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Partitioning hydrologic contributions to an 'old-growth' riparian area in the Huron Mountains of Michigan, USA

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Abstract

Over the past century, annual snowfall has increased across the 'snow-belt' region of the Upper Peninsula of Michigan, yet total annual precipitation has not changed, with potential impacts on hydrological processes and ecosystem composition. Using an integrated hydrochemical approach, we characterized groundwater discharge and quantified the contribution of snow- and rain-derived waters to groundwater for an old-growth riparian area within the Huron Mountains in northern Michigan. We then quantified the relative contribution of lateral, hillslope-derived groundwater and upstream lake-water to streamwater, and the extent of hyporheic zone expansion and contraction during one growing season. During a period of above-average snowfall, yet below average growing season precipitation, ~80% of the riparian area's groundwater reservoir was derived from snowmelt. The relative contribution of groundwater to streamflow ranged from 70% in June to 100% in August. The remainder was derived from upstream lakes and wetlands, which dropped in elevation and relative contribution from June to August. Finally, the extent of the hyporheic zone was small (<50cm from streambed surface) and contracted towards the stream during the recession limb of the hydrograph. We conclude that if snowfall continues to rise while total annual precipitation declines, in line with climate change scenarios for the region, then water fluxes from snowmelt will increasingly dominate summer baseflow from 'snow-belt' watersheds contributing to Lake Superior.

Introduction

The riparian area connects upland and in-stream ecosystems, where the amount and distribution of upland precipitation drive the recruitment, retention, and release of water and its constituents (carbon, nitrogen, etc.) to downstream ecosystems (Hynes, 1970; Naiman and Decamps, 1997).

Consequently, efforts to quantify patterns of subsurface and surface water movement through riparian areas are needed to inform simulation models that forecast the effects of chronic (e.g., global temperature increases) or acute (e.g., 100-year flood) climatic events on ecosystem processes (National Research Council, 2002; Naiman et al., 2005).

Across the Upper Peninsula of Michigan, USA, annual precipitation falls nearly equally as snow and rain (Eichenlaub et al., 1990; Stottlemyer and Toczydlowski, 1996). Some climate change scenarios predict an alteration in the amount and seasonality of precipitation inputs for the Lake Superior region, where predicted increases in temperature lead to drier summers, yet increasing amounts of snow precipitation during winters (Kattenberg et al., 1996; Kunkel et al., 2000). In line with model predictions, there is evidence that annual snowfall in the region has increased over the past century (Burnett et al., 2003; Norton and Bolsenga, 1993; Leathers and Ellis, 1996). Based on Houghton, MI annual records from 1890 to 2007 (http://www.admin.mtu.edu/alumni/snowfall/), snowfall has increased at 30 mm yr^{-1} ($r^2 = 0.45$, $p < 0.01$); increases in snowfall from 1958 to 2007 for Marquette, Michigan is 64.8 mm yr^{-1} ($r^2 = 0.33$, $p < 0.01$) (NOAA). For Marquette, there does not appear to be a change in total precipitation (Marquette's $r^2 = 0.008$, $p = 0.58$), in line with climate change models that predict altered patterns of precipitation distribution for the region. The measured increase in 'lake-effect' snow within the Upper Peninsula is perceived to be due in part to greater rates of winter evaporation from the surface of Lake Superior, where rising annual temperatures of Lake Superior result in a longer duration of ice-free (evaporative) surface area during winter (Burnett et al., 2003; Leathers and Ellis, 1996). Annual increases in snow precipitation lead to greater amounts of spring snowmelt, which in turn can lead to elevated pulses of either "acidic" and/or "dilution" events that can affect local streams and lakes by altering stream chemistry and productivity (Stottlemyer and Toczydlowski, 1991; Rascher et al., 1987; Johannessen and Henriksen, 1978). Furthermore, where annual precipitation amounts stay constant or even rise, but growing season precipitation decreases (i.e., more snow, less rain), then ecosystem composition, structure and function are likely to change in response to altered hydrological processes. Considering the numerous scenarios and implications for northern ecosystems under a changing climate (Schlesinger, 1991; Levine, 1992; Davis et al., 2000; Nijssen et al., 2001), quantifying current connections between climate and forest hydrology in near-pristine north-temperate forests will provide an important baseline for quantifying future changes.

