently been categorized (Wei *et al*., 2007). Six main aquifer types were identified based on general aquifer properties (e.g. permeability) and geological settings (Table I, column 1).

As part of this study, for each category of aquifer, the expected recharge mechanism (Table I, column 2), the degree of connection to surface streams (column 3), and the degree of confinement of the aquifer (column 4) were identified. In consideration of these attributes, we have broadly classified these aquifer types into two main aquifer-stream system types, based on the anticipated responses of these various aquifer types. There are two main types:

1. Direct recharge-driven: Groundwater is recharged solely by precipitation and predominantly discharges to

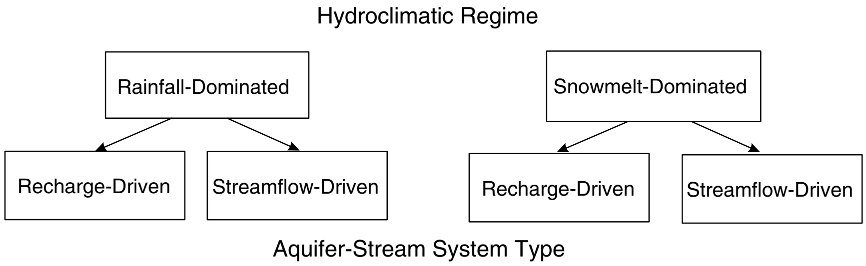

Figure 1. Framework for evaluating the responses of aquifer systems. For simplicity, the hydroclimatic regime includes only rainfall- and snowmelt-dominated regimes. Hybrid regimes are not represented, but are a blend of these two main types. Both recharge-driven and streamflow-driven aquifer-stream types may be found in each hydroclimatic regime

streams during periods of low flow. The aquifer-stream system is generally raised above the surrounding land surface and drains to lower elevation.
2. Stream-driven systems: Groundwater flow to and from streams is bi-directional, and varies seasonally depending on stream stage. These aquifer-stream systems are found in association with major streams/rivers.

Distinguishing between these two cases ranges from very simple to very difficult. In the case of an aquifer which is raised above the surrounding area, the relationship is clearly that recharge is driven by precipitation, and that groundwater discharges to the local stream over the entire year. During the late summer, local streamflow is sustained primarily by groundwater discharge, with the occasional stormflow, provided it is not fed by glacier melt. During the winter, these streams may be quite flashy when the water levels in the aquifer are high, and local soils are wet, and streams respond directly to rainfall through surface runoff. We can describe this groundwater system as process linkages:

$$\text{P} \rightarrow \text{R} \rightarrow \text{Q during the entire year} \tag{1}$$

where P is the precipitation, R is the groundwater recharge, and Q is the stream runoff.

At the other extreme, aquifers associated with large streams, whose annual hydrograph is generated by processes remote from the aquifer (i.e. allogenic), have an annual water level pattern that primarily reflects the changes in the discharge (and hence the level) of water in the stream (Scibek *et al.*, 2007). In this case the process linkages are:

$$\text{P} \rightarrow \text{stored as snow} \rightarrow \text{Q} \rightarrow \text{R}$$
$$\text{during one portion of the year} \tag{2a}$$

and

$$\text{R} \rightarrow \text{Q during the balance of the year} \tag{2b}$$

Thus, the magnitude and timing of the response of the groundwater system will depend on whether the system is stream-driven or recharge-driven. Characterizing the seasonal timing of the response, however, requires consideration of the hydroclimatology of the region: rainfall-dominated (pluvial), snowmelt-dominated (nival) or hybrid, as discussed above.

The overall framework used in this study for evaluating the responses of aquifers is shown in Figure 1. It is important to note at this time that the observation well responses analysed in this study are considered to be representative of the entire aquifer response. This assumption is reasonable based on the overall consistency of other, but less complete, observation well records in other parts of the respective aquifers (Moore *et al.*, 2007).

METHODS AND DATA SOURCES

Groundwater level information was obtained from the BC Observation Well Network (BC Ministry of Environment, 2007a). Well water levels were measured continuously with Stevens Type F chart recorders (accuracy level ± 1 mm) and are referenced from ground level. These records were manually digitized using Water Survey of Canada (WSC) procedures. Daily average water levels were (manually) extracted, and data were verified. Most records had minor errors, e.g. data shifts, or missing data. The records were corrected and missing values in-filled using linear approximation aided by mean annual hydrograph fitting.

The nine groundwater observation wells are located across southern BC; they span from the western coastal area eastward to just west of the Rocky Mountains (Figure 2). The hydrogeology of each of these wells, their depth and the distance from local streams are

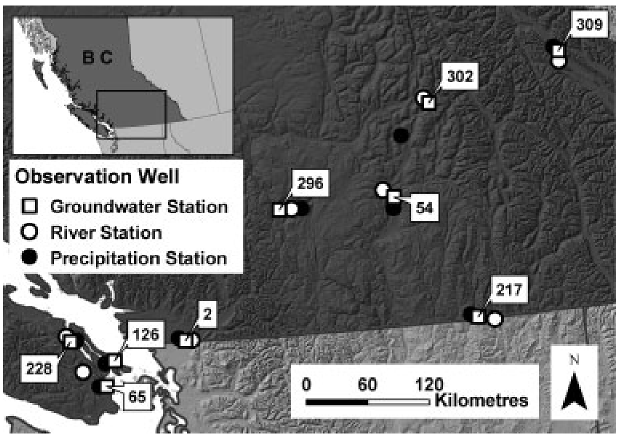

Figure 2. Location of BC observation wells. Wells are identified according to whether they are situated in a rainfall- or snowmelt-dominated hydroclimatic regime. BC observation well number is also provided

Table II. The nine 'natural' observation wells (in bold) with reconstructed daily observations and their associated hydrometric and climate (in italics) stations

Station number	Station name	Latitude	Longitude	Record length	Drainage area (km^2)	Hydroclimatic regime
002	**Fraser Valley**	49·01	−122·34	1972–1998		
08MH029	Sumas R. Near Huntingdon	49·00	−122·23	1935–2005	149	Rainfall
1100030	*Abbotsford Int'l Airport*	49·02	−122·36	1953–2002		
065	**Saanich**	48·64	−123·41	1974–1992		
08HA001	Chemainus R. near Westholme	48·88	−123·70	1914–2004	355	Rainfall
1018620	*Victoria International Airport*	48·65	−123·43	1953–2002		
126	**Mayne Island**	48·86	−123·29	1972–1998		
08HA001	Chemainus R. near Westholme	48·88	−123·70	1914–2004	355	Rainfall
1014931	*Mayne Is.*	48·85	−123·32	1973–1998		
228	**Cassidy**	49·04	−123·87	1978–1998		
08HB034	Nanaimo R. near Cassidy	49·07	−123·89	1965–2005	684	Rainfall
102537	*Nanaimo Airport*	49·05	−123·87	1954–2002		
054	**Carrs Landing**	50·14	−119·40	1969–1998		
08 NM174	Whiteman Cr. Above Bouleau Cr.	50·21	−119·54	1971–2005	112	Snowmelt
112895	*Winfield*	50·04	−119·42	1971–2002		
217	**Grand Forks**	49·02	−118·43	1977–1998		
08NN002	Granby R. at Grand Forks	48·98	−118·21	1914–2004	9840	Snowmelt
1133270	*Grand Forks*	49·03	−118·47	1941–2002		
296	**Merritt**	50·11	−120·79	1989–1998		
08LG010	Coldwater R. at Merritt	50·11	−120·80	1913–1995	914	Snowmelt
1125079	*Merritt STP*	50·11	−120·80	1968–2002		
309	**Golden**	51·26	−116·92	1989–1998		
08NA002	Columbia R. at Nicholson	51·24	−116·91	1903–2005	6660	Snowmelt
1173210	*Golden Airport*	51·30	−116·98	1991–2002		
302	**Malakwa**	50·94	−118·79	1988–1998		
08LE024	Eagle R. near Malakwa	50·94	−118·80	1913–2005	904	Hybrid
1166945	*Salmon Arm Airport*	50·67	−116·98	1988–1998		

presented in Table II based on information from the BC Wells Database (BC Ministry of Environment, 2007b). The nine observation wells were classified into aquifer type; Table III gives the aquifer type (following Wei *et al*., 2007), along with information on well depth, aquifer materials and proximity to any surface water. Table III also attempts to broadly categorize the aquifer according to aquifer-stream system type as described above. Verification of these types is discussed later based on quantitative assessments.

Meteorological Survey of Canada (MSC) climatological stations were then selected based on their close proximity to the well of interest and their period of record (Table II). Data were retrieved from the 2002 CDCD (Canadian Daily Climate Data) West archive (Environment Canada, 2002). Hydrological records were downloaded from the WSC Archived Hydrometric Data site (Environment Canada, 2004) for the nearest station representative of the local hydrology (Table II).

Time series plots were first constructed to demonstrate the variations in long-term water levels, seasonal patterns and record length. Of the 183 observation wells currently operational in the province, nine records were of sufficiently high quality to undertake further analysis.

Observation wells were then grouped according to hydroclimatic regime and a comparison of the responses (as 18-month series) was made for the period of record with Julian day zero as 1 January. Six (of the nine) wells were selected to represent each of unconsolidated and bedrock aquifers in each of rainfall-dominated and snowmelt-dominated regions. For each well, median precipitation recorded at the nearest meteorological station was plotted using 11-day bins. Two 18-month period hydrographs were also constructed, one representing stream discharge at the nearest representative hydrometric station and the other representing the groundwater levels in the observation well. These 18-month period hydrographs combine the water year and calendar year and assist with viewing variables that are continuous over the calendar year boundary. The relationship between the timing of precipitation, streamflow and groundwater levels at each site is evaluated.

