



Watershed-scale response of groundwater recharge to inter-annual and inter-decadal variability in precipitation (Alberta, Canada)

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Abstract Groundwater recharge sets a constraint on aquifer water balance in the context of water management. Historical data on groundwater and other relevant hydrological processes can be used to understand the effects of climatic variability on recharge, but such data sets are rare. The climate of the Canadian prairies is characterized by large inter-annual and inter-decadal variability in precipitation, which provides opportunities to examine the response of groundwater recharge to changes in meteorological conditions. A decadal study was conducted in a small (250 km²) prairie watershed in Alberta, Canada. Relative magnitude of annual recharge, indicated by water-level rise, was significantly correlated with a combination of growing-season precipitation and snowmelt runoff, which drives depression-focussed infiltration of meltwater. Annual precipitation was greater than vapour flux at an experimental site in some years and smaller in other years. On average precipitation minus vapour flux was 10 mm y⁻¹, which was comparable to the magnitude of watershed-scale groundwater recharge estimated from creek baseflow. Average baseflow showed a distinct shift from a low value (4 mm y⁻¹) in 1982–1995 to a high value (15 mm y⁻¹) in 2003–2013, indicating the sensitivity of groundwater recharge to a decadal-scale variability of meteorological conditions.

Keywords Groundwater recharge · baseflow · Canada · Snowmelt runoff · Climate change

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Introduction

The scientific foundation of groundwater resource management is an understanding of the balance between recharge and discharge of aquifers (Gleeson et al. 2012). Groundwater extraction needs to be managed in such a manner to minimize negative impacts of storage depletion in aquifers and capture of discharge that would become stream baseflow (Sophocleous 2000; Bredehoeft 2002). The literature shows various views regarding the importance of quantifying groundwater recharge from those that suggest ‘natural’ recharge rate has no relevance on sustainable pumping rate (Bredehoeft 2002) to those that suggest natural recharge is important because it sets the upper limit of baseflow capture (Zhou 2009). In arid and semi-arid regions, where the margin between precipitation input and evapotranspiration output is small or even negative in some years, the amount of groundwater recharge has a major influence on the water balance. Watershed-scale recharge and its short- and long-term variability put important constraints on the range of management options.

Recharge rates can be influenced by regional-scale land-use change (Allison et al. 1990; Scanlon et al. 2005) and climatic variability (Crosbie et al. 2013). Water resource managers are becoming increasingly interested in potential impacts of climate change on groundwater resources. However, groundwater recharge is a complex process involving feedbacks in the soil-vegetation-atmosphere system. The response of groundwater recharge to changes in climatic variables such as air temperature and precipitation, likely varies depending on climate, vegetation, land use, soil, and geology, which makes the prediction of groundwater recharge under future climate challenging (Green et al. 2011).

The vast prairie region of Canada is characterized by a cold, semi-arid climate, in which annual precipitation is exceeded by potential evaporation (Winter 1989), and soil freezes to depths of 1–2 m in winter. It is also characterized by the glaciated terrain generally having low topographic relief but numerous small depressions and clay-rich glacial till deposits (van der Kamp and Hayashi 2009). Dry weather and long daylight during the growing season allows plants to consume essentially all precipitation inputs, implying that groundwater recharge is strongly dependent on snowmelt infiltration. Frozen soil

has low infiltrability due to the blockage of soil pores by ice (Seyfried and Murdock 1997). As a result infiltration-excess (i.e. Horton), overland flow is generated by snowmelt over frozen soil (Gray et al. 2001), which fills numerous topographic depressions (van der Kamp et al. 2003). The snowmelt water trapped in depressions rapidly infiltrates after the soil thaw (Hayashi et al. 2003). Geophysical mapping conducted in Saskatchewan, Canada showed leaching of soil salts under depressions, but not under the lands outside of depressions, suggesting that groundwater recharge is strongly focussed under depressions (Keller et al. 1988; Berthold et al. 2004). If groundwater recharge is primarily driven by snowmelt runoff and subsequent infiltration in depressions, then a change in winter climate likely has a strong influence on recharge. However, it is not clear if snowmelt is indeed solely responsible for recharge. Also, climate is spatially variable within the prairie region, which may influence the relative roles of snowmelt and summer rain.

To understand the influence of climatic variability on groundwater recharge, it is necessary to have groundwater level data covering a sufficiently long time period (e.g. century). These data should be accompanied by other hydrological data such as precipitation, evaporation, snowmelt runoff, and soil moisture. However, long-term data encompassing all relevant processes are limited to recent years. While there is a lack of long-term data covering different climatic regimes, the meteorological condition of the Canadian prairies has a large inter-annual and inter-decadal variability (Bosal and Regier 2007), allowing for observation of the effects of variable conditions (e.g. drought and deluge) on groundwater recharge. The understanding gained from these observations can be used to gain insights into the effects of longer-term climatic variability on recharge.

The objective of this study is to identify major meteorological factors affecting groundwater recharge in the western part of the Canadian prairies by combining detailed measurements of hydrological processes and groundwater-level observations at the scale of a small watershed, and place the results of short-term observation into the context of longer-term climate data.

Study area

The field study was conducted in the West Nose Creek watershed (Fig. 1), located directly northwest of Calgary, Alberta, Canada. The watershed in this study is defined by the stream gauging station formerly operated by the Water Survey of Canada during 1982–1995 (51°12'42" N, 114°9'52" W) (Fig. 1), and has a gross drainage area of 250 km². The gauging station was re-activated by the University of Calgary in 2003 (Grieff and Hayashi 2007). The climate of the area is characterized by cold winter and low precipitation, typical of the Canadian prairies. The 1981–2010 normal monthly mean air temperature at the Calgary International Airport, located 14-km southeast of the gauging station was -7.1 °C in January and 16.5 °C in

July (Environment Canada 2014). Mean annual precipitation in 1981–2010 was 482 mm, of which 124 mm fell during the winter months of November–April (Mekis and Vincent 2011). The soil typically starts freezing in early November and does not completely thaw until late April to early May (Mohammed et al. 2013). Since soil freezing and snow accumulation usually start in early November, the hydrological year in this study is defined as November 1–October 31; for example, the hydrological year 2013 starts on November 1, 2012. The majority of land use in the watershed is agricultural, consisting of roughly a half-half mixture of croplands and grass pasture for cattle grazing. Croplands are subjected to a typical crop rotation of cereal crops and oil seeds.

Much of the watershed is covered by clay-rich glacial till and generally has hummocky or undulating topography with numerous depressions that are internally drained. As a result, numerous non-contributing areas occur within the watershed boundary (Godwin and Martin 1975), which make the effective drainage area considerably smaller than the gross drainage area (Ehsanzadeh et al. 2012). An estimated effective drainage area of the West Nose Creek watershed is 135 km² (AAFC 2012). The till is generally a few to 30 m thick (HCL 2002) and underlain by the Paleocene Paskapoo Formation (Burns et al. 2010). Up to 30-m-thick sand and gravel deposits occur between the till and the Paskapoo Formation in southwestern parts of the watershed (HCL 2002). The Paskapoo Formation is mudstone- and siltstone-dominated fluvial system with a series of sand channels that can form isolated aquifer units (Hamblin 2004).

There are approximately 890 domestic and livestock water supply wells within the watershed (Mohammed et al. 2011), the majority of which are screened in the sandstone units of the Paskapoo Formation. The depth to the bottom of the screen varies between 5 and 150 m, but the majority of wells are shallower than 80 m (Grieff and Hayashi 2007). Based on population and agricultural census data, total groundwater extraction within the watershed is estimated to be on the order of $7 \times 10^5 \text{ m}^3 \text{ y}^{-1}$, or 3 mm y^{-1} averaged over the watershed (Mohammed et al. 2011). The majority of groundwater is extracted for domestic usage, and wastewater is discharged into the soil through septic systems. Part of the septic-system discharge is consumed by evapotranspiration, and the rest recharges groundwater; therefore, net consumption of groundwater (i.e. extraction minus recharge) is expected to be substantially smaller than 3 mm y^{-1} .