Overland flow and direct precipitation inputs are minor contributors to headwater streams in northern temperate forests (Brooks et al., 2003), and so field-based hydrology studies in these systems have focused on riparian groundwater fluxes to streamflow (Walker and Krabbenhoft, 1998; McGlynn et al., 1999; Morrice et al., 1997; Vidon and Hill, 2004; Wondzell, 2005). Groundwater contributions of terrestrially-derived nutrients and elements contribute to biological and chemical processes within the surface water environment (Gilbert et al., 1994; Hemond and Fechner-Levy, 2000; Hill, 2000; Holmes, 2000), and the functional significance of riparian soils on nutrient cycling and flux regulation is well recognized (McClain et al., 2003; Mulholland, 1992; Cirmo and McDonnel, 1997; Schindler and Krabbenhoft, 1998; Baker et al., 2000; Thomas et al., 2001; Valett et al., 2002). Further, riparian groundwater provides a stable source of water to streams and transpiring vegetation. A change in precipitation inputs to groundwater could potentially alter riparian ecosystem processes, where the distribution (timing, duration, and amount) of inputs are likely to affect solute fluxes and concentrations.

In this study we used three approaches to quantify the water sources to a headwater stream in the Huron Mountain Reserve in the Upper Peninsula of Michigan, USA. First, we compared upstream and downstream discharge to estimate groundwater contribution along a stream reach (Harvey and Wagner, 2000; Brooks et al., 2003; Ward & Trimble, 2004). Secondly, we measured the isotopic composition for oxygen (O^{18}/O^{16}) and hydrogen (H^2/H) within stream and source waters to partition ground- and stream-sources (Winograd et al., 1998; Burns et al., 2001; Katsuyama et al., 2001; Atekwana and Richardson, 2004; Pardo et al., 2004; Monteith et al., 2006, Cey et al., 1998; McGlynn et al., 1999; Buttle, 1998; Wenninger et al., 2004; Reddy et al., 2006). Lastly, we used semi-conservative parameters of conductivity, temperature and chloride concentration to create a more complete description of groundwater hydrology (Stream Solute Workshop, 1990; Christopherson et al., 1990; Hooper et al., 1990; Mazor, 1991). This diverse hydrochemical approach was used to partition the hillslope's hydrological contribution to the downslope riparian area, stream channel, and hyporheic zone (McGlynn et al., 1999; Burns et al., 2001; Ladouche et al., 2001; Seibert, 2003; Wenninger, 2004).

The Fisher Creek riparian area, where the current study was conducted, has no known history of management, including land clearing or harvesting for timber, and so is an important pristine or old-growth site for conducting baseline forest-hydrology research. We build on previous isotope-based hydrology studies of northern hardwood forests (McGlynn et al., 1999; Cey et al., 1998; Buttle et al., 2001; Monteith et al., 2006), by describing the baseflow conditions and relative contributions of an old-growth northern hardwood riparian area. Our objectives were to characterize the riparian subsurface hydrology for two old-growth riparian reaches. Specifically, we quantified groundwater discharge and the relative contributions of: 1) rainfall and snowfall to riparian groundwater; and 2) groundwater and upstream sources to streamwater. We also used the isotopic signature of groundwater and streamwater to examine the extent and dynamics of the hyporheic zone. We hypothesized that: 1) snowmelt would be the dominant source to groundwater during baseflow; 2) lateral groundwater inputs from the hillslope to streamwater would increase in relative contribution along the recession limb of the hydrograph, as longitudinal inputs from upstream sources decrease; and 3) the zone of hyporheic mixing would contract towards the stream during the recession limb of the hydrograph as upstream inputs and surface streamflow decreases.