To better explore the relationship between groundwater levels and stream discharge, hysteresis plots (or scatter plots) and cross-correlation plots were used to assess the lags and timing associated with specific aquifers. These plots enable the aquifer-stream system types to be further characterized. Hysteresis plots were constructed for the individual wells, which compare the groundwater level and the corresponding stream discharge each day. Three water year cycles were considered (1989–1990; 1990–1991; 1991–1992). Cross-correlation plots between stream discharge and groundwater level were then constructed using the ccf() function in the R statistics program (R Development Core Team, 2006). Cross-correlation is a measure of similarity of two waveforms as a function of a time lag applied to one of them, and demonstrates not only the degree of fidelity between

Table III. Classification and attributes of observation wells[a]

Observation well		Well depth (m)	Distance to stream (km)	BC aquifer number	Aquifer type[b]	Aquifer-stream system type
002	**Fraser Valley**	20	3	015	Type 4a: Unconfined glaciofluvial sand and gravel	Recharge-driven
065	**Saanich**	150	1·3	608	Type 6b: Fractured crystalline rock	Recharge-driven
126	**Mayne Island**	70	None	447	Type 5a: Clastic sandstone and mudstone aquifers	Recharge-driven
228	**Cassidy**	60	107	160	Type 4b: Confined sand and gravel aquifers of glacial or pre-glacial origin (glaciofluvial or glaciolacustrine)	Stream-driven
054	**Carrs Landing**	14	None	N/A	Type 5a or 6b: Clastic sandstone or fractured crystalline bedrock	Recharge-driven
217	**Grand Forks**	9	0·7	158	Type 1a: Along major higher stream order river valleys influenced by surface water (high-energy sand and gravel aquifer)	Stream-driven
309	**Golden**	45	Adjacent	450	Type 4b: Confined sand and gravel aquifers of glacial or pre-glacial origin (glaciofluvial or glaciolacustrine)	Stream-driven
296	**Merritt**	17	1·2	074	Type 1a: Along major higher stream order river valleys influenced by surface water (high-energy sand and gravel aquifers).	Stream-driven
302	**Malakwa**	23	0·3	307	Type 1a: Along major higher stream order river valleys influenced by surface water (high-energy sand and gravel aquifers)	Stream-driven

[a] Aquifer type according to descriptions in Table I. Aquifer-stream system type as either recharge-driven or stream-driven.
[b] Aquifer type based on Wei *et al*. (2007).

two variables, but also the correlation between two variables at specific time lags, in this case, between stream discharge and groundwater level.

RESULTS

Time series plots of groundwater levels for the nine observation wells are shown in Figure 3. For comparison purposes, horizontal grid lines are marked every 0·5m. The plots also show where each record was corrected for incorrect or missing values. These time series plots demonstrate the variations in long-term water levels as well as seasonal patterns. Periods of record vary (9 years for well 302 to 29 years for well 054). All records show annual variations in groundwater level ranging from just over 1 m to several metres. Seasonal high groundwater levels occur in the late winter to early spring, and lower levels occur in the late summer and early fall. All records show inter-annual variability.

To better illustrate seasonality in groundwater levels, Figure 4 compares the 18-month series for the period of record at each well. The responses have attributes that are characteristic to the area in which they are situated in the province. For example, wells 002, 065, 126 and 228 (Figure 4a–d) all have their annual lowest water levels in the September to November period. After this period, groundwater levels increase and peak during February or March. Groundwater levels decline from April onwards. In well 002, rates of rise in groundwater level are similar to the rates of decline. Similarly, in wells 065 and 126, the winter rise in water level results in a prolonged period wherein the well remains at an annual maximum level for an extended period (Figure 3a–c), which on a long-term average shows lengthy periods (70–100 days) at maximum levels (Figure 4a–c). The response at well 228 is different; the peak groundwater levels do not remain high for as long (50–75 days), and the recession period is characterized by very low inter-annual variability.

Wells 054, 217, 296 and 309 (Figure 4e–h) are more characteristic of the climate of the interior region of BC in that the lowest water levels are reached in January to March. Water levels in these four aquifers begin to increase during March and reach their annual maxima in June. These wells show sharper peaks in the time series (Figure 3e–h) and long-term summary (Figure 4e–h). Well 302 (Figures 3i and 4i) is also located in the interior, but shows a more complex signal than the other wells as there is more than one peak. Two peaks are evident in the annual cycle.

The variability in groundwater levels between years is reflected by the wide bands of quantiles in many of these wells (Figure 4), with the exception of 228 and 309 (Figure 4d and g). These wide bands reflect the year to year variability of a relatively consistent pattern of variable water level throughout the year. The other wells (228 and 309) demonstrate more variation around the annual peak than during the remaining part of the year.

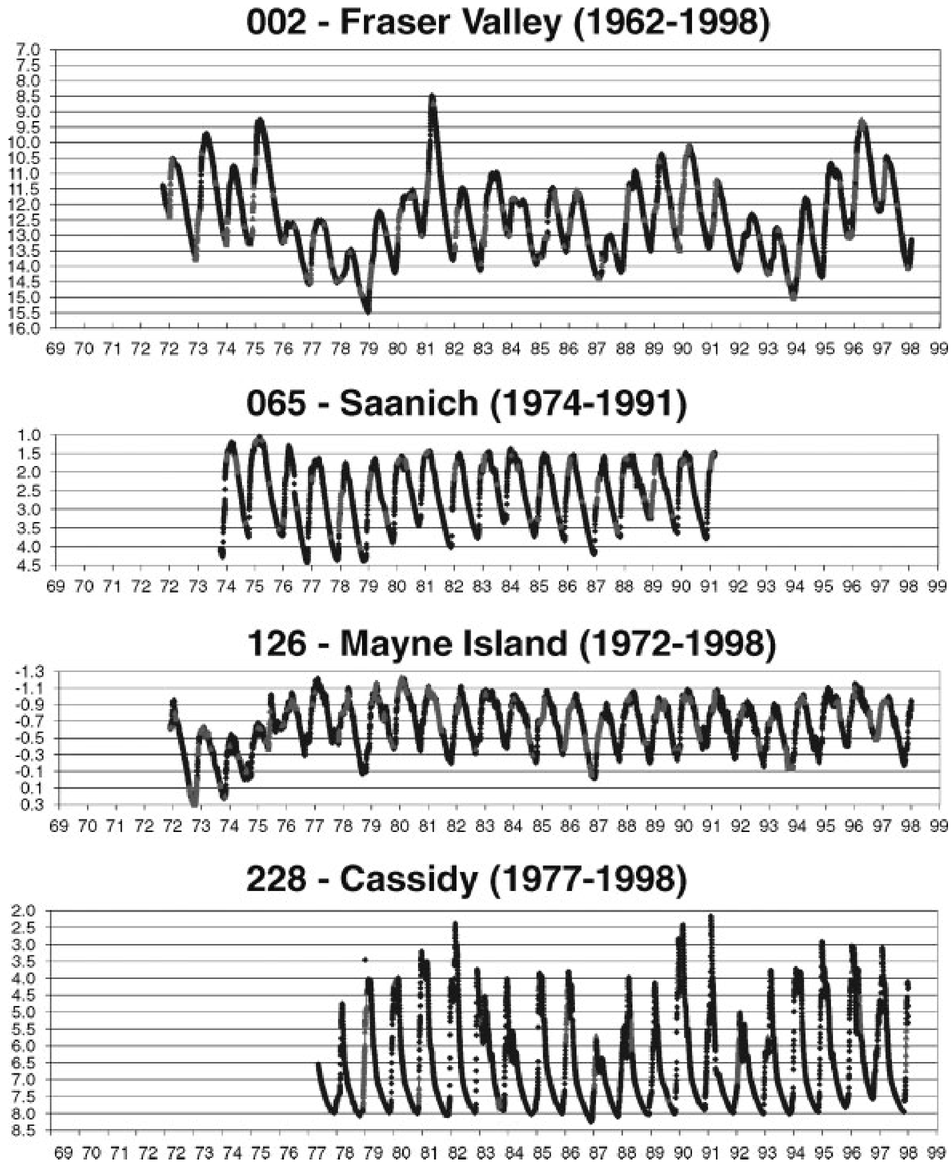

Figure 3. Groundwater level time series from the nine observation wells. Horizontal grid lines are marked every 0·5m. All water level depths plotted relative to ground level. Julian day 0 corresponds to 1 January. Original observations retained are in black; data corrections and in-filled data in grey

The relationship between the timing of precipitation, streamflow and groundwater levels is explored for each of six selected wells (002, 065, 228, 054, 217 and 302) in Figures 5–10, respectively. At the top of each figure, precipitation at the nearest climate station is plotted as 11-day bins; the width of the bar reflects the frequency of precipitation and the height indicates the amount; grey (dark) shading shows snow amounts, while blue (pale) shows rain, which is more fitting for this temporarily discrete variable. The precipitation graph is offset from the hydrographs and coincides with Julian day zero (1 January). Two 18-month period hydrographs are also shown: stream discharge at a nearby hydrometric station (upper) and groundwater level in the observation well (lower). Median stream discharges and groundwater levels are shown, as are the quantiles 25/75, 10/90 and 5/95%. Observations outside this interval are shown as dots. For some wells, data for 2 years fell outside the 95% range as indicated by the double lines.

Wells at Fraser Valley (002), Saanich (065), Mayne Island (126) and Cassidy are situated in coastal BC. The Fraser Valley well (002; Figure 5) is situated in a rainfall-dominated regime. The well is completed in a shallow Type 4a aquifer comprised of unconsolidated coarse-grained materials with high permeability (Table III). In mid- to late-October intense early winter rainfall begins. These early winter rains generate high stream discharge and rains continue throughout the winter sustaining streamflow into spring. This intense early winter rain also rapidly recharges the aquifer by direct infiltration, although the peak groundwater levels appear to lag precipitation by approximately 100 days due to the high storage capacity of this permeable aquifer type. Groundwater levels eventually reach a relatively constant level that persists for several months (~100 days) similar to the extended peak in streamflow (Figure 5).