To monitor the watershed-scale dynamics of groundwater levels, a network of community-based groundwater monitoring wells were established in 2004–2005 using domestic water-supply wells that met a set of criteria including relatively short (<7 m) well screen, and a fast response allowing the water level to recover quickly after pumping (see Grieff and Hayashi 2007 for details). To examine plot-scale hydrological processes, instrumented study sites were established within an alfalfa field (32 ha) and a grass pasture (32 ha) of the Spyhill Farm in 2003,

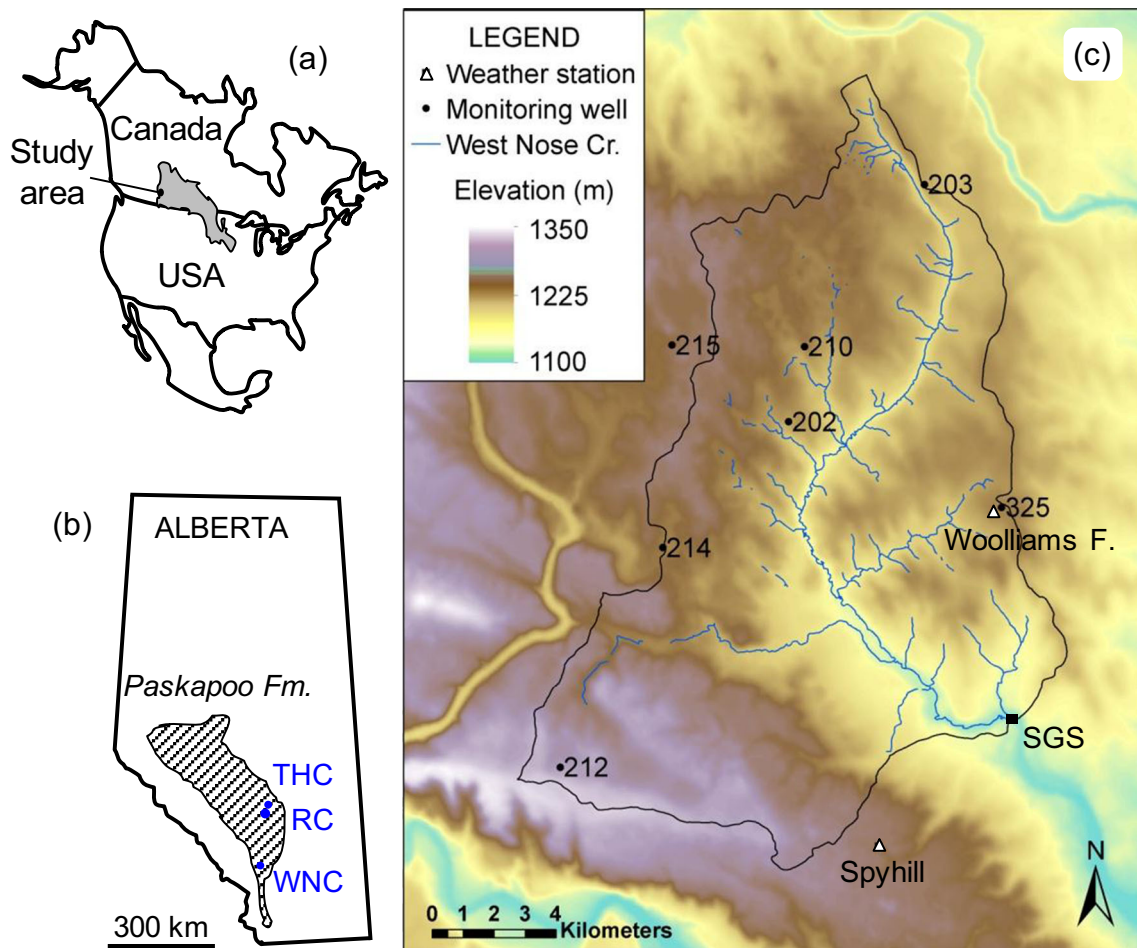


Fig. 1 a Map of North America showing the extent of the northern prairies region and location of the study area. b Map of Alberta (Canada) showing the extent of the Paskapoo Formation and location of West Nose Creek (*WNC*), Ray Creek (*RC*), and Three Hills Creek (*THC*) watersheds. c Elevation map of the West Nose Creek watershed (bounded by *solid black line*) and the surrounding area. Location of bedrock monitoring wells, automatic weather stations, and stream gauging station (*SGS*) are shown in the map

and within a cropland (64 ha) of Woolliams Farm in 2004 (Fig. 1; see the following for details).

Land cover of the grass pasture at the Spyhill site consists of smooth brome (*Bromus inermis*), alfalfa (*Medicago sativa*), smooth meadow grass (*Poa pratensis*), tufted hair grass (*Deschampsia caespitosa*), and Canadian thistle (*Cirsium arvense*) (Zaitlin et al. 2007). Willow shrubs (*Salix planifolia*) and trembling aspen (*Populus tremuloides*) grow around depressions. The alfalfa field at the Spyhill site has been harvested each summer since the field was converted from grassland in 1999. Crops at the Woolliams Farm site are on a 1-year oil seed (canola) and 3-year barley rotation, with canola in 2004, 2008, and 2012. Both sites are covered by clay-rich glacial till. The top 2–3 m of the till is fractured and has hydraulic conductivity up to 10^{-5} m s^{-1} , which decreases to $10^{-10} \text{ m s}^{-1}$ in the deeper, unfractured part (van Dijk 2005). At the Spyhill site, the till is roughly 10 m thick and underlain by 20–30-m-thick gravel layer, which in turn is underlain by the Paskapoo Formation. At the Woolliams Farm site, the till is roughly 2–3 m thick, and directly underlain by the Paskapoo. Using the chloride

mass balance technique (Allison and Hughes 1983), van Dijk (2005) estimated a long-term average groundwater recharge rate of 3–4 mm y^{-1} at the Spyhill site.

Methods

Groundwater monitoring

Water level in the Paskapoo Formation aquifer system was monitored at seven wells within and close vicinity to the West Nose Creek watershed (Fig. 1). These were the community-based groundwater monitoring wells (see the preceding) that had continuous data beyond 2009. Water level was measured manually using a water-level sounder at bi-weekly to monthly intervals starting in 2005, and switched to automated reading by pressure transducers during 2006–2010. A vented transducer (Geokon, AL4500) was used with a datalogger (Campbell Scientific, CR10X) at Well 325, and non-vented self-recording transducers (Solinst, Levelogger) was used with barometers (Solinst, Barologger) for barometric correction at all other wells. Water level was recorded every 30 min,

and daily average values are used in this study. Well 325 is a dedicated monitoring well made of a 5-cm diameter PVC pipe, installed at the Woolliams Farm site for this study, while all other wells are domestic water supply wells having a casing diameter of 10–15 cm. Manual measurements were taken when the water level was not affected by pumping, and daily average values of transducer reading were computed after removing those points that were affected by pumping. All wells except well 325 have fast response with the basic time lag (Hvorslev 1951) of 1 h or less. Well 325 has the screen open to a low hydraulic conductivity part of the Paskapoo Formation resulting in a large basic time lag of 31 days. An inflated packer was installed in this well in June 2010 to isolate the screened interval and reduce the basic time lag to practically zero. The screen depth and ground surface elevation of the monitoring wells are listed in Table 1.

Several piezometers consisting of 5-cm diameter PVC pipes were installed in the Spyhill site in March 2003 (van Dijk 2005). They were installed in 15-cm diameter auger holes with a sandpack surrounding the slotted screen and bentonite seal above the sandpack. This study uses the data from a piezometer installed in the middle of a depression located in grass pasture to examine the relation between the shallow water table and the water level in bedrock aquifers. The piezometer had a screen length of 0.3 m and mid-screen depth of 2.7 m.