Methods

Site Description

This study was conducted in the Huron Mountain Reserve (HMR) (46°52' north latitude, 87°50' west longitude), a conservation area within the larger, privately-owned Huron Mountain Club property in the Upper Peninsula of Michigan, USA near Lake Superior (Figure 1a). The HMR contains one of the largest (~2600-hectares) pristine old-growth forests within the Great Lakes region (Frelich, 1995; Davis, 1996a; 1996b; Woods, 2000; Flaspohler and Meine, 2006). The climate of the HMR is characterized by a relatively even distribution of annual precipitation, low potential evapotranspiration, and a strong local influence from the proximity to Lake Superior, which includes moderated temperatures and elevated snowfall (Figure 2; Denton & Barnes, 1988). Three NOAA weather stations located in Marquette, Houghton and Herman are within 55 km of the research site. Based on isohyetal interpolation, we estimate a 30-year average (1971-2000) for mean annual temperature of 4.2° C, a mean precipitation of 918 mm, and a mean snowfall of 5453 mm for the HMR. Snow-free season rainfall data were collected daily from two locations approximately 3-km north and east of the Fisher Creek using graduated rain collectors during the study period from April 7 to Nov. 11, 2005 (total = 522 mm). To account for the spring snowmelt, snow water equivalent was found to be 0.72 mm mm^{-1} (± 0.112; n= 6) for late March, which for the average measured snowpack depth of approximately 400 mm was equal to about 290 mm of meltwater precipitation per unit area. Together, snowmelt plus rainfall, the localized 812 mm of precipitation corroborates the below average conditions for the study period.

Our study was conducted along Florence Pond Drain (FPD), a 1st order reach that drains Florence Pond, and Fisher Creek (FC), a 2nd order reach that drains Trout Lake and other small headwater wetlands (Figure 1b). The two reaches were selected based on mature forest condition, and similarity in lithotopography (Montgomery, 1999) and channel characterization (Rosgen, 1994). The FC study area is approximately 600 m in straight length, with an approximate 840 m of stream channel length, while the FPD study area is approximately 300 m in length, with an approximate stream channel length of 540 m.

The riparian areas of FC and FPD have been characterized as yellow birch (*Betula allegheniensis*), eastern hemlock (*Tsuga canadensis)*, northern white cedar (*Thuja occidentalis*), red maple (*Acer rubrum)* forest type (Simpson et al., 1989; 1990), although sugar maple (*Acer saccharum)*, white pine (*Pinus strobus)*, white spruce (*Picea glauca)*, and balsam fir (*Abies balsamea)* occur throughout the riparian area. The canopy is composed of super-dominant individuals of white pine that often exceed 40 m in height and 1.2 m in diameter (Wells and Thompson, 1976), which attest to the absence of timber harvesting activities within the watershed. ANOVA analyses revealed that reaches did not differ with respect to amounts of large woody debris (volume, length, or biomass) or decay class frequency. Because characteristics of large woody debris within a riparian forest often is related to disturbance history (Barnes et al., 2003; Bragg and Kershner, 1999; Duvall, 1997; Gregory et al., 2000;

Hedman et al., 1996; McClure et al., 2004; Naiman et al., 2002), we expect that the FC and FPD reaches to be similar in disturbance history.

The Huron Mountains consist of Huronian and Archean formations, which are of Precambrian metamorphic origin resulting from uplifting of the Canadian Shield (Dorr & Eschman, 2001). They were subject to glacial processes until ~10,000 ybp. Floodplains of HMR riparian areas consist of deep sandy glacial outwash sediments, and are characterized as sandy stream terraces with deep, moderately well drained loamy sands (Simpson, 1990). Soils are mapped as either Kalkaska Sands or the Evart-Pelkie-Sturgeon Complex, in which all soils are sands with hydraulic conductivity values that range from 0.000423-0.0141 cm s^{-1} and pH values that range from 3.6-8.4, depending on depth. The higher pH Evart type is composed of 0-10 percent calcium carbonate, but when soils were sampled to a depth of 50cm throughout the riparian area, application of 10% HCl did not result in a characteristic bubbling reaction, and so indicates little or no calcium carbonate.

Streamflow

Stream discharge was measured using velocity and cross-sectional area measurements throughout the two reaches. Velocity was measured with a Marsh-McBirney™ electromagnetic flow meter (Hauer & Lamberti, 1996; Brooks et al., 2003). Discharge was determined for multiple stage heights, while stage was recorded regularly using 3-staff gauges positioned within the stream's thalweg at two locations along the FC reach and at one location within the FPD reach.

To predict discharge during periods when no field data were collected, a discharge-to-discharge relationship was developed using regression analysis against a nearby USGS stage recording data station (http://waterdata.usgs.gov/nwis/rt). A discharge-to-discharge power-function was determined to be the best fit for FC and FPD discharge. Power functions have been used in similar studies of other regional watersheds (Cey et al., 1998; Goebel, 2001). The Yellow Dog River USGS station located approximately 20 km from Fisher Creek provided the best continuous discharge data with which to predict FC and FPD flow (r^2 = 0.76 for FC, r^2 = 0.90 for FPD; $p \leq 0.05$).