After precipitation drops off, stream discharge and groundwater levels decline gradually over the spring and

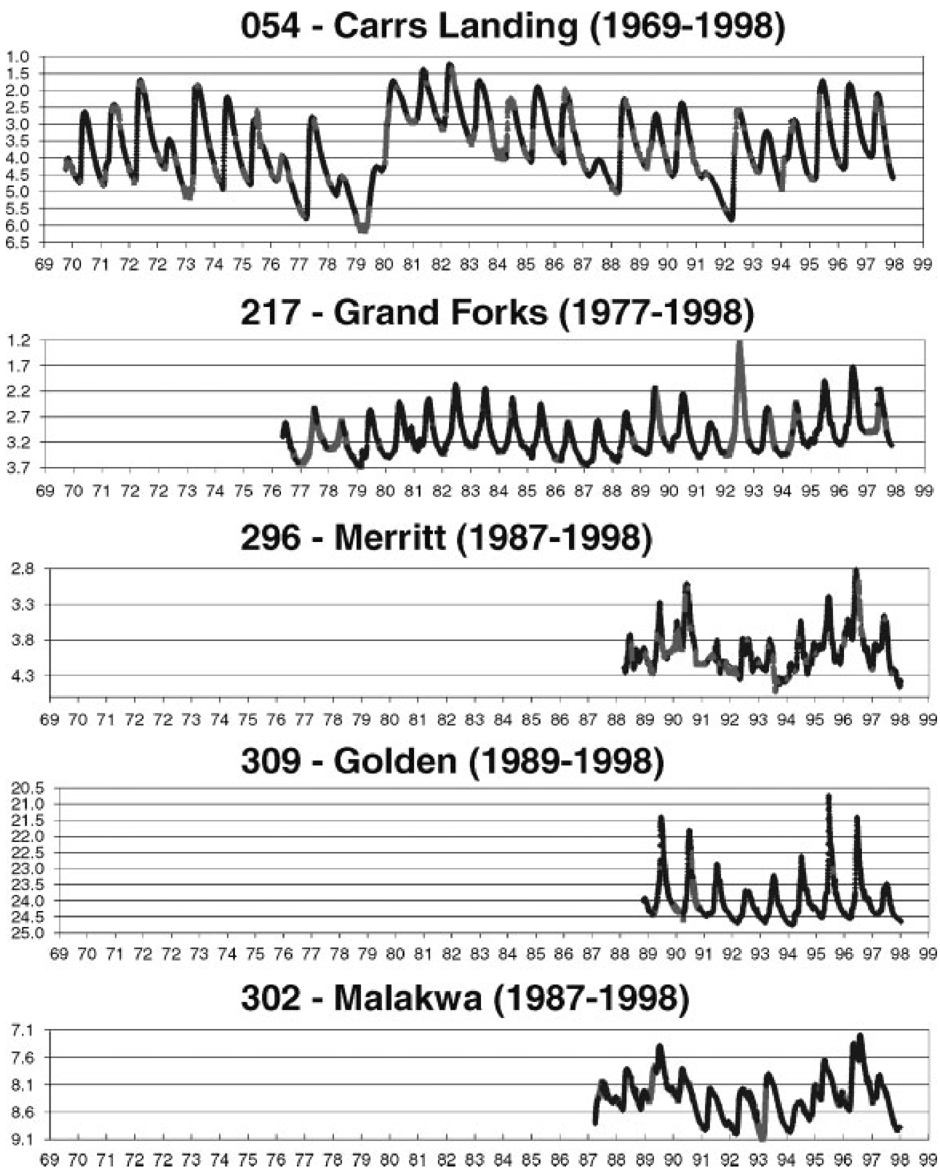

Figure 3. (*Continued*)

summer, attaining low levels in late summer. During this recession period, streamflow appears to more closely parallel groundwater levels than precipitation, suggesting a strong component of groundwater discharge. At the Fraser Valley well (002), the rate of groundwater recharge and the decline following the prolonged peak are different, with slopes during the recharge period being greater than during the initial decline.

The Saanich well (065; Figure 6) and the Mayne Island well (126; not shown) are both completed in bedrock aquifers (Type 6b and 5a, respectively; Table III). These wells have a seasonal response similar to the Fraser Valley well (002), but the characteristics of the groundwater level hydrographs are quite different due to these wells being completed in bedrock. In both of these wells, groundwater levels respond rapidly to the onset of winter precipitation (more rapidly than well 002), reaching an early maximum level roughly 50 days following peak precipitation, which persists for a relatively short period of time compared to well 002. The rate of decline of groundwater levels appears to be slower in wells 065 and 126 than in well 002. Discharge in nearby streams responds in this same fashion, but similar to the Fraser Valley, at the end of the winter rainy period the streams exhibit a slow decline in flows.

The Cassidy well (228; Figure 7) is completed in a Type 4b aquifer comprised of unconsolidated aquifer material (Table III). This type of aquifer is considered to be possibly stream-driven, particularly if a stream is located nearby and is connected to the confined aquifer (Table III). Comparing the groundwater level to climate data and the discharge for the nearby Nanaimo River (Figure 7), it is apparent that water levels in the aquifer start to rise roughly 1 month later than streamflow levels begin to rise in response to winter rainfall. Furthermore, the slope of the recharge (with time) and the initial decline are similar. These results suggest that the aquifer at well 228 may be stream-driven, but additional analysis is required as discussed below.

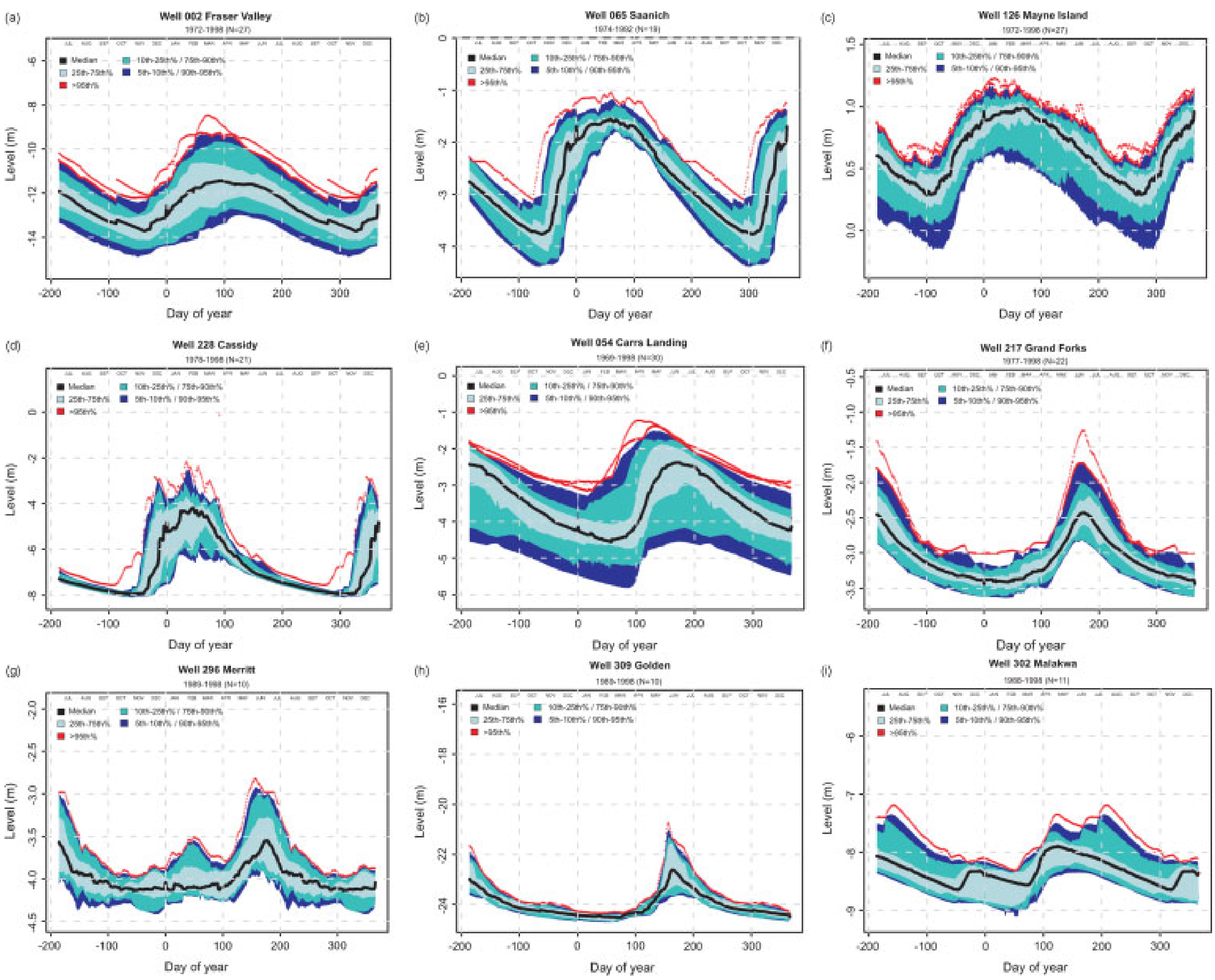

Figure 4. Groundwater hydrographs over 18 months based upon period of record for wells (a) 002, (b) 065, (c) 126, (d) 228, (e) 054, (f) 217, (g) 296, (h) 309 and (i) 302. The solid line shows the period of record median and the other bands show the intervals 25–75, 10–90 and 5–95%. The points plotted above are outside this last interval. Note that vertical scales differ and are scaled to represent the full range of data at each site. Water levels are relative to ground level. Julian day 0 corresponds to 1 January

Wells at Carr's Landing (054), Grand Forks (217), Golden (309) and Merritt (296) are situated in the BC interior. Carrs Landing (054; Figure 8) is completed in a Type 5a or 6b (unknown bedrock type) and is situated at high elevation at some distance from any stream. Its response would be most likely dominated by snowmelt, the timing of which is likely similar to that reflected in a hydrograph of any nearby streams; however, the response would be delayed due to the low permeability of the rock. In this particular case, well 054 is relatively shallow, and so it likely responds a bit more quickly than a deeper well might in the same area. In Figure 8, the peaks of both the streamflows at nearby Whiteman Creek and groundwater level appear to be coincident (within 10–20 days), suggesting that both these are being generated directly from snowmelt. While Whiteman Creek tends to be more peaked and responsive to surface events, the groundwater levels change more slowly; streamflow recession is much more rapid than are water levels in this well. The groundwater recession appears to be delayed, similar to what was observed in the other bedrock wells (065 and 126) in the rainfall regime.