Meteorological and soil moisture measurements

The Spyhill site (Fig. 1) was established in February 2003 with an automatic weather station located within a grass pasture (van Dijk 2005). The weather station was equipped with sensors measuring temperature and humidity (Campbell Scientific, CS500), wind speed (RM Young, 05103), net radiation (Kipp & Zonen, NR-LITE), and snow depth (Campbell Scientific, SR50); a tipping bucket rain gauge (Campbell Scientific, TE525); and thermocouples measuring soil temperature at depths of 0, 20, 40, 60, 80, 100, and 150 cm. The weather station was moved 500 m within the grass pasture in June 2006, due to the landcover disturbance adjacent to the original location. At this time, capacitance sensors (Campbell Scientific, CS616) for soil moisture measurement at depths of 10, 30, 60, and 100 cm; four-component radiometer (Kipp & Zonen, CNR1); and an eddy-covariance system consisting

Table 1 Identification (ID) number, mid-screen depth, and ground surface elevation of bedrock aquifer monitoring wells (see Fig. 1 for location)

ID	Depth (m)	Elevation (m)
202	36.6	1,201.8
203	63.4	1,202.9
210	41.1	1,221.6
212	35.1	1,288.8
214	27.4	1,227.5
215	13.7	1,237.0
325	41.4	1,219.1

of a sonic anemometer (Campbell Scientific, CSAT3) and a krypton hygrometer (Campbell Scientific, KH20) were added. In addition, a weighing precipitation gauge equipped with an Altar shield (Geonor, T200B) was installed in a clearing within a wooded area adjacent to the grass pasture, 400 m from the new weather station. Solid precipitation data were corrected for wind undercatch using the equation of Smith (2007, Eq. 4). Meteorological, soil, and eddy-covariance data were recorded at hourly or half-hourly intervals using Campbell Scientific dataloggers (CR10X and 23X). Details regarding sensor heights, calibration, and eddy-covariance data processing are described by Hayashi et al. (2010) and Mohammed et al. (2013).

Eddy-covariance data had frequent gaps due to malfunctioning sensors during precipitation events. Daily average values were computed for those days that had less than 4 h of data gap, which were approximately 70 % of the days during the study. Monthly average values of vapour flux (sum of evapotranspiration and snow sublimation) were computed from the mean of all available daily values within the month. Since all-season precipitation data (including winter) from the Spyhill site were available only after November 2006, precipitation data from Calgary airport were used for most of the analysis requiring long-term data. The Spyhill data were used for the detailed water balance analysis in hydrological years 2007–2013. Seasonal total precipitations in Calgary (P_{Cal}) and Spyhill (P_{SH}) had linear relations: $P_{Cal}=0.96 P_{SH}$ (RMS=20 mm) for November–April and $P_{Cal}=1.04 P_{SH}$ (RMS=25 mm) for May–October, where RMS indicates root-mean-squared difference between the P_{Cal} computed by the equations and the actual P_{Cal} .

The Woolliams Farm site (Fig. 1) was established in August 2004 with an automatic weather station similar to the Spyhill weather station, but without an eddy-covariance system. The weather station is located adjacent to well 325.

Snowmelt runoff measurement

At Spyhill and Woolliams Farm, snowmelt runoff was estimated from the volume of runoff water collected in closed topographic depressions (see Mohammed et al. 2013 for details). Water levels were monitored in eleven depressions located in different landcover areas (four in grass pasture, four in alfalfa field, and three in cropland) for this purpose using pressure transducers (In-Situ, Mini-Troll), and estimated areal average runoff (mm) by dividing the runoff volume by catchment areas of depressions ranging from 3,600 to 24,000 m². This method neglects the loss of water to the unsaturated soil in depressions during the initial flooding period, and hence underestimates snowmelt runoff (van der Kamp et al. 2003). The relative magnitude of underestimation is expected to be more significant in low runoff years, when the total amount of runoff is relatively small compared to the initial loss.

Creek discharge measurement

The Water Survey of Canada (WSC) operated the West Nose Creek gauging station during ice-free period (May–October) in 1982–1995. A new gauging station was established 50 m downstream of the former WSC gauging station in March 2003 using a straight channel reach as natural control. This is the same channel reach used by the WSC to establish stage-discharge rating curve during 1982–1995. Stream discharge was measured manually using a horizontal-axis flow meter (Global Water, FP101) and the velocity-area method (Dingman 2002, p. 604) on weekly to bi-weekly intervals between the ice break up (usually in April) and freeze up (usually in late October). Daily average flow was calculated from the water level measured using a pressure transducer (In-Situ, Mini-Troll) and the state-discharge rating curve, which was updated every year. Expected accuracy of discharge measurement is within 10–15 %.

Statistical analysis and time frame of analysis

For statistical correlation analysis of annual hydrological data series, data sets were first examined for normality by visually examining normal probability plots and conducting probability plot correlation coefficient analysis (Helsel and Hirsch 2002, p. 113). Only those data that were deemed normal based on Looney and Gullledge (1985) criterion were used for the calculation of Pearson's correlation coefficient (r), t -statistic, and significance level (p) using the methods described by Helsel and Hirsch (2002, p. 218).

This study uses multiple data sets of various hydrological variables whose observation period started at different times. The main focus is on the relationship between bedrock aquifer water levels and precipitation for the period of 2005–2013. Complementary data set are used to examine snowmelt runoff during 2003–2013, West Nose Creek baseflow during 2003–2013, and soil moisture and evapotranspiration during 2006–2013. Archived meteorological and stream-discharge data for longer time periods are used to compare the conditions of 2003–2013 to previous decades.

Results

Water level in bedrock aquifers

Water levels in the Paskapoo aquifer wells showed overall increasing patterns during 2005–2007 (Fig. 2), indicating the recovery from the effects of severe drought in the Canadian prairies prior to this study (Hanesiak et al. 2011), which is consistent with the general patterns of groundwater levels observed in the Canadian prairies (Lambert et al. 2013). The water levels showed distinct patterns characterized by a sharp rise in spring and summer followed by a decline in fall and winter, indicating the effects of seasonal recharge events. All wells showed similar seasonal and inter-annual patterns with some years (e.g. 2005 and 2013) having larger

magnitude of water-level rise than other years (e.g. 2009 and 2012). The average peak water level occurred in late July to mid September in most years (Table 2). Figure 2h shows monthly water levels relative to the mean for each well. On a closer look, water levels started to rise in April in 2006, 2007, 2010, 2011, and 2012, coinciding with snowmelt and soil thaw (see next section for details on snowmelt and soil freeze-thaw). Figure 3a shows an example of water-level rises starting in late April 2011. Irregular fluctuations in some of the wells indicate the effects of barometric loading on pore pressure in the aquifers (van der Kamp and Gail 1983). In this year soil temperature data indicated that the complete thawing of soil profile occurred around April 20 at Spyhill and April 30 at Woolliams Farm. In contrast, water level started to rise after large rainfall events in May and June in 2005, 2008, and 2013. Figure 3b shows an example for 2013, in which most wells responded sharply to heavy rain in mid June. Very little water-level rise was observed in 2009.

The timing and magnitude of seasonal water-level fluctuations in deeper aquifers reflect the water-table fluctuations in the overlying glacial till (Anochikwa et al. 2012). The shallow (2.7 m) piezometer in a depression at the Spyhill site showed the seasonal water-level fluctuations (Fig. 4) similar to bedrock aquifer wells. Water-level rises in the bedrock aquifer wells were computed from the difference between the lowest pre-spring water level and the peak water level, and an average of all seven wells were calculated for each year. The average water-level rise in bedrock aquifer wells had significant correlation ($p < 0.005$) with the water-level rise in the shallow piezometer ($r = 0.98$, where r is Pearson's correlation coefficient) in those years with reasonably wet growing season (May–September precipitation > 370 mm at Spyhill site), but no correlation in those years with drier growing season (Fig. 5). These observations (Figs. 3, 4 and 5) suggest that groundwater recharge has large inter-annual variability, depending on the amount of snowmelt and summer rainfall.