Well Network

Throughout FC and FPD, 11-meter segments of straight reaches were used as the upper and lower bound of each plot. A total of 15 plots were randomly chosen from a population of 46 selected 11-meter segments of similar morphological characteristics within the reaches. Each rectangular plot spans the farthest extent of the historical floodplain on either side of the stream (Figure 1c). Within each plot, at least 6-wells were randomly located at: 1) the approximate bankfull width of the stream (Ward & Trimble, 2004), and 2) the estimated floodprone width of the stream, where floodprone is considered the width of the stream at twice the depth of the thalweg. Beyond the floodprone wells on both sides of the stream, a floodplain well was installed at the farthest edge of each plot, which coincided with the farthest extent of the historical floodplain. Terrace wells were positioned above the floodplain (n= 4 in FC, n= 2 in FPD) irrespective of plot location (Figure 1c). There were 11 plots positioned within the FC reach, with a total of 72-bankfull wells, 71-floodprone wells, and 22-floodplain wells. Within the FPD reach, a total of 4 plots, with 26-bankfull wells, 26-floodprone wells, and 8-floodplain wells were installed.

All wells were installed using a bucket-auger with each bankfull and floodprone well installed to approximately 30-cm below the stream bed elevation; floodprone and terrace wells were installed 2-3 m below ground-surface, in order to extend below the point of contact with the water table. All wells were constructed of 5.1-cm inside-diameter PVC pipe of various lengths with perforations along the underground portion of the pipe. Each perforated section of the pipe was then covered with a nylon filter to keep sediment from entering the wells, while each pipe bottom and top was capped with a fitted PVC cap. All wells were back-filled with native material and capped with 5cm of Portland cement. Each cap was then sealed with 5cm of bentonite clay to resist preferential flow down the well exterior.

Additionally, streambed wells (or mini-piezometers, as described in Dahm and Valett, 1996) of 1.9 cm diameter PVC were installed into the middle of the stream thalweg; these wells were perforated from 10- to 50-cm below the streambed. At least 3 mini-piezometers were randomly placed within each plot (see Fig. 1c; n=37 for FC, n=13 for FPD). All, wells were installed in 2004 and not measured or sampled until the spring of 2005 to allow wells to settle.

Water Sampling and Analyses

Samples of streamwater for the $\boldsymbol{\delta}^{18}$O and $\boldsymbol{\delta}^{2}$H analyses were collected by grab-sampling while groundwater samples were collected with a peristaltic pump from wells and mini-piezometers. Groundwater and streamwater samples were taken from 4 of the 15 randomly selected plots in June and September, 2005. Precipitation was collected using 6 rainfall collectors placed throughout the watershed; while snowwater was collected from 10 snowpack cores sampled along 2 transects spanning a 100 m gradient of elevation. Precipitation samples were collected for 6 events from June through September, 2005 and snowpack samples were collected on a single occasion in April 2005. All samples were collected into acid-washed HDPE 125ml bottles, then kept chilled on ice until filtration within 24-hours of collection (0.7µ glass fiber filters within a polypropylene inline filter holder attached to a peristaltic pump using sterilized tygon tubing). The samples were then kept in a dark refrigerator (~ 2°C) until sent to the USDA Forestry Sciences Lab in Moscow, Idaho for isotope analysis using Finnigan Delta+ Continuous Flow IRMS (Thermo Scientific, Waltham, MA).

Chloride analyses of monthly samples collected from all wells, piezometers and stream grab-stations, were conducted following vacuum filtration with an acid-washed polysulfone filter apparatus (0.7µ glass fiber filter paper), on a Dionex DX 500™ ion chromatograph analyzer (Dionex, Sunnyvale, CA) at the USDA Forest Service Forestry Sciences Lab in Grand Rapids, MN. Monthly *in situ* measurements of temperature and conductivity were collected for all wells and stream sampling locations using a YSI 556™ multi-parameter meter (YSI Inc., Yellow Springs, OH). Outliers that were more than 2 times the standard error were omitted before analyses. Precipitation values for conductivity and chloride concentration were assumed to equal those measured at the nearest National Atmospheric Deposition Program (NADP) site in Chassel, MI approximately 30-km northwest of the study site (http://nadp.sws.uiuc.edu/sites/).