The Grand Forks well (217; Figure 9) and the Merritt well (296; not shown) are situated in the highly productive Type 1a aquifers alongside large rivers draining extensive upstream areas. Figure 9 shows precipitation, discharge in the Granby River at Grand Forks, and groundwater level for well 217. The precipitation plot shows winter snowfall and summer convective rains. Stream discharge is generated by snowmelt, and the groundwater levels both mirror the shape of the stream discharge and lag it by about 30 days. Merritt (296; not shown) shows similar observation data to well 217, despite being in a different part of the province. Well 296 is situated in a sand and gravel deposit in between two major streams; the aquifer is highly productive. Groundwater levels do not appear to climb until discharge volumes are at their highest in the Nicola River (near Merritt) and then they climb very steeply. Similar to Grand Forks (well 217), the discharge is generated by snowmelt, and the groundwater levels both mirror the shape of the stream discharge and lag it by about 30 days. The well at Golden (309; not shown) is situated within a Type 4b confined aquifer, which may be stream-driven if the well is situated close to a stream. The response at this

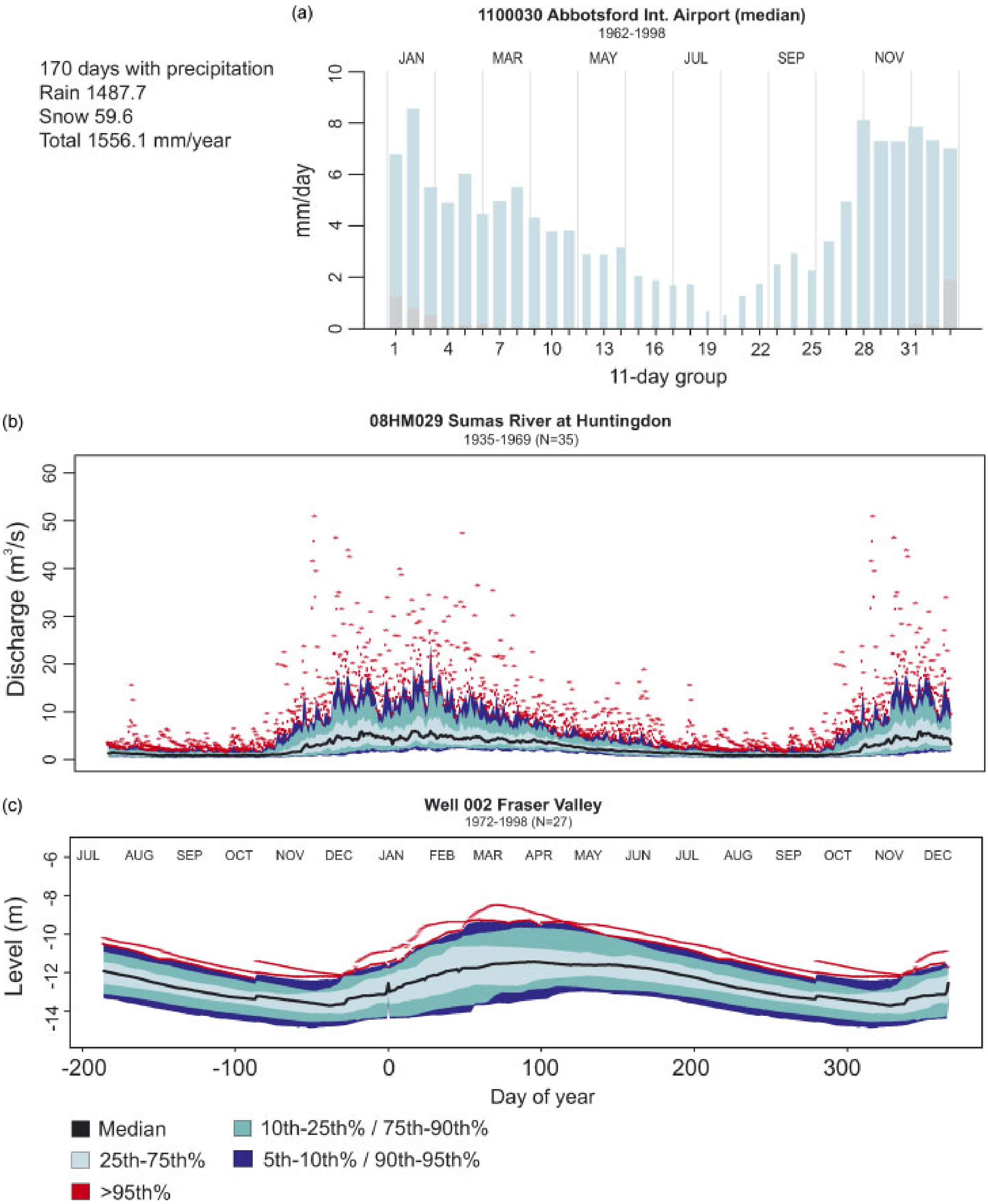

Figure 5. Comparison of local hydroclimatology. (a) Precipitation at Abbotsford, (b) hydrograph for 08MH029 Sumas River near Huntingdon and (c) well 002 (Fraser Valley) water levels. Data of 2 years fell outside the 95% distribution

well is very similar to the wells 217 and 309. There is a strong correspondence between the stream and groundwater level hydrographs, suggesting that the aquifer at this location has a stream-connection. But the shapes are distinctively different, and the time lag is very short, only about 5 days between the well Golden and the adjacent river (see Figure 3).

Finally, the well at Malakwa (302; Figure 10) is an interesting hybrid regime. Well 302 is situated some 300 m from the Eagle River and in a valley bottom aquifer similar to Grand Forks and Merritt, corresponding to a Type 1a aquifer. While this should indicate that aquifer is expected to be stream-driven, the well and stream hydrographs are quite different. The groundwater level hydrograph also has two peaks (see median) within a single water year, first in November/December and the second in March/April (Figure 10). The first of these peaks corresponds with early fall and winter rains, while the second peak corresponds to the period when rainfall starts to increase after a late winter low along with timing of early snowmelt. The second peak is not coincident with the peak in stream discharge, which is

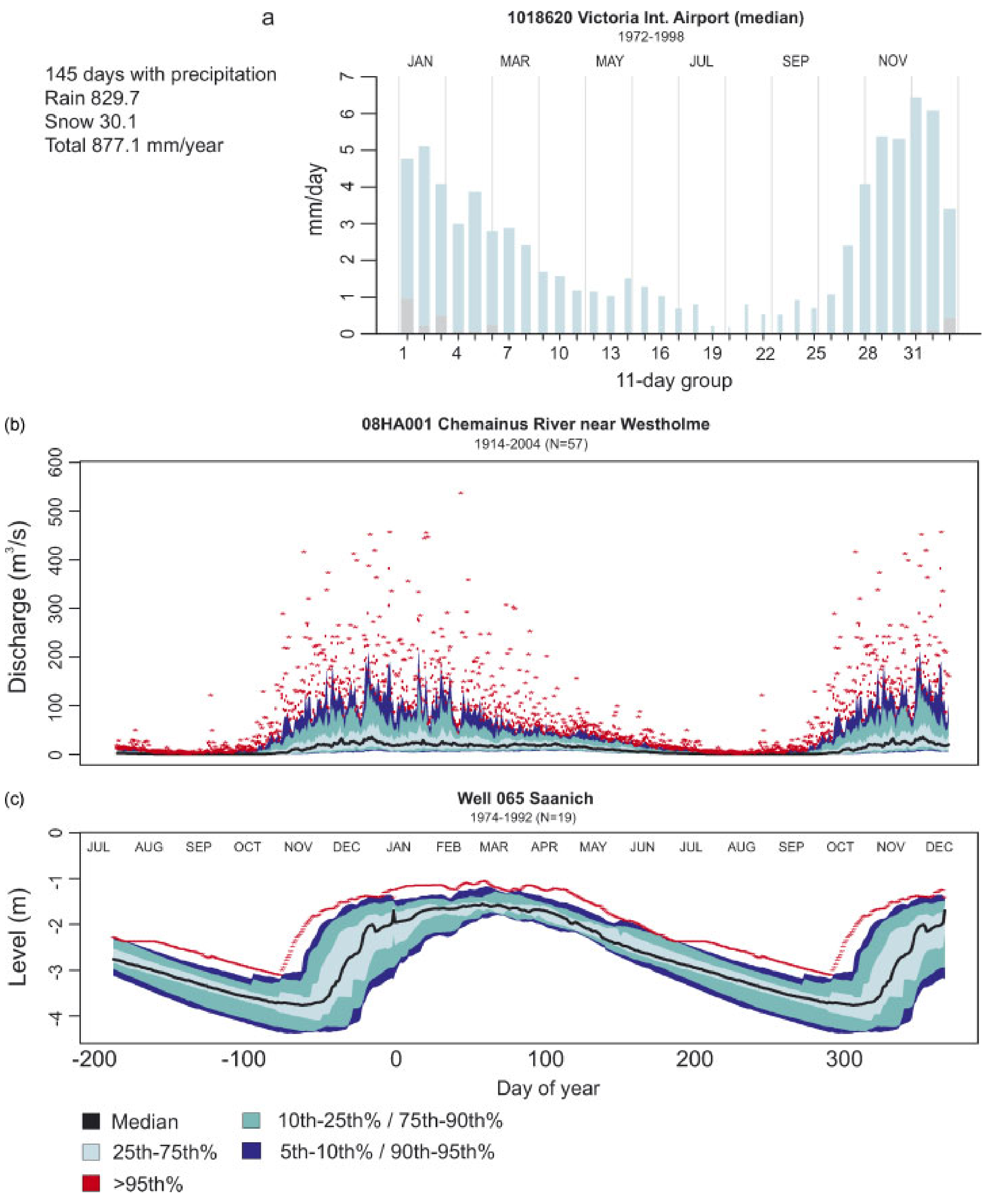

Figure 6. Comparison of local hydroclimatology. (a) Precipitation at Victoria, (b) hydrograph for 08HA001 Chemainus River near Westholme and (c) well 065 (Saanich) water levels

linked to the snowmelt generated stream discharge during May, June and July. In fact, the second peak in groundwater level appears to precede peak streamflow by about 50 days, suggesting that local direct recharge may be important. During some years, high stream discharges and groundwater levels extend into July and August (see >95% line in Figure 10), indicating a glacier component within the river system that follows to the groundwater level.