Snowmelt runoff

Snowmelt runoff had large inter-annual variability (Fig. 6). Croplands generally generated the highest amount of runoff, and grass pastures the lowest. This is consistent with the findings of van der Kamp et al. (2003) in Saskatchewan, where perennial grasslands had much smaller runoff than croplands due to the enhanced infiltrability of frozen soil provided by the macropore network. Snowmelt runoff in the Canadian prairies occurs when the snowpack melts at a relatively high rate in mid March to late April while the underlying soil is still frozen (Gray et al. 2001; Mohammed et al. 2013). For the purpose of understanding the effects of frozen soil on snowmelt runoff, the thaw date is defined as the date when daily average soil temperature at 20 cm is clearly above the freezing point (> 0.5 °C). The thaw date varied from April 2 in hydrological year (HY) 2010 and May 10 in HY 2011. The average thaw date during the 11-year

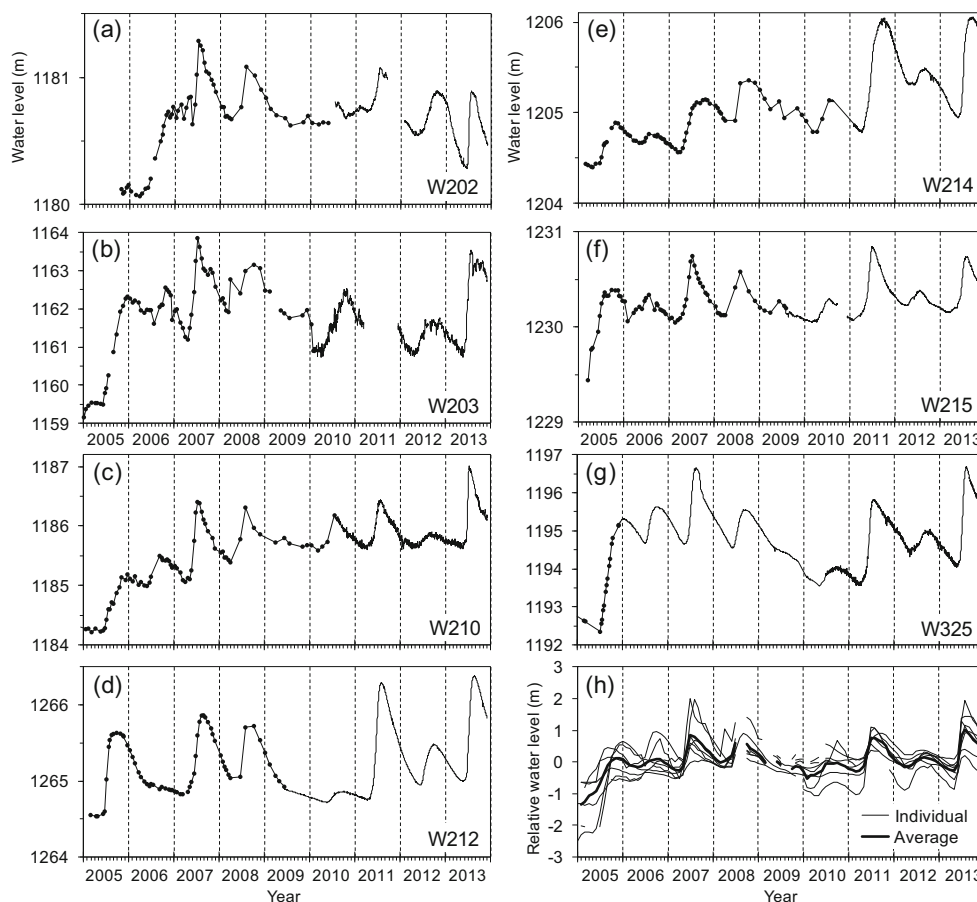


Fig. 2 a–g Water levels (m above mean sea level) measured in bedrock aquifer wells. *Solid circles* indicate manual measurements, and *solid lines* without symbols indicate daily values calculated from pressure transducer measurements. **h** Relative water levels of all wells as monthly mean values (*thin line*) and their average (*thick line*)

period (HY 2003–2013) was April 23, and 8 out of 11 years had thaw dates in April 19–28. Snowmelt infiltration and runoff are affected by numerous meteorological and soil physical factors (Gray et al. 2001), and it is difficult to find a clear relationship between the amount of runoff and simple variables such as winter precipitation. In this study, snowmelt runoff was found to be generally small when the amount of winter precipitation over frozen soil (November 1 to the thaw date) was less than 150 mm, and was highly variable when it was greater than 150 mm (Fig. 7). The

high variability may be related to the soil moisture condition prior to freezing (Gray et al. 2001), but there was no correlation between snowmelt runoff and fall soil moisture (see the following).

Correlation between water level and meteorological forcing

Depression-focused infiltration of snowmelt runoff is considered a major source of recharge in the Canadian prairies (e.g. Lissey 1971; van der Kamp and Hayashi 1998). However, the amount of snowmelt runoff had no correlation with the average water-level rise observed in bedrock wells (Fig. 8a). High runoff years (HY 2007 and 2011) had large water-level rises, but some low runoff years (HY 2005 and 2013) also had large water-level rises in response to high precipitation in May and June. Significant correlation ($r=0.91$, $p<0.0008$) was observed between the water-level rise and growing-season (May–September) precipitation (Fig. 8b), suggesting that growing-season precipitation sustains recharge in high snowmelt runoff years (2007 and 2011) and triggers recharge in low runoff years (2005 and 2013). Using total annual precipitation by adding winter precipitation to growing-season did not improve the correlation with the

Table 2 Mean date of water level peak in bedrock monitoring wells shown in Figure 2, and the standard deviation of peak date

Year	Mean date	SD (days)
2005	Nov. 15	36
2006	Sep. 12	45
2007	Aug. 4	39
2008	Sep. 5	36
2009	June 10	0 ^a
2010	Aug. 22	42
2011	July 29	34
2012	Aug. 29	36
2013	Aug. 5	23

^a Only four wells showed water level rises in 2009, and all four wells had peak water level measured manually on June 10. *SD* standard deviation

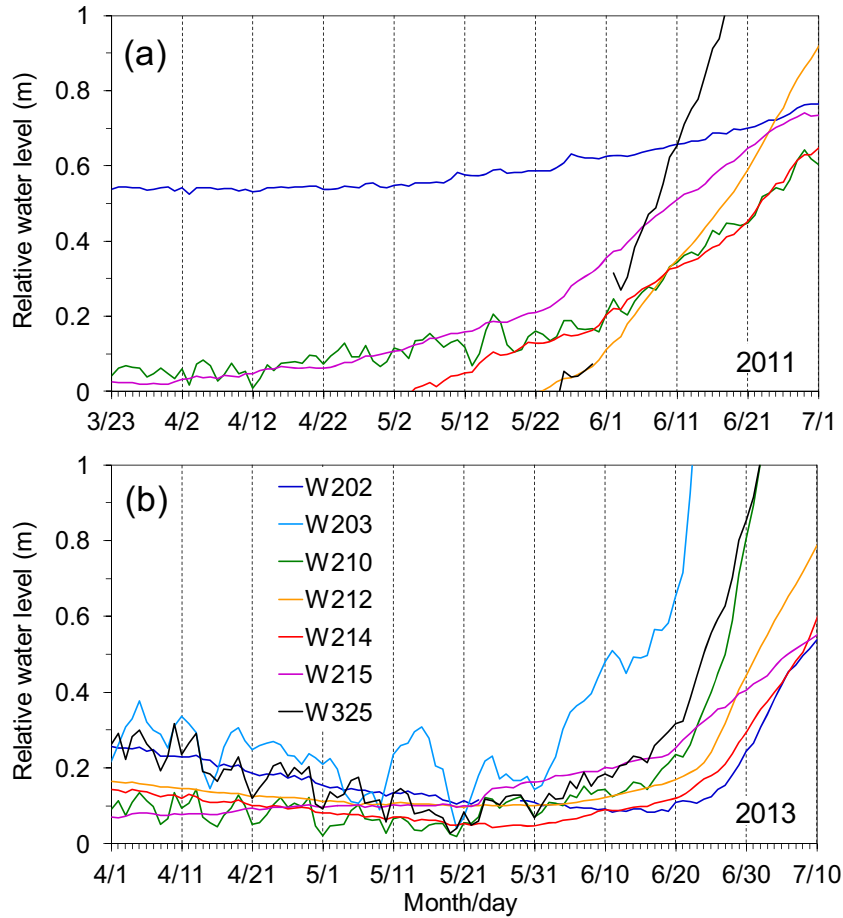


Fig. 3 Daily average water levels in bedrock aquifer wells in **a** 2011 and **b** 2013. Relative water levels with respect to arbitrary references for individual wells are shown. The data for well 203 were not available in 2011

water level (data not shown). To evaluate the combined effect of growing-season precipitation snowmelt runoff, the average runoff multiplied by an arbitrary weighting factor is added to precipitation, and the weighting factor is adjusted by least-squares regression to obtain the highest value of r (Fig. 8c). This resulted in a higher correlation coefficient ($r=0.95$, $p<0.0001$), supporting the idea that

groundwater recharge is sourced by both snowmelt runoff and growing-season precipitation.