Groundwater Discharge

Stream Gauging Method: As one measure of groundwater contribution along each stream reach, the difference in discharge using stream gauging between an upstream and downstream pair of sample points was determined. The difference between upstream and downstream pairs was fitted for a regression (for FPD, r^2= 0.93, $p<0.05$; for FC, r^2= 0.96, $p<0.05$) which was used to predict groundwater discharge from the previously described daily discharge estimates. Given local topography constraints, we assume gaining reaches with no losses of streamwater.

Partitioning Water Sources

Stable Isotopes: Isotope data were analyzed using a mixing model procedure to partition water sources. This approach assumes no between-population correlation between isotopic signatures. An analysis of model error was performed with the Environmental Protection Agency, Western Ecology Division's free software program IsoError© (Phillips and Gregg, 2001; 2003). The simplified model equation used to partition different sources of each chemical and physical parameter, is expressed as:

$$C_{mixture} = XC_{sourceA} + (1\text{-}X)C_{sourceB}$$

where $C_{mixture}$ is the mean of the water mixture of the two end-members, and $C_{sourceA}$ is the mean for one source end-member, while $C_{sourceB}$ is the mean for the other end member. Solving for X provides the percent contribution by each end member in the mixture.

To estimate the source contributions of water within the groundwater aquifer mixture (floodplain and terrace wells), the end-members were pooled into late-winter snowpack isotopic values and into summer rain precipitation concentration values. For estimating the source contributions within the hyporheic zone (streambed mini-piezometers and bankfull wells), streamwater and groundwater concentration were considered the two end-members. The two concentration end-members used to partition streamwater were groundwater from streamside wells (mean of bankfull and flood prone locations) and surface water from the upstream Trout Lake and Florence Pond.

Conservative Tracers: Because chloride is considered a highly soluble and a somewhat conservative natural tracer (Stream Solute Workshop, 1990; Hart et al., 1999; Hinkle et al., 2001; Thomas et al., 2003), we used chloride concentration to partition hyporheic water sources of groundwater and streamwater. We also used measurements of conductivity and temperature as semi-conservative tracers for water source partitioning (Robson & Neal, 1990; Kleissen et al., 1990; Mazor, 1991; Cey et al., 1998; Battin et al., 2003; Wenninger et al., 2004; Monteith et al., 2006) within the hyporheic zone and streamwater (groundwater vs. upstream reservoirs) estimates, respectively.

Statistical analyses

ANOVA was used to test for differences between well positions and sampling locations, while linear and non-linear regressions were performed for isotope and discharge comparisons. The univariate models, descriptive statistics, and Least Significant Differences (LSD) comparisons were performed using SPSS© statistical software, while all regressions were performed using SIGMAPLOT© software. All differences are considered significant at the $p \leq 0.05$ level, unless otherwise stated.

Results & Discussion

Groundwater Discharge

The stream gauging approach yielded estimates of groundwater discharge for the study period that ranged from 10.8-14.4 m^3 $hour^{-1}$ for FC and 1.8-144 m^3 $hour^{-1}$ for FPD. Groundwater discharge for each reach decreased from onset of snowmelt through the summer growing season, but increased with autumnal precipitation inputs, likely as a result of increased inputs and reduced evapotranspiration demands (Figure 3). The greater range/relative flashiness of FPD, compared to FC, is likely due to a more constrained floodplain along the study reach with a shorter residence time of the relatively steep upslope recharge.