Hysteresis plots are shown for each of the nine observation wells in Figure 11. A 3-year selection of data common to all nine wells is plotted, using a log scale for stream discharge. Each month is given a separate symbol, and each water year was given a different colour. Note that in some cases, the nearby stream has no actual connection to the specific aquifer, rather it reflects the hydrological pattern of streams in the area. In others, the stream, while nearby, does not necessarily reflect local hydrology as it is 'exotic' (or allogenic)—carrying water generated further upstream of the area where the well is located. This is particularly the case for streams in the interior, which derive runoff from large catchments that have a substantial portion of their area at high elevations. One would expect groundwater levels to vary with local

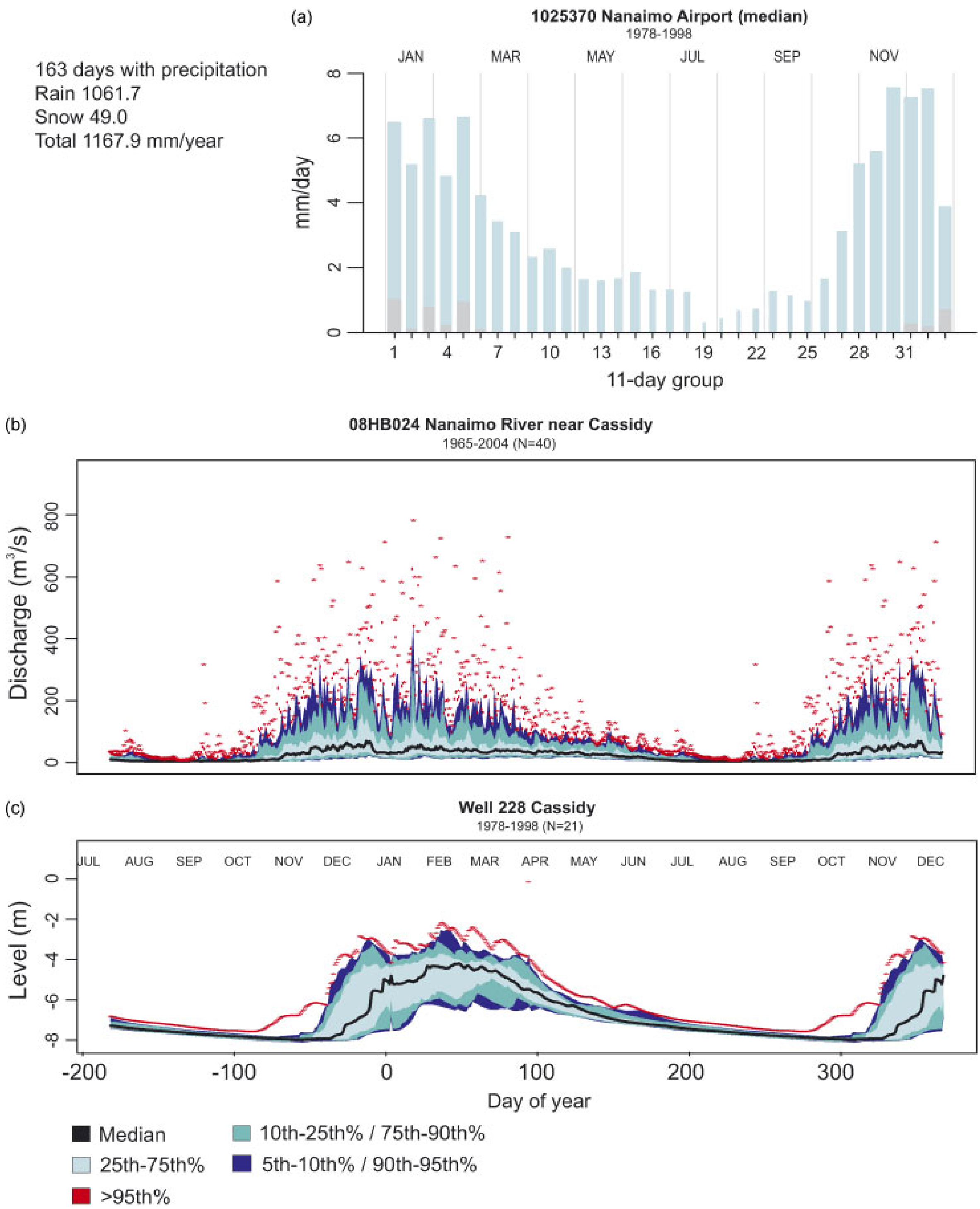

Figure 7. Comparison of local hydroclimatology. (a) Precipitation at Nanaimo, (b) hydrograph for 08HB034 Nanaimo River near Cassidy and (c) well 228 (Cassidy) water levels

recharge or by connection with streams (which may or may not be of local origin).

The patterns shown in Figure 11a–d reflect a coastal setting where recharge is generated by precipitation rather than by streamflow. In these panels, the changes in groundwater levels are near synchronous with streamflow discharge at low values. During the summer (low-flow period), the decline of groundwater level and stream discharge is very consistent between years and evident in the repeated declines of both water level and discharge on the left of Figure 11a–c. In contrast, groundwater levels are inconsistent with large stream events during the recharge period. These excursions are shown by large variations in discharge without changes in water level. As stream discharge increases, the groundwater levels remain the same for some time (e.g. there is a horizontal line of data points above the *x*-axis). As stream discharge decreases, groundwater levels do not drop, instead they remain constant for some time. The unique response for well 228, identified previously, is evident in Figure 11d

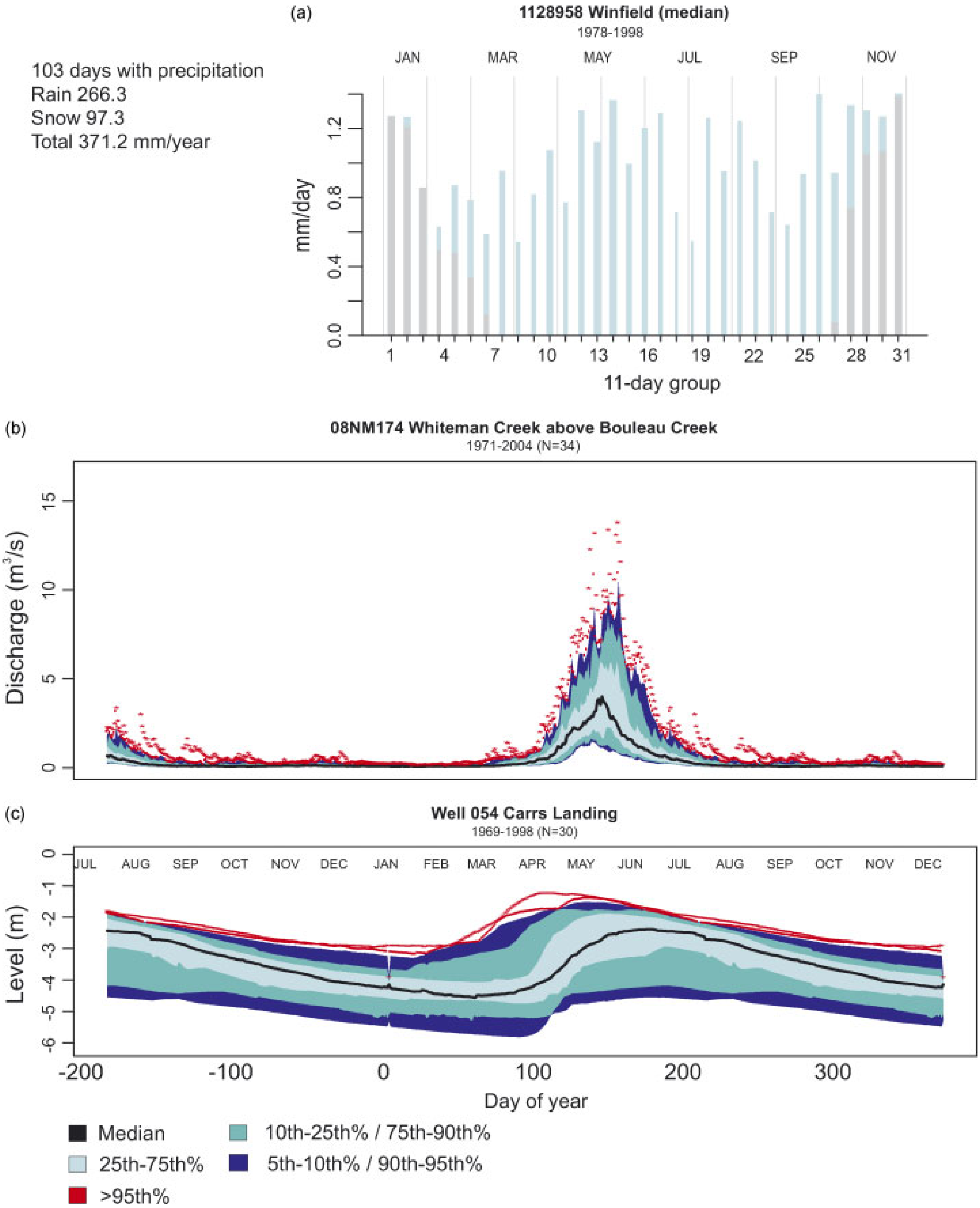

Figure 8. Comparison of local hydroclimatology. (a) Precipitation at Winfield, (b) hydrograph for 08 NM174 Whiteman Creek above Bouleau Creek and (c) well 054 (Carrs Landing) water levels. Data of 2 years fell outside the 95% distribution

where the annual base level has low variability when contrasted to the considerable inter-annual variability during the peak flows with little evidence of linkages to the nearby stream.

In snowmelt-driven streams, there is a consistent annual pattern with variations between years (Figure 11e–h). Water levels increase as soon as stream discharge volumes increase, and decrease as soon as stream discharge volumes decrease. It is interesting to note that the response over the 1991–1992 water year was exceptionally low in these snowmelt-driven systems. Water levels were low in this year relative to 1989–1990 and 1990–1991 (Figure 3). A strong La Niña event in 1989–1990 may have contributed to elevated water levels as snowpack and streamflow have been shown to increase during La Niña events in this part of BC (Rodenhuis *et al.*, 2007).