This idea is also supported by the stable isotope composition of water samples. Grief (2006) collected 23 groundwater samples from domestic water supply wells and springs in the West Nose Creek watershed and adjacent areas, and analyzed them for $^2\text{H}/^1\text{H}$ and $^{18}\text{O}/^{16}\text{O}$

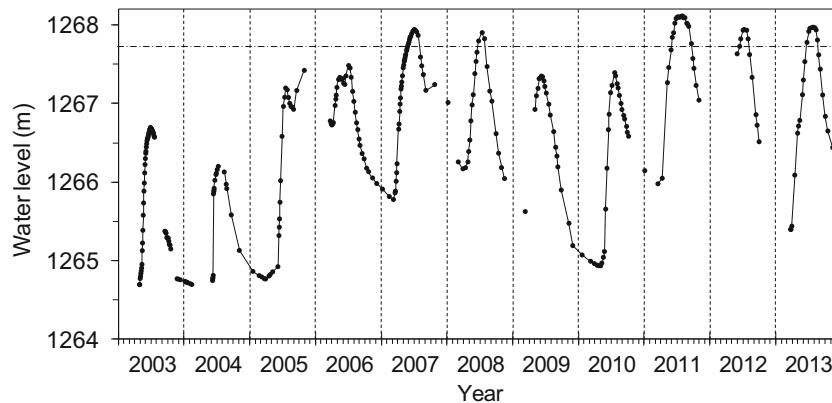


Fig. 4 Water level recorded in a shallow (2.7 m) piezometer under a depression at the Spyhill site. The horizontal line indicates the ground surface at the lowest point within the depression. Measurements were infrequent during some periods, where the symbols are not connected

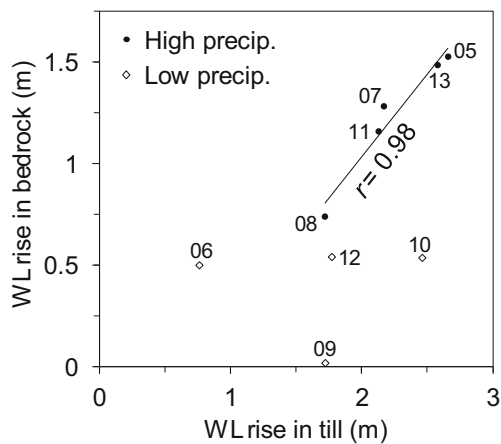


Fig. 5 Comparison of the magnitude of water level (WL) rises in the glacial till and the bedrock aquifer (average of all wells shown in Fig. 2). Data points are classified by the amount of precipitation (<370 mm or >370 mm) during May–September. The *solid line* indicates the least-squares regression of high precipitation points, and *labels beside points* indicate hydrological years

ratios of water. Figure 9 shows the data along with the stable isotope ratios of precipitation samples in Calgary published by Peng et al. (2004), where the isotopic composition is expressed as δ value in per mil with respect to the Vienna-Standard Mean Ocean Water (Gonfiantini 1981). The local meteoric water line (LMWL) is given by the least-squares fitting of all precipitation data as

$$\delta^2\text{H} = 7.74\delta^{18}\text{O} - 0.06. \quad (1)$$

The volume-weighted mean composition of precipitation is $[\delta^{18}\text{O}, \delta^2\text{H}] = [-17.9, -136]$ for annual, $[-16.3, -124]$ for May–October, and $[-23.6, -184]$ for November–April (Fig. 9). Cluster of groundwater samples slightly deviates from the LMWL indicating the effects of isotopic fractionation during recharge processes (Fig. 9), presumably due to evaporitic enrichment in the vadose zone. The intersection of the subsurface water trend line

(dashed line in Fig. 9) and the LMWL line may indicate the average composition of precipitation contributing to groundwater recharge (Maulé et al. 1994). The composition of the intersection $[-18.9, -146]$ is shifted more towards November–April mean precipitation than the annual mean (Fig. 9), suggesting that snowmelt water makes preferential contributions to groundwater recharge.

Vertical water balance: precipitation, vapour flux, and soil moisture storage

The preferential contribution of snowmelt water can be explained by evapotranspiration during the growing season, which returns a large fraction of precipitation to the atmosphere. Monthly data from the Spyhill site (Fig. 10a,b) shows that precipitation accumulates as snowpack despite losing 53–86 mm to vapour flux (i.e. sum of sublimation and evapotranspiration) during November–April (Table 3). The ratio of total vapour flux (E) to precipitation (P) in November–April ranged from 34 % in HY 2011 to 58 % in HY 2008. Figure 10d shows the amount of total moisture in the top 100 cm of soil column at the Spyhill site, estimated from the liquid water content measured at 10, 30, 60, and 100 cm. The data for the frozen period are not shown because the capacitance sensor only detects liquid water and underestimates total water content. Soil moisture storage increases during April to early June in response to snowmelt and rainfall in excess of evapotranspiration. Soil moisture storage generally decreases during the remainder of the growing season (Fig. 10d). This pattern is reflected in cumulative precipitation minus vapour flux ($P-E$) (Fig. 10c). Total $P-E$ during May–September ranged between -132 and -38 mm (Table 3), indicating that recharge during summer months would be zero even in wet years (e.g. 2011 and 2013) without contributions from snowmelt water. It is likely that snowmelt infiltration increases soil moisture and prepares a favorable condition for recharge in those years with a sufficient amount of summer precipitation, which mixes with pre-existing soil water and percolates down to the water table. Annual total $P-E$ ranged from -31 to +41 mm (Table 3), with an average of 10 mm.

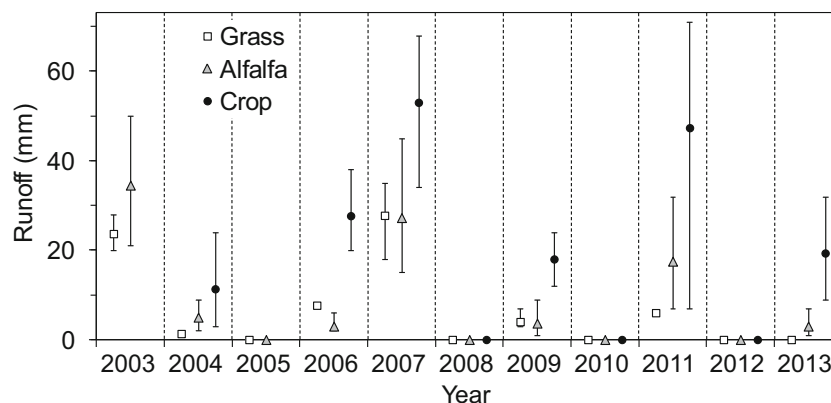


Fig. 6 Graphs showing snowmelt runoff for 2003–2013 in three different land-cover types. *Symbols* show the average of all measurements within each land cover and *vertical bars* indicate the range of values

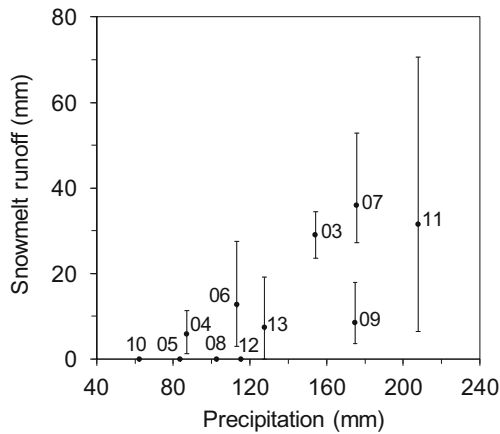


Fig. 7 Relation between winter precipitation over frozen soil (see the texts for definition) and average snowmelt runoff for all land-cover types. The vertical bars indicate the range of runoff values among the three land-cover types, and labels beside points indicate hydrological years

Since there is no surface drainage at the Spyhill site, 10 mm y^{-1} provides a rough estimate of the net addition of water to the soil, or potential recharge (de Vries and Simmers 2002) at a scale of the foot print of eddy-flux measurement (i.e. several hectares).