Partitioning Water Sources

Precipitation Inputs: The distinct isotopic signatures of rain and snow precipitation permitted us to quantify the relative contributions as source waters to groundwater and streamwater. By regressing $\boldsymbol{\delta}^2$H (‰) against values of $\boldsymbol{\delta}^{18}$O (‰) for precipitation, we developed a local meteoric water line (LMWL) where $\boldsymbol{\delta}^2H = 7.8\ \boldsymbol{\delta}^{18}O + 14.1$ ($R^2 = 0.99$) (Figure 4). The LMWL very closely approximates the recognized global meteoric water line for precipitation with the formula $\boldsymbol{\delta}^2H = 8.0\ \boldsymbol{\delta}^{18}O + 10$ (Craig, 1961). Upon superimposing our values for groundwater, streamwater, and upstream reservoirs (lake-waters), a local evaporation line (LEL) with the equation $\boldsymbol{\delta}^2H = 5.0\ \boldsymbol{\delta}^{18}O - 26.5$ ($R^2= 0.83$; $p< 0.0001$) is formed. The divergence of the LEL from the LMWL distinguishes the evaporative enrichment that occurs for the site, while the LEL intersection with the LMWL closely approximates the mean annual precipitation signature (Mazor, 1991; Gibson et al., 2005; Reddy et al., 2006), which was approximately -14.5 ‰ for the Fisher Creek watershed during 2005. Walker and Krabbenhoft (1998) found a 2-year volume weighted average of approximately -11 ‰ for a Northern Wisconsin site. Since the Fisher Creek watershed is closer in proximity to Lake Superior it experiences more lake-effect snow precipitation, therefore the relative depletion in signature is expected. The evaporative trend is very similar to Reddy et al.'s (2006) LEL for a north-central Minnesota watershed, where most groundwater closely resembled the LMWL. FC's and FPD's groundwater and streamwater do not show much divergence from the LMWL, therefore evaporative enrichment is relatively low within the stream. Conversely, the values for the upstream lakes (Trout Lake and Florence Pond) indicate strong enrichment, where ^{2}H preferentially evaporates over ^{18}O during the summer and/or rain dilution continues to enrich the chemical signature of the lakes.

Groundwater Sources: The signature of meteoric water has been shown to follow a sine function relationship with the seasons (Reddy et al., 2006; Dewalle et al., 1997; Gibson et al., 2005), but for shorter time steps the LMWL provides an indication of whether ground, stream, or lake-waters are derived from rain or snow. For 2005, Fisher Creek streamwater was positioned between the range of values found for snow and rain. Isotopic analyses revealed that streamwater closely resembled groundwater (Figure 5), and that both stream and groundwaters derived primarily from snowmelt, with minor contributions from rain or upstream lakes. Because streamwater during base flow was on average 80% groundwater, and groundwater was 85% snowmelt, we conclude that streamwater during baseflow was up to 70% of snowmelt origin.

The distinctness of our results is sensitive to any isotopic enrichment resulting from the loss of lighter water during sublimation of snow or evaporation of meltwater and/or intercepted rainwater. In fact, several laboratory and *in situ* studies estimated the $\delta^{18}O$ enrichment of snow to snowmelt water to range from + 1.4 ‰ to + 5.6 ‰ (Hermann et al., 1981; Cooper et al., 1993; Mast et al., 1995; Suzuki, 1995; Taylor et al., 2002). Mast et al. (1995) found an enrichment of +

1.4 ‰ for a Colorado site while Taylor et al. (2002) found an enrichment of + 4.5 ‰ for another Colorado site and an enrichment of > 5 ‰ for a Vermont site. To address enrichment in the mixing model, we conservatively assumed that at our site, snowmelt was enriched to a maximum of + 4 ‰ relative to snow. Additionally, soil evaporative enrichment can be large in arid climates (Gat, 1998; Yakir, 1998), but an enrichment of +1.5 ‰ is considered a limit in humid climates (Gat, 1998). Considering this potential enrichment along with other selective enrichment factors (e.g. selective runoff processes and canopy interception), a maximum rain enrichment of 1.5 ‰ was evaluated within the mixing model.

Based on our analyses of the possible range of enrichment, the 95% confidence limit for the percent of groundwater that was snow derived for May ranged from 73-100% (Table 1). For August the range was slightly lower at 69-97% snow-derived groundwater, which may be an indication of slight dilution with rain or evaporative enrichment that occurred since May. Given all the potential evaporative enrichment effects, our analysis conservatively suggests that ~ 85% of groundwater is snowmelt derived. Given evidence of low enrichment from stream values, we believe that this is a low estimate for snowmelt's contribution to groundwater within the Fisher Creek Watershed. This conservatively high estimate of contribution underscores the importance of snowmelt to this riparian system.