A hysteresis effect is also evident in all three aquifers. In each of these cases, the lag between stream discharge and water level generates a loop structure which repeats itself in shape but not in position between years. We speculate that the pattern itself is a function of

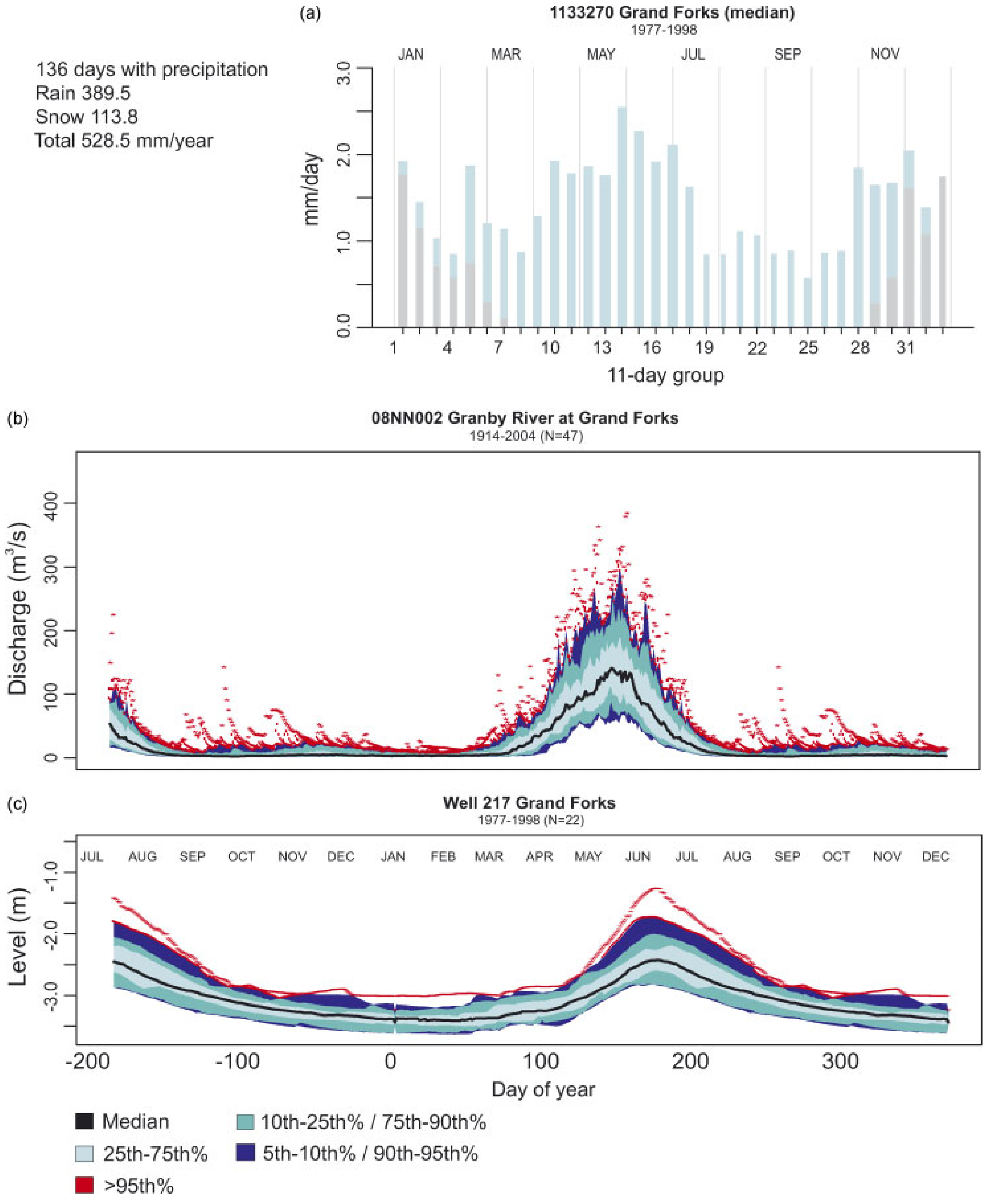

Figure 9. Comparison of local hydroclimatology. (a) Precipitation at Grand Forks, (b) hydrograph for 08NN002 Granby River near Grand Forks and (c) well 217 (Grand Forks) water levels. Data of 2 years fell outside the 95% distribution

the connectivity between the aquifer and the stream. Additionally, the smoothness of the response could be attributable to the input of water from the singular pulse of snowmelt over the season, which is more continuous over time than the contrasting individual rainfall events that result in the flashy response in streamflow and, to some degree, in groundwater in the coastal regions. At Malakwa (302; Figure 11i), the pattern reflects the bimodal nature of the groundwater levels and discharge. The groundwater response is linked to the stream discharge of the Eagle River, but it appears that the discharge in the river must have a large enough change in stage before the groundwater starts to rise.

Cross-correlation plots (Figure 12) show that peaks (and troughs) repeat roughly at yearly intervals (lags of multiples of 365 days). A high cross-correlation factor (CCF) indicates fidelity (high R^2) between stream discharge and groundwater level (similar shape), while a time shift reflected in the lag shows the timing delay

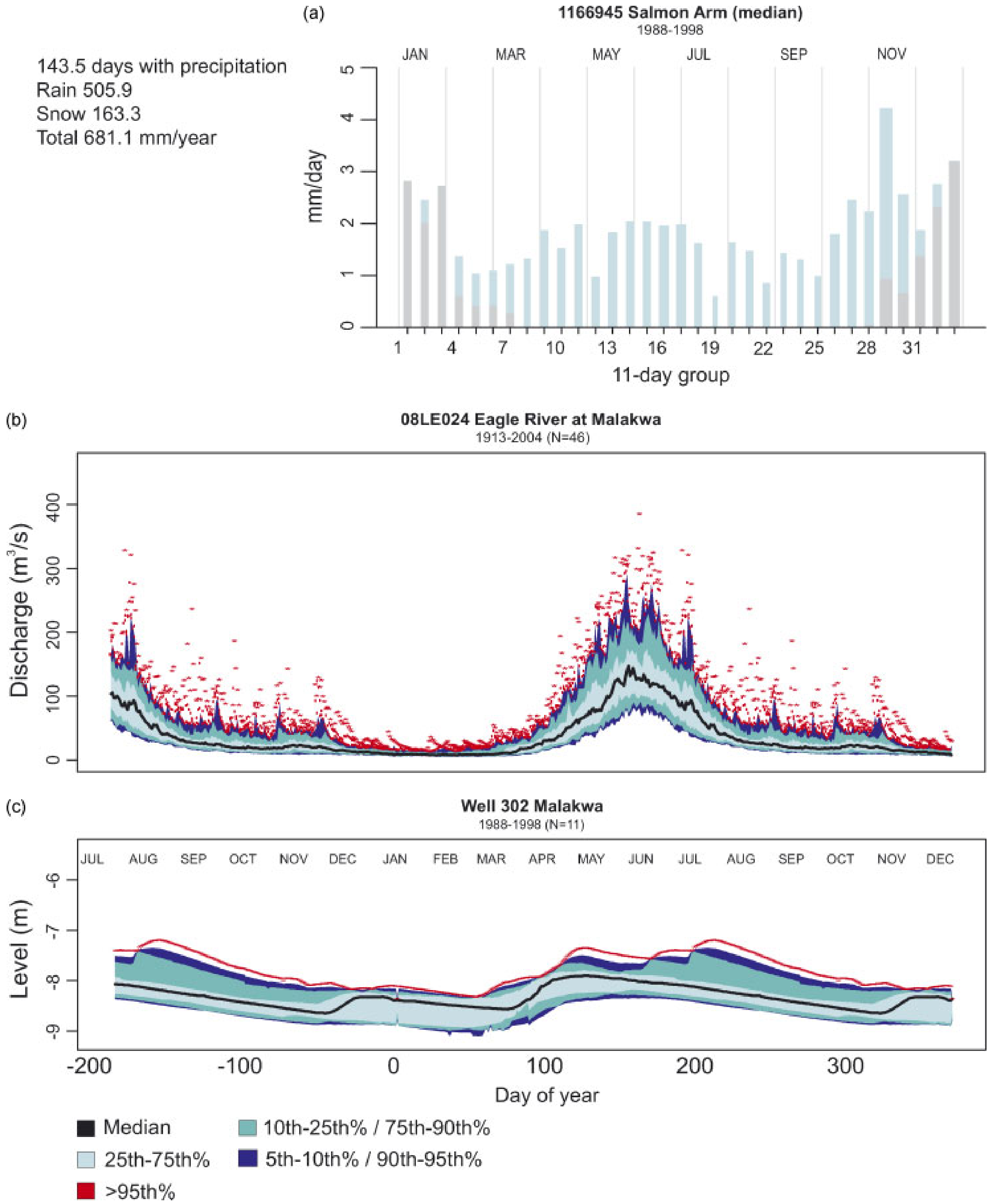

Figure 10. Comparison of local hydroclimatology. (a) Precipitation at Eagle River Hatchery, (b) hydrograph for Eagle River at Malakwa, and (c) well 302 (Malakwa) water levels

of the response of the groundwater level relative to the stream discharge. If there is a high R^2 value at zero lag, this means that the two waveforms are of similar shape and are synchronous.