Soil moisture storage on October 20, prior to freezing, ranged from 160 mm in 2010 to 221 mm in 2007 (Fig. 10d). Correlation was examined for pre-freezing soil moisture with snowmelt runoff and with water-level rise in the following spring–summer. No significant correlation was found between these two variables and soil moisture, indicating that the effect of fall soil moisture on snowmelt runoff and groundwater recharge may be overwhelmed by other effects such as winter precipitation and growing-season precipitation.

Creek baseflow analysis

The uncertainty in vapour-flux estimates based on the eddy-covariance measurement is expected to be on the order of 10 %, or 50 mm y^{-1} , and the data shown in Fig. 10c represents a hectare-scale estimate of potential

recharge. To compare the estimated value with a watershed-scale estimate of recharge, the hydrograph of West Nose Creek is examined. Comparison of hydrographs from several years (Fig. 11) shows that discharge in May–September is highly variable depending on the magnitude and frequency of storm events, but discharge in October before freeze up is fairly stable. Discharge in summer and early fall is affected by the water uptake by riparian vegetation as indicated by diurnal drop in discharge (data not shown), which becomes negligible by early October. Therefore, it is assumed that the average discharge in October 1–10 represents the groundwater contribution to baseflow of the creek.

Baseflow data are expressed in mm y^{-1} by dividing the volumetric flow rate by the gross drainage area of 250 km^2 . According to the hydraulic potential map of the watershed (Grieff and Hayashi 2007), groundwater flow within the entire watershed converges to the creek, suggesting that using the gross drainage area is a reasonable approximation. The baseflow in West Nose Creek increased from low values in 2003–2004 immediately after the drought to high values in 2005–2008, decreased in 2009–2010, and increased even higher in 2013 (Fig. 12a). A similar pattern was observed for October average water level for well 325, which is the only well with a record going back to 2004 (Fig. 12a), indicating the close linkage between groundwater level and the creek baseflow. The increase in baseflow in 2005 is associated with a large recharge event that raised groundwater level in all bedrock aquifer wells (Fig. 2), the decrease during 2009–2010 is associated with two consecutive years of relatively low recharge, and the final increase during 2011–2013 is associated with high recharge in 2011 and 2013. Average baseflow during 2003–2013 was 15 mm y^{-1} . The long-term water balance of the groundwater in tills and the Paskapoo aquifers within the watershed may be written as:

$$R + G_{in} = D + (1-x)P_m + G_{out} \tag{2}$$

where R is recharge, D is baseflow discharge, P_m is pumping, and G_{in} and G_{out} are groundwater inflow from

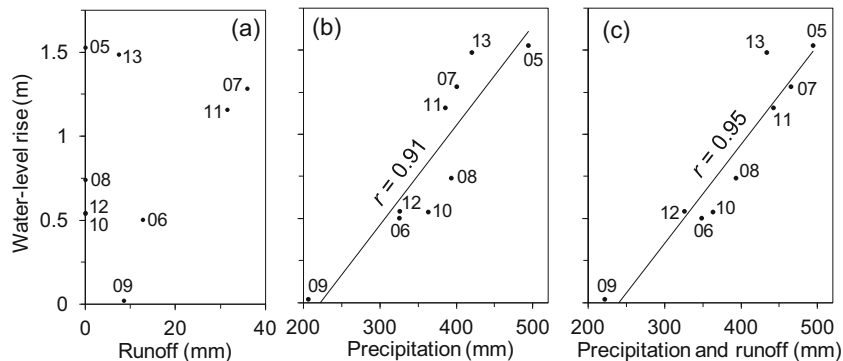


Fig. 8 Relation between water-level rises observed during spring and summer of 2007–2013 and a snowmelt runoff, b May–September precipitation, and c May–September precipitation plus snowmelt runoff multiplied by a weighting factor (see texts). Straight line indicates linear regression and r is Pearson’s correlation coefficient. Labels beside data points indicate hydrological years

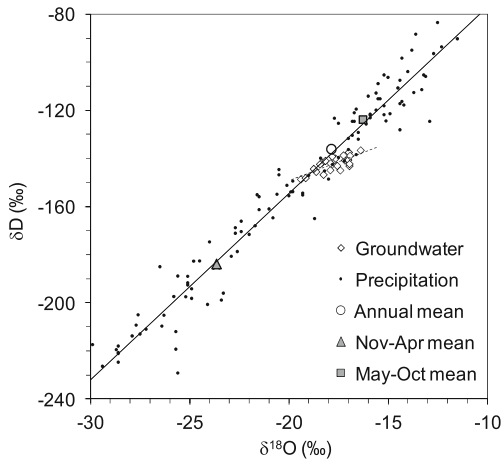


Fig. 9 Stable isotopic composition of local precipitation (Peng et al. 2004) and groundwater samples from the West Nose Creek watershed (Grieff 2006). The solid line indicates local meteoric water line, and the dashed line shows the linear regression of all groundwater data. The volume-weighted annual and seasonal means for Calgary precipitation are indicated by symbols.

and outflow to neighboring watersheds and the bedrock below the Paskapoo Formation. It is assumed that a fraction x of pumped water is returned to groundwater through septic systems. All terms have units of mm y^{-1} .

Assuming that the effects of G_{in} and G_{out} are secondary, Eq. (2) is simplified to:

$$R \approx D + (1-x)P_m. \tag{3}$$

For a range of $0 < x < 1$ and $P_m = 3 \text{ mm y}^{-1}$ (see section “Study area”), $D = 15 \text{ mm y}^{-1}$ gives R in a range of $15\text{--}18 \text{ mm y}^{-1}$, which is comparable in order of magnitude to the average potential recharge (10 mm y^{-1}) measured at the Spyhill site.

The West Nose Creek discharge data has a gap between 1996 and 2002, but the comparison of October baseflow between 1982–1995 (data by WSC 2014) and 2003–2013 indicates a significant shift in baseflow condition. Average baseflow in 1982–1995 was much smaller (3.9 mm y^{-1}) than in 2003–2013 (Fig. 12a), suggesting a shift in meteorological conditions. To examine possible changes in snowmelt runoff, winter precipitation over frozen soil is estimated by total precipitation from November 1 to April 22 (Fig. 12b). During 1982–1995, there was no year with winter precipitation over frozen soil exceeding the threshold value of 150 mm to generate a large amount of snowmelt runoff (Fig. 7), suggesting that the depression-focused recharge by snowmelt runoff was smaller during