Approximately 50% of annual runoff in the region occurs during and immediately after snowmelt (Stottlemyer & Toczydlowski, 1996; Stottlemyer & Toczydlowski, 1999; Stottlemyer & Toczydlowski, 2006), with snowfall equaling approximately 50% of annual precipitation inputs (Eichenlaub 1970; Eichenlaub et al., 1990; Stottlemyer & Toczydlowski, 2006). Because snowmelt occurs before the growing season commences, during which evapotranspiration losses are minimal, it is likely that a greater percentage of snowmelt water will reach the riparian groundwater system than growing season precipitation inputs. This may explain why the groundwater and streamwater signatures varied very little between May and August (Fig. 5). The uneven distribution of snowmelt to rain precipitation during a moderately droughty 2005 (Figure 2), led to a snow-dominated riparian groundwater reservoir.

Streamwater Sources: An isotope mixing model was used to separate groundwater and upstream lake water sources that contributed to streamwater in the FC and FPD reaches of study. Groundwater in May contributed ~75% of the streamwater, while groundwater in August contributed ~90% to streamwater. These results indicate that upstream lakes and ponds in May resemble snowmelt more than in August, and that groundwater is more influential in August due to lower surface water elevations of upstream lakes. Therefore, our hypothesis of an increasing percentage of groundwater derived streamwater during the recession limb of the hydrograph is supported.

Other results from this study support this isotope-based conclusion. Specific conductivity of waters varied by riparian position (Table 2), with streambed, bankfull and floodprone positions exhibiting the highest conductivities, while more distant groundwater positions (floodplain + terrace wells) had the lowest conductivities. These results indicate that precipitation with low conductivity (< 0.02 mS cm^{-1}) gains ions as it percolates through soils along a course to the stream. McGlynn et al. (1999) found similar increases in solute concentrations along riparian flow paths. Based on mixing model results for conductivity, the June contribution to streamwater by upstream lakes (precipitation values as a proxy) was estimated at 40%, while in August it decreased to 23%. If one separates the analysis by reach, upstream sources contribute less to FPD streamwater than the FC reach, similar to earlier indications derived from isotope data. Additionally, both reaches show increases in groundwater contribution from June to August, which corroborate earlier isotope data. The conductivity model results in a greater (2X) contribution from upstream lakes than the isotope model results (25% in May/June to 10% in August), however the difference between months is similar; with a 12-15% decrease in upstream lake/upstream precipitation inputs to streamwater from June to August. The conductivity and isotope data both suggest that streamwater is dominated by groundwater inputs and upstream-inputs to streamwater are reduced in August when surface water elevations in the upstream lakes have dropped. When the late autumnal period is analyzed for conductivity, the contribution from upstream lakes rises to nearly 53% in October, which is a 13% increase from June. This pattern in upstream contribution correlates well with the observed hydrograph (Figure 3), where periods of elevated recharge to upstream lakes, such as early season snowmelt and autumn rain, result in reduced contribution of groundwater to streamwater.

Hyporheic Zone: Isotope, chloride and water temperature mixing models were performed to describe the extent of the hyporheic zone and the relative contributions of groundwater and streamwater to within hyporheic waters (Hinkle et al., 2001; Battin et al., 2003). Based on temperature and chloride concentration data, the stream contributed approximately 25% of the water found within waters < 50 cm from the streambed (within bankfull and streambed wells) in early June, while the late summer values for these wells were indistinguishable from groundwater. With the onset of autumn rains, the stream contributed nearly 36% to bankfull and streambed wells, as determined from temperature measurements in October. Oxygen isotope signatures resulted in a 38% streamwater contribution to bankfull and streambed wells in late May, and 0 % contribution in August due to identical groundwater and streamwater end-members. Although there is a difference between the results for determining the percent contributions to the waters within bankfull and streambed wells, all results indicate that the hyporheic boundary was detectable within our sampling design, was consistently close to the streambed's margin (< 50cm), and contracted seasonally in unison with the discharge hydrograph, as hypothesized. For these sandy bottom stream reaches, there was no hyporheic mixing beyond 10-cm during baseflow conditions for the moderately droughty summer.