Cross-correlation analysis for well 002 and the Sumas River shows moderate fidelity (R^2 slightly greater than 0·50) at a positive lag, as evidenced by the shift in the centre peak to the right of the centre line (Figure 12a). Cross-correlation for wells 065, 126 and 228 and their respective streams shows relatively low fidelity ($R^2 <$ 0·50) and the groundwater response similarly has a positive lag (Figure 12b–d), although, the lag does not appear to be as great for wells 126 and 228, suggesting that the groundwater response is more closely timed to the streamflow response. Furthermore, there is a consistent correlation between the hydrographs throughout the year, suggesting that annually, the responses do not vary significantly—this is a general characteristic of all graphs in Figure 12. The low R^2 values and positive lags exhibited by all four rainfall-dominated

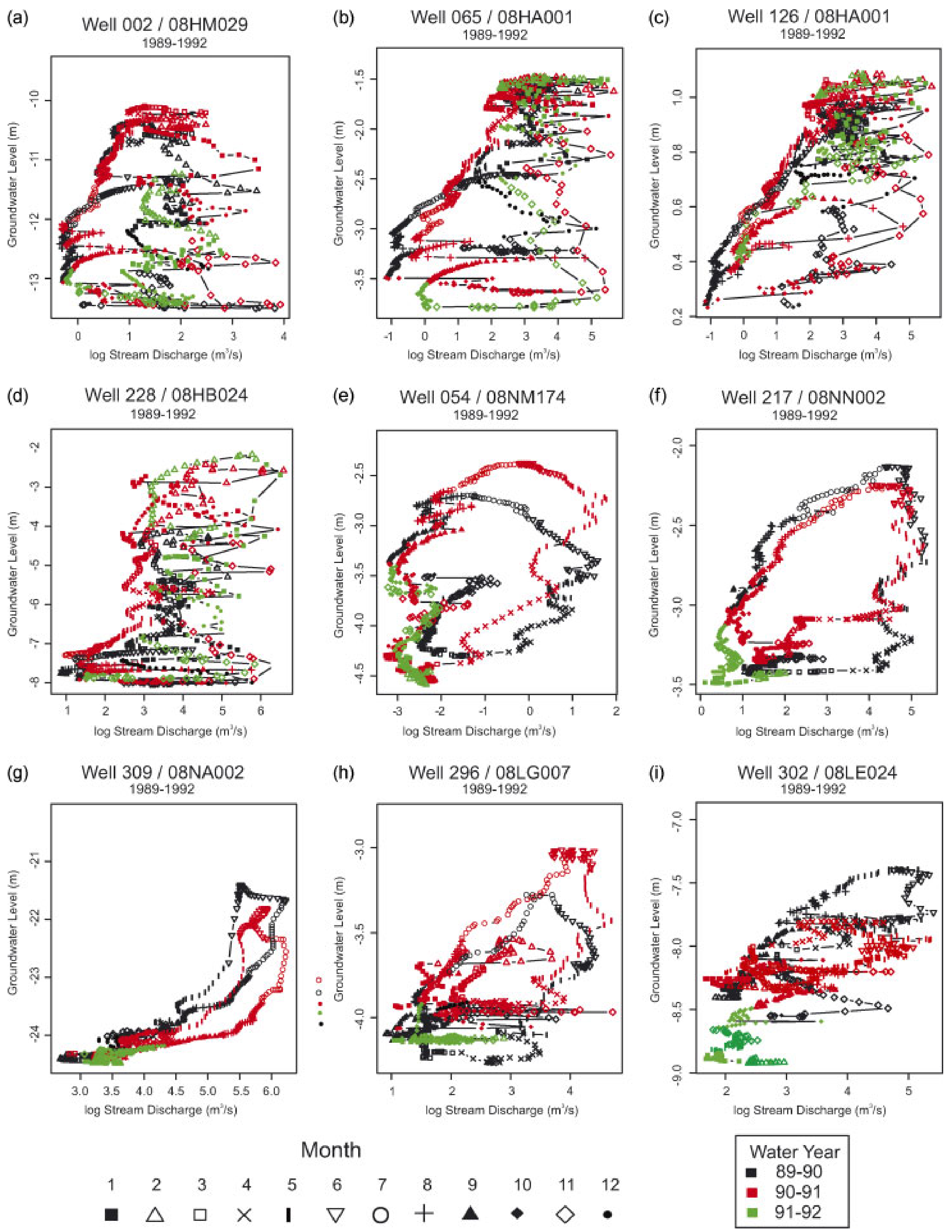

Figure 11. Hysteresis plots for water years 1989–1992: (a) 002, (b) 065, (c) 126, (d) 228, (e) 054, (f) 217, (g) 309, (h) 296 and (i) 302

graphs point to the low fidelity and lack of synchronicity between the groundwater level and stream discharge hydrographs. Based on these results, it would appear that none of these wells are strongly connected to surface water.

For well 054, in the interior, a weak cross-correlation is observed, suggesting low fidelity between the groundwater level and stream discharge (Figure 12e), with a positive lag, similar to that observed in the other bedrock wells (065 and 126) in the rainfall regime, suggesting a delayed response of the groundwater relative to streamflow.

In contrast, for wells 217, 296, 309 and 302 in the interior, the cross-correlation analysis indicates that overall, there is a high fidelity between the hydrographs ($R^2 > 0{\cdot}5$ and up to 0·8) (Figure 12f–i), and that groundwater

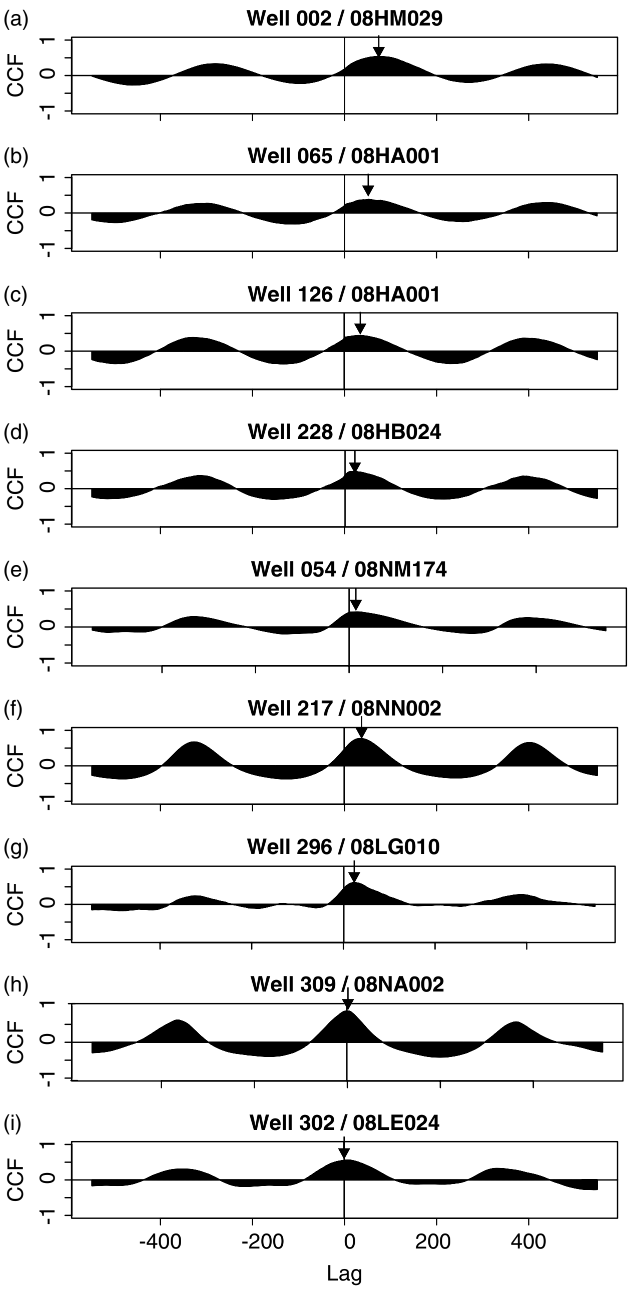

Figure 12. Cross-correlation between groundwater levels and stream discharge. A high CCF indicates fidelity (high R^2) between stream discharge and groundwater level (similar shape), while a time shift reflected in the lag shows the timing delay of the response of the groundwater level relative to the stream discharge

lags stream discharge slightly. This suggests an overall strong connection to surface water, as was shown in the hysteresis plots discussed above.

DISCUSSION

Rainfall regime

Precipitation regimes in coastal BC are characterized by heavy winter precipitation and dry summers (Figure 13a—centre graph). In coastal areas, snow pack is minimal and streams are not supported by snowmelt in the summer months (except at higher elevations). Many of these streams have low discharges during the months of July, August and September (Figure 13a—centre graph) (Wade *et al*., 2001). Where there is streamflow during late summer, it is generally groundwater discharge (Berg and Allen, 2007) (Figure 13a—centre graph). Groundwater in coastal rain-dominated regimes is similarly recharged during the wet winter season, and the well hydrographs support this conclusion. Wells 002 (Fraser Valley), 065 (Saanich), 126 (Mayne) and 228 (Cassidy) all have responses that are typical of a rainfall regime, with peak groundwater levels occurring in mid to late winter, a variable period of sustained groundwater levels in the aquifer and a recession that lasts into the fall.

Three broad types of responses were observed. In well 002, the sluggish response of groundwater level to precipitation is attributed to the high storage capacity of the aquifer. So, despite the fact that the aquifer has a high permeability, and should respond quickly, the high storage capacity results in the necessity of more water to be added to the aquifer to observe a groundwater level change. As well, the high storage capacity of the aquifer leads to sustained groundwater levels over a long period of time. It is important to note that well 002 is located at some distance from any stream, and perhaps if the well had been closer to a stream, even in this type of aquifer, there may have been some influence from high stream discharge in the winter due to the high permeability. But regardless of this, the aquifer itself appears to be classified as a recharge-driven system because significant recharge to such ‘raised’ aquifers occurs directly from precipitation.

Wells 065 and 126, completed in bedrock aquifers, have a seasonal response similar to precipitation as well 002, but the timing of the response is quicker and there is a faster recession. The low permeability and storage capacity of bedrock aquifers means that when it starts to rain in the fall, there is a limited capacity for infiltration, but what does enter the groundwater system translates rapidly into an increase in groundwater level. Thus, groundwater levels in the aquifer will generally rise more rapidly than in more productive aquifers, and will reach their maximum value within a relatively short period of time due to the low storage capacity of the rocks. The recession is also quicker because water is removed from the limited storage readily. Due to the low permeability of the rocks, there is limited capacity for surface water in a stream to enter the aquifer. Thus, streamflow remains relatively confined to the channel. It might be expected, therefore, that bedrock aquifers in general will have little connection with surface water and that they will be largely recharge-driven.