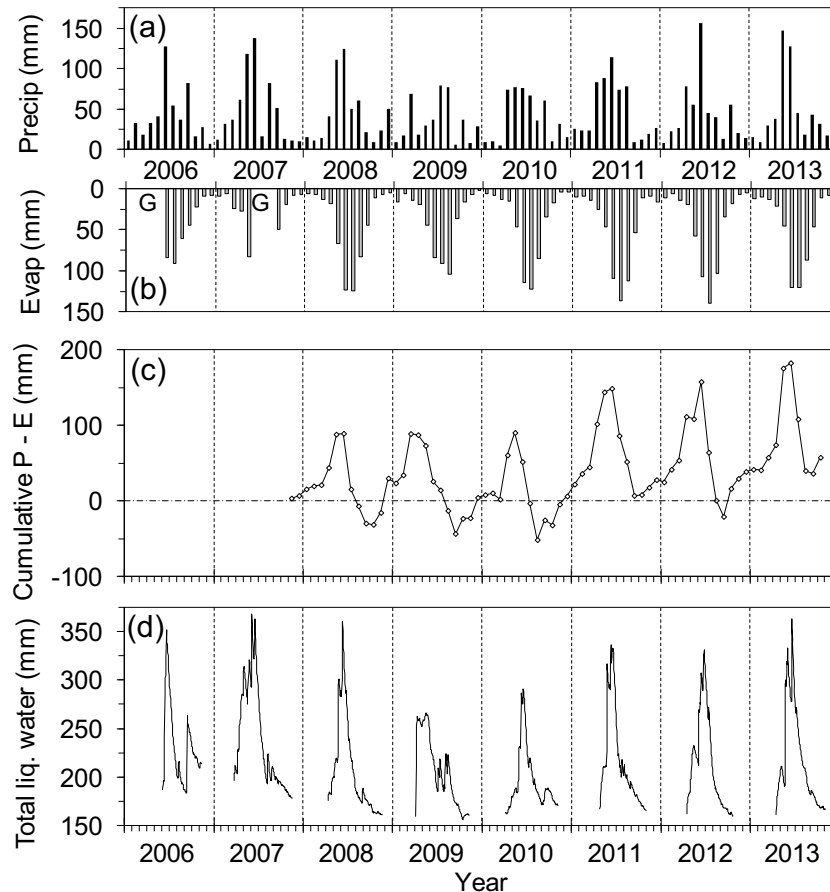


Fig. 10 a Monthly precipitation and b monthly vapour flux at the Spyhill site, where G indicates a data gap. c Cumulative precipitation minus evaporation ($P - E$). d Total liquid moisture in 0–100 cm soil profile at the Spyhill site, where winter values affected by freezing are not shown

Table 3 Seasonal precipitation (P), and vapour flux (E) measured at the Spyhill site for hydrological years (HY) 2007–2013. No data were available for May–September 2007 due to equipment repair and replacement

HY	Nov–Apr (mm)			May–Sep (mm)			Nov–Oct (mm)		
	P	E	$P-E$	P	E	$P-E$	P	E	$P-E$
2007	177	86	90	406			597		
2008	104	60	44	369	443	-74	482	514	-31
2009	187	68	119	229	360	-131	453	445	8
2010	136	53	84	317	403	-86	464	473	-9
2011	203	69	134	363	458	-95	578	538	40
2012	180	77	103	310	443	-132	546	538	8
2013	127	69	58	381	420	-38	541	499	41

these years. In addition, the mean annual (November–October) precipitation was 456 ± 59 mm, one standard deviation (1 SD), in 1982–1995 and 525 ± 63 mm in 2003–2013, indicating a significantly ($p < 0.005$) wetter condition in the recent decade (Fig. 12c). Therefore, it is likely that increased snowmelt runoff and growing-season precipitation have contributed to the recent increase in groundwater recharge and creek baseflow.

There are two other watersheds in the region having similar gross drainage areas (Ray Creek, 44 km²; and Three Hills Creek, 199 km²; see Fig. 1b for location). October baseflow at these creeks show temporal patterns similar to that of West Nose Creek (Fig. 13), suggesting that the observed shift in meteorological conditions is not limited to the West Nose Creek watershed.

Discussion

Roles of snowmelt runoff and growing-season precipitation

Since groundwater recharge is sourced by precipitation, a significant correlation between the relative magnitude of recharge represented by water-level rise and precipitation (Fig. 8b) is expected. Similar correlations are commonly observed in many climatic regions, including the Canadian prairies (e.g. Chen et al. 2004). Seasonal water balance of the grass pasture at the Spyhill site (Table 3) shows relatively large values of total annual precipitation minus vapour flux ($P-E$) for 2011 and 2013, which coincide with the years with relatively high magnitude of recharge; however, recharge was also observed in 2008, when $P-E$ was negative. While a large degree of

uncertainty exists in the measurements, these results suggest that the hectare-scale, vertical water balance of grass pasture may under-represent the effects of focussed infiltration in small depressions where snowmelt runoff accumulates. This is supported by Fig. 8, where adding the effects of snowmelt runoff to growing-season precipitation significantly improved the correlation between the precipitation and the magnitude of water-level rises. These observations suggest that the complex winter processes involving snow and frozen soil (Gray et al. 2001; Iwata et al. 2010) have a strong influence on snowmelt runoff and groundwater recharge.

Prior to this study, it has been commonly assumed that the focused infiltration of snowmelt runoff under depressions is the key driver of groundwater recharge in the Canadian prairies (e.g. Lissey 1971; Zebarth et al. 1989; Berthold et al. 2004) because of the large moisture deficit during summer months (Table 3). These previous studies were conducted in the central part of the Canadian prairies characterized by colder and drier climate than southern Alberta. This study indeed corroborated the importance of snowmelt runoff in some years, but also found occurrence of recharge in 2008 and 2010 when winter precipitation was low and little snowmelt runoff was observed in depressions (Fig. 7). In contrast, almost no recharge was detected in 2009, when sizable snowmelt runoff (Fig. 6) was followed by very dry summer. These findings indicate the importance of understanding the interplay between depression-focussed recharge driven by snowmelt runoff and distributed recharge driven by summer rainfall, at least in the western part of the Canadian prairies. This region is characterized by frequent occurrence of mid-winter Chinook events (Nkemdirim 1996) that melt and sublimate snow and reduces the availability of snowpack that melts rapidly during the spring melt season and generates a large amount of snowmelt runoff.

Effects of long-term climatic fluctuation

The analysis of baseflow in West Nose Creek and two other similar-size creeks in the region clearly indicated a shift in baseflow discharge (Fig. 13) and hence, groundwater recharge from the consideration of watershed-scale water balance (Eq. 3). Relatively high groundwater recharge during 2003–2013 appears to be linked to frequent occurrence of winter precipitation exceeding a

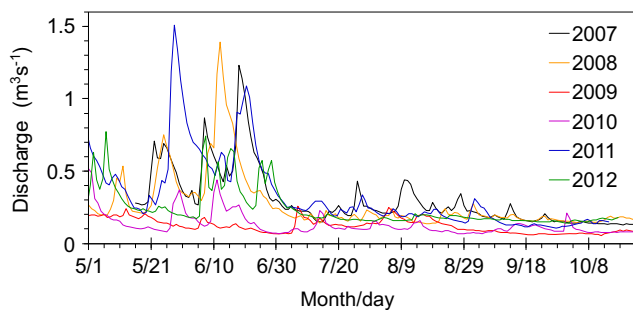


Fig. 11 Daily average discharge of West Nose Creek for years 2007–2012

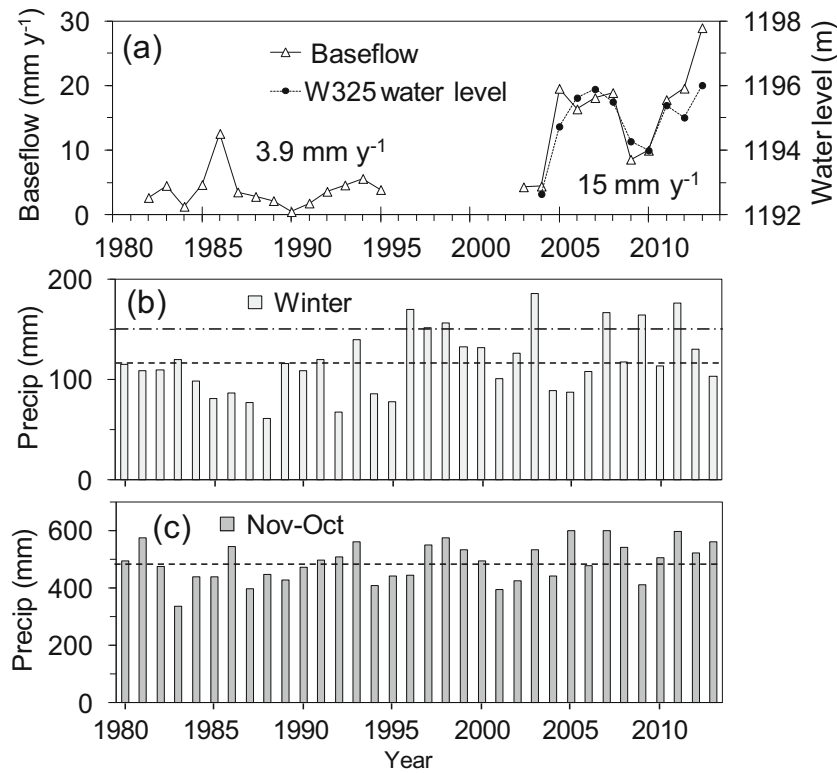


Fig. 12 **a** Estimated baseflow of West Nose Creek expressed in mm y^{-1} . Note that the gauging station was closed between 1995 and 2003. **b** Winter and **c** annual precipitation in Calgary. Dashed lines indicate the mean precipitation during 1980–2013 (**b** and **c**), and the dash-dot line indicates 150 mm (**b**)

threshold for generating significant runoff (Figs. 7 and 12b), as well as higher annual precipitation compared to 1982–1995 (Fig. 12c). From a longer-term perspective, 1982–1995 and 2003–2013 represent the decades of low and high winter precipitation, respectively (Fig. 14a). In terms of annual precipitation, these periods also represent relatively dry and wet conditions, respectively, but there were wetter and drier periods in the recorded history (Fig. 14b).