Finally, the seasonal response at well 228 is similar to that observed in the other three wells in this rainfall-dominated regime, but shows more variation between the annual peaks, and less variation between annual minimum levels; here the annual maximum does not persist for as long as in the other three wells. These results suggest that the aquifer near Cassidy may be, at least partially, stream-driven. However, the hysteresis plots

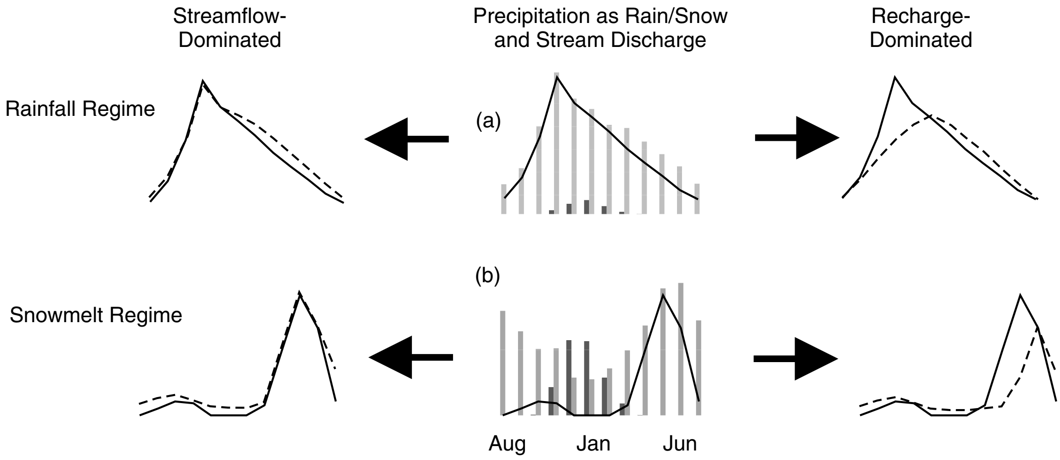

Figure 13. Schematic diagram showing precipitation (snow: dark bars and rain: light bars) and streamflow (centre panel) for each of (a) rainfall regime and (b) snowmelt regime. Precipitation data for the snowmelt regime are reflective of valley bottom precipitation. Precipitation increases with elevation, but there are very few climate stations situated at high elevation. Left and right graphs show the stream hydrograph (solid line) from the centre panel along with the groundwater hydrograph (dashed line). Groundwater hydrographs are generally representative of the valley bottom responses. The offset between the groundwater response and the stream hydrograph illustrates the nature of the response in each of recharge-driven (right graphs) and streamflow-driven (left graphs) aquifer systems. In recharge-driven systems there is a disconnection between streamflow and groundwater level during the recharge period and a connection during the recession period as groundwater is the main contribution to baseflow. In streamflow-driven systems there is a connection between streamflow and groundwater level both during the recharge period and during the recession

and cross-correlation plots are somewhat indeterminate, possibly because the Nanaimo River may not be as representative as perhaps some smaller, more local streams in this aquifer.

Therefore, wells 002, 065 and 126 are all considered characteristic of recharge-driven aquifer systems (Figure 13a—right graph), whereas well 228 may be partly representative of a stream-driven aquifer (Figure 13a—left graph).

Snowmelt regime

Snowmelt regimes in BC are characterized by accumulation of winter precipitation in the form of snow, followed by spring runoff and a dry summer period (Figure 13b—centre graph). Precipitation increases with elevation and results in winter snowpack accumulation at high elevation fall from October to March. Air temperatures (data not shown) start to increase in mid-March, on average, bringing the mean air temperature above the 0 °C melting point of the available snow pack. Rainfall rates are greatest from May to July in this region. These rainfall events are thought to be brought on by convective rather than frontal patterns, and often this rain is evaporated before it has time to infiltrate the land surface. In fact, many regions of the interior (e.g. Okanagan) experience recharge deficits during the summer due to high evaporation (Smerdon *et al*., in 2010).

Within a snowmelt regime, the interactions between the driving conditions of climate, streamflow and groundwater are complex due to the high relief. Streamflows are supported by snowmelt into late spring and early summer months (Figure 13b—centre graph). The snowpack at high elevation generates the majority of runoff. Streamflows peak between April and mid-June in this region. These streams often eventually form larger rivers or lake systems within the valley bottoms. Groundwater is also recharged both at high elevation and in the valley bottom by snowmelt and spring/early summer precipitation. Summer baseflow in streams is typically supported by discharging groundwater, or by a combination of glacier runoff and groundwater discharge through the months of July, August and September. Groundwater may discharge to streams both in transit from high elevation catchments to low elevation valley bottoms; discharge is particularly significant where the topography changes, such as at the bedrock–valley bottom interface. Mountain soils and aquifers tend to be shallow with limited storage capacity, and during a dry summer it is not unusual for small streams in the southern part of the Cordillera to become dry in August or September. Along the valley bottom, local groundwater may interact with streams. The extensive alluvial aquifers in the larger valleys across the region can provide significant late summer baseflow to rivers after being recharged from the river during the spring freshet (Scibek *et al*., 2007).

The groundwater level responses in Figure 13 are generally representative of valley bottom aquifers because this is where the majority of the observation wells are situated. This point is important because the response of the aquifer will reflect a combination of local climate influences and remote climate influences. For example, direct recharge to the aquifer may occur from spring snowmelt within the valley and from spring and early summer precipitation. Indirect recharge from the river, however, may also be significant in some aquifers. These streams originate at higher elevation in headwater regions of the watershed. Thus, the timing of the groundwater response may be more strongly tied to climatic conditions outside of the valley bottom.

Two main types of aquifer responses were found in the interior. Well 054, completed in a bedrock aquifer, has a very different seasonal response compared to similar bedrock wells in the rainfall-dominated regime, but the timing of the response is quite similar. This well, like 065 and 126, responds rapidly to snowmelt and has a rapid recession. Thus, it is characteristic of a well in a recharge-driven aquifer system in a snowmelt regime.

The responses at wells 217, 296 and 309 are all very similar, and are perhaps best explained by consideration of well 217, which is situated in an aquifer that has been extensively studied through numerical modelling of the interaction between streamflow and groundwater in the Grand Forks aquifer (Scibek *et al*., 2007). The modelling demonstrated that groundwater levels in the floodplain area of the aquifer (well 217 is in this area) are strongly correlated with stream levels. At peak flow, river water recharges the aquifer and moves laterally away from the channel, causing groundwater levels to rise over a broad area. Within 30–60 days following the peak discharge, when river levels begin to fall, the groundwater direction is reversed and contributes to baseflow. Water balance results from the model indicate that the river–aquifer interaction has a maximum flow rate between 11 and 20% of river flow during spring freshet—on average, the river contributes to about 15% of its spring freshet flow into aquifer storage. Direct recharge to the aquifer from precipitation also results in a rise in water levels; however, the overall effects of direct recharge are very small in comparison with the indirect recharge from the rivers, except in areas removed from the influence of the rivers (i.e. the benches along the valley sides). Based on the known response at well 217, all of these wells are considered to show characteristic responses of aquifers that are stream-driven.

It is not surprising that there are a greater number of wells representing stream-driven aquifer systems in the interior compared to the coast. This is largely because most provincial observation wells are situated in populated valley bottoms. Due to the physiography of this mountainous region, these valley bottom aquifers are often comprised of highly permeable aquifer materials and there is often a major stream (or lake system) flowing through them. As a generality, then, many valley bottom aquifers in interior mountain region will likely be stream-driven (Figure 13b—left graph), while the aquifers comprising the upland areas will be bedrock and recharge-driven (Figure 13—right graph).

Hybrid regime

Well 302 (Malakwa) is interpreted to be situated in a hybrid regime. Although not formally introduced in the aquifer-stream system type classification, hybrid regimes are a blend of the rainfall- and snowmelt-dominated regimes, and thus the responses of streams and aquifers are more complex. A double peak characterizes this regime—one related to fall rains and the other to snowmelt. In fact, the second peak (Figure 10) also appears to be composed of two smaller peaks—one related to peak snowmelt (as observed in the stream hydrograph), and the other possibly related to glacier melt, which sustains groundwater levels into the recession period. The cross-correlation between well 302 and streamflow suggests that the system is stream-driven.

CONCLUSIONS

This study demonstrated the use of a series of diagnostic tools that can be used to compare and contrast the responses of groundwater systems, as exhibited by groundwater level variations in wells. The well hydrographs, which were reasonably assumed to reflect the overall response of the aquifer, were best analysed using a combination of diagnostic tools including time series plots, hysteresis plots, and cross-correlation plots; no single method proved to be superior.

This study also offers a classification system for interpreting the responses of aquifers. The classification system considers both the hydroclimatology of the region and the aquifer-stream system type. Characterizing the seasonal timing of the response requires consideration of the hydroclimatology, specifically, whether the system is rainfall-dominated (pluvial), snowmelt-dominated (nival) or hybrid (mixture of rain and snow). The magnitude and timing of the recharge and discharge response of the groundwater system were shown to depend not only on the storage and permeability characteristics of the aquifer, as might be anticipated, but also on whether the system is *stream-driven* or *recharge-driven*. These two dominant stream-aquifer system types were defined based on classifying the different aquifer types found in the study region. The recharge-driven systems include primarily bedrock aquifer types and some occurrence of sand and gravel aquifers of glacial or pre-glacial origin where there is little opportunity for interaction with streams. The stream-driven systems, which dominate the interior region, include fluvial/glaciofluvial aquifers (in stream valleys), deltaic aquifers or alluvial/colluvial fan aquifers. Each one of these aquifer types may be found within any hydroclimate regime: rainfall regime, snowmelt regime, hybrid regime; thus, there are many possible combinations of potential responses of wells. Of the nine observation wells considered in this analysis, not all combinations were available; thus, the classification scheme, as presented, could not be rigorously tested. As well, it is likely that there are some aquifers that behave as both recharge-driven and stream-driven aquifers, although the evidence for such mixed behaviour was not strong in this study. Due to the complex physiography of mountainous regions, as often defined by steep mountains and low-lying valley bottoms, stream-driven aquifer systems are likely more common in interior valley bottom regions compared to aquifers situated in the coastal region, which tend to be dominantly recharge-driven.

The classification scheme and diagnostic tools presented in this study have the potential to provide a framework for evaluating the responses of wells in other mountainous regions. Anticipating the type of response of an aquifer based on its physical characteristics and hydroclimatological setting would allow for more strategic data collection for detailed studies, such as water sampling for geochemical or isotopic analysis, and physical characterization of the linkages between hydrology and hydrogeology. In addition, understanding the driving mechanisms and consequent aquifer responses would aid in selecting appropriate codes for modelling and setting boundary conditions within the models themselves. Such specialized studies would provide insight into processes at the local scale that influence the aquifer responses at small spatial and temporal scales. Finally, it is suggested that such a framework could also be used to guide studies or perhaps provide a broader view on the potential consequences of future climate change on groundwater systems, particularly when detailed analyses are not possible.

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