The observed shift in baseflow and groundwater recharge from the dry decade (1982–1995) to the wet decade (2003–2013) is likely connected to the inter-decadal precipitation variability inherent in the climate of the Canadian prairies (Bosal and Regier 2007; Perez-

Valdivia et al. 2012). However, groundwater recharge is also sensitive to other processes such as land-use conversion, which may strongly influence aquifer water levels over a long term (e.g. Allison et al. 1990; Scanlon et al. 2005). In the Canadian prairies, conversion of native grassland to cultivated fields (van der Kamp et al. 2003) and change in tillage practice from conventional to minimum tillage (Elliott and Efetha 1999) can have strong influence on snowmelt infiltration and runoff, which likely affects groundwater recharge. Therefore, the interpretation of the relationship between groundwater level and climatic variables over multi-decadal scale needs to include land-use variables.

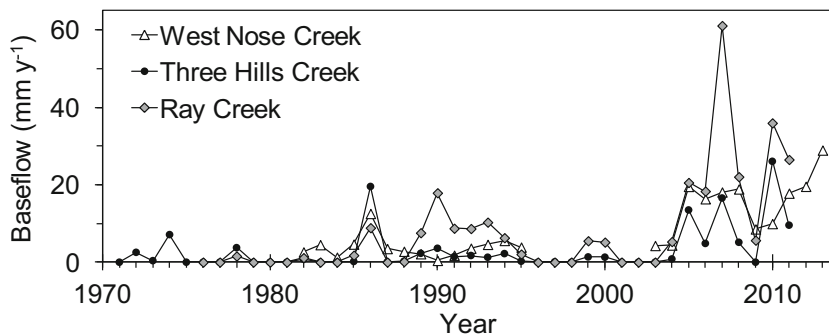


Fig. 13 Estimated baseflow of West Nose Creek, Three Hills Creek and Ray Creek

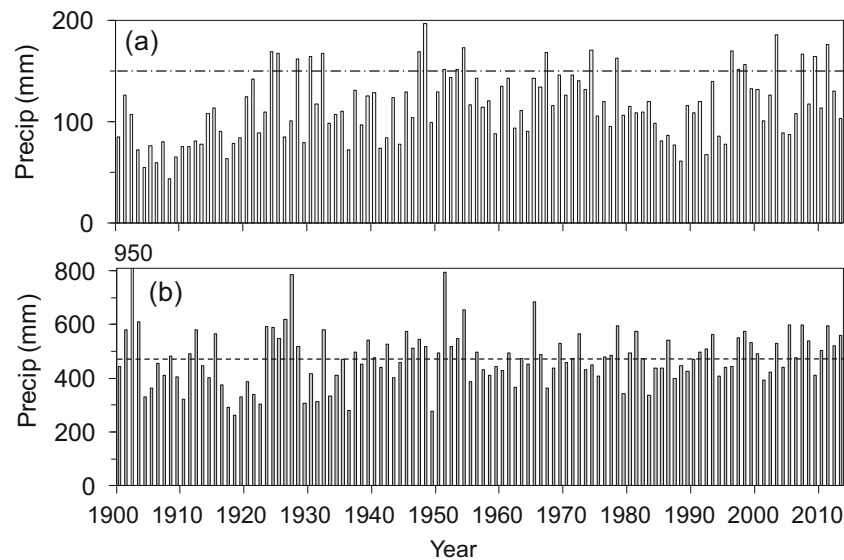


Fig. 14 a Winter (November 1–April 22) and b annual precipitation in Calgary. The dash-dot line indicates 150 mm (a), and the dashed line indicates mean annual precipitation (478 mm) for 1900–2013 (b)

Conclusions

Magnitude and timing of water-level rises in bedrock aquifers reflect the water-table rises in the overlying glacial till in response to recharge. Water levels in deep aquifers integrate the local-scale variability resulting from heterogeneous land cover and micro-topography. It is difficult to quantify absolute amounts of recharge using standard methods (e.g. Healy and Cook 2002) due to uncertainty in storage coefficients and in the quantitative relation between water-table rises in glacial till and water-level rises in bedrock aquifers. However, the magnitude and timing of water-level rises contain valuable information regarding the inter-annual variability of recharge in response to meteorological forcing. Such information is useful for understanding potential impacts of future and past climatic variability on groundwater recharge.

In the 250-km² West Nose Creek watershed and adjacent areas, bedrock aquifers consist of disconnected sandstone units embedded in mudstones. The seven monitoring wells in bedrock aquifers had similar patterns of water-level fluctuations such as the recovery from a severe drought and seasonal responses to snowmelt and heavy rains, indicating the collective response of individual aquifer units to meteorological forcing. Contrary to the initial expectation of snowmelt runoff being the main driver of recharge, the correlation of water-level rises with snowmelt runoff and growing-season precipitation showed that both snowmelt and summer rain are important drivers of recharge.

Hectare-scale vertical water balance based on precipitation (P) and vapour flux (E) measurements showed that $P - E$ was on the order of 10 mm y^{-1} during hydrological years 2007–2013, which represents potential recharge. The magnitude of $P - E$ roughly matched the magnitude of recharge (15–18 mm y^{-1}) estimated from the baseflow of West Nose Creek during the same period. The range of

these values, 10–20 mm y^{-1} gives an estimate of groundwater recharge in the study area under the current condition. Recharge is likely a combination of depression-focused infiltration of snowmelt water in high runoff years and distributed infiltration of rainwater in years with high precipitation.

The average baseflow of West Nose Creek increased from 4 mm y^{-1} in 1982–1995 to 15 mm y^{-1} in 2003–2013, clearly indicating a shift in watershed-scale groundwater recharge due to a shift in meteorological conditions. The comparison between the two periods, as well as among individual years during 2003–2013, shows that the conditions favourable for large recharge are winter precipitation in excess of 150 mm, which can generate large snowmelt runoff, and high May–September precipitation. The shift from low baseflow to high baseflow state in the region appears to be connected to inter-decadal variability in precipitation inherent in the climate of the Canadian prairies.

Under the current condition the creek baseflow is an order of magnitude larger than groundwater extraction rate from the West Nose Creek watershed (3 mm y^{-1}), implying that there is some room for increased extraction without significantly altering creek flow. However, if the low-baseflow period like 1982–1995 returns, extraction rate will become close to baseflow, meaning that increased extraction could alter the creek flow and aquatic ecosystem. This needs to be factored in the water resource planning. It is also important to consider land-use effects on snowmelt infiltration and runoff, which can strongly affect groundwater recharge, in long-term planning.

This study demonstrated the linkage between groundwater recharge and meteorological forcing at a scale of a small watershed. Future studies should examine the small-scale processes that result in the observed linkage; for example, the roles of depression-focused recharge and evenly distributed recharge and how they complement

each other under different meteorological conditions and land-use practices. It is also important to understand the connection between the soil moisture dynamics, shallow water-table fluctuations, and their transmission to deep bedrock aquifers.

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