Conclusions

The groundwater dynamics during a period of moderate drought provided a snapshot of changing climatic effects on the riparian hydrology within a Lake Superior watershed. Snowfall is increasing throughout the region, while total precipitation appears to be unchanged (Burnett et al., 2003; Norton and Bolsenga, 1993; Leathers and Ellis, 1996). The redistribution of precipitation is a predicted outcome from global climate change. If snowfall continues to rise, while total annual precipitation declines, in line with climate change scenarios for the region (Kattenberg et al., 1996; Kunkel et al., 2000), then it is likely that riparian ecosystems feeding Lake Superior will experience a greater range of water and nutrient fluxes from snowmelt to summer baseflow. Stottlemyer and Toczydlowski (1996; 1999; 2006) estimated that regional snowpacks contribute ~ 50% to annual runoff or streamflow. However, our calculations indicate that baseflow conditions of an old-growth riparian area are not evenly distributed, at least for a year with an above average snowmelt-to-rain precipitation ratio. The isotope-derived mixing model estimated that snowmelt accounted for approximately 80% of the inputs to the riparian groundwater during 2005 baseflow conditions with the remaining 20% of inputs likely from rain during the previous non-growing season (spring and fall, 2004). Models also allowed for the observation that groundwater's relative contribution to streamflow increases along the recession limb of the hydrograph, as upstream reservoirs decrease in relative influence downstream. Future increases in snowfall, without an increase in rain, may further lead to riparian groundwater with snowmelt origin, and stream baseflow of groundwater origin. The changes in stream chemistry, let alone streamflow, could greatly alter the productivity of in-stream ecosystems.

We also observed that in our riparian areas, the hyporheic zone was very small in extent (< 50 cm from the streambed surface) and shrank during the growing season, as streamwater contribution and hyporheic zone expansion and contraction also followed the hydrograph. As the hyporheic zone boundary was indistinguishable during the drought conditions of summer baseflow, an argument could be made that the hyporheic zone processes are minimal and/or contracted during this period, while higher flow conditions expand the boundary and zone of hyporheic mixing, potentially leading to a greater impact on ecosystem processing of nutrients.

Our isotope – based analyses allowed us to track the flux and fate of water of a remote northern old-growth watershed, and highlighted the dominant role that snowmelt plays in the functioning of old-growth riparian ecosystems of the Great Lakes. Faced with ecosystems that are being altered by climate change, our research also highlights the need for long-term, diverse hydrological research within unaltered ecosystems that exhibit pronounced variation in precipitation as they may be sensitive to future changes in climate.

Acknowledgements

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Table 1. *Mixing model results for determining proportionality of source waters to groundwater for Fisher Creek, 2005.*

Groundwater		Snowmelt (N=8; March)				Rain (N=23; June - Sept.)			
Sample Date & $\delta^{18}O$ Corrections*	**$\delta^{18}O$ (‰)**	**$\delta^{18}O$ (‰)**	**% of GW**	**SE**	**95% C.L.**	**$\delta^{18}O$ (‰)**	**% of GW**	**SE**	**95% C.L.**
May *(N=9)*	-14.3	-19.1				-6.2			
snow +3‰	-14.3	-16.1	82	4.3	73-91	-6.2	18	4.3	9-27
snow +4‰; rain +1.5‰	-14.3	-15.1	92	4.3	83-100	-4.7	8	4.3	0-17
Aug. *(N=5)*	-13.9	-19.1				-6.2			
snow +3‰	-13.9	-16.1	78	3.9	69-86	-6.2	22	3.9	14-31
snow +4‰; rain +1.5‰	-13.9	-15.1	88	3.9	80-97	-4.7	12	3.9	3-20

** Interpolated enrichment corrections based on data from Taylor et al., 2002 & Gat, 1998.*

Table 2. *ANOVA Results with Least Significant Differences (LSD) for temperature, conductivity, and chloride of waters from the Fisher Creek watershed by position in riparian landscape, June-October 2005.*

Riparian Position	Temperature			Conductivity			Chloride		
	ºC	S.E.	LSD	mS cm^{-1}	S.E.	LSD	ppm	S.E.	LSD
Streamwater	11.5	0.17	A	0.086	0.009	B	0.68	0.01	A
Streambed	10.4	0.12	B	0.149	0.003	A	0.66	0.01	A
Bankfull	9.84	0.07	C	0.148	0.003	A	0.63	0.01	B
Floodprone	9.76	0.07	C	0.141	0.003	A	0.62	0.01	B
Floodplain	8.67	0.10	D	0.085	0.006	B	0.64	0.01	B
Terrace	8.82	0.30	D	0.033	0.002	C	0.53	0.03	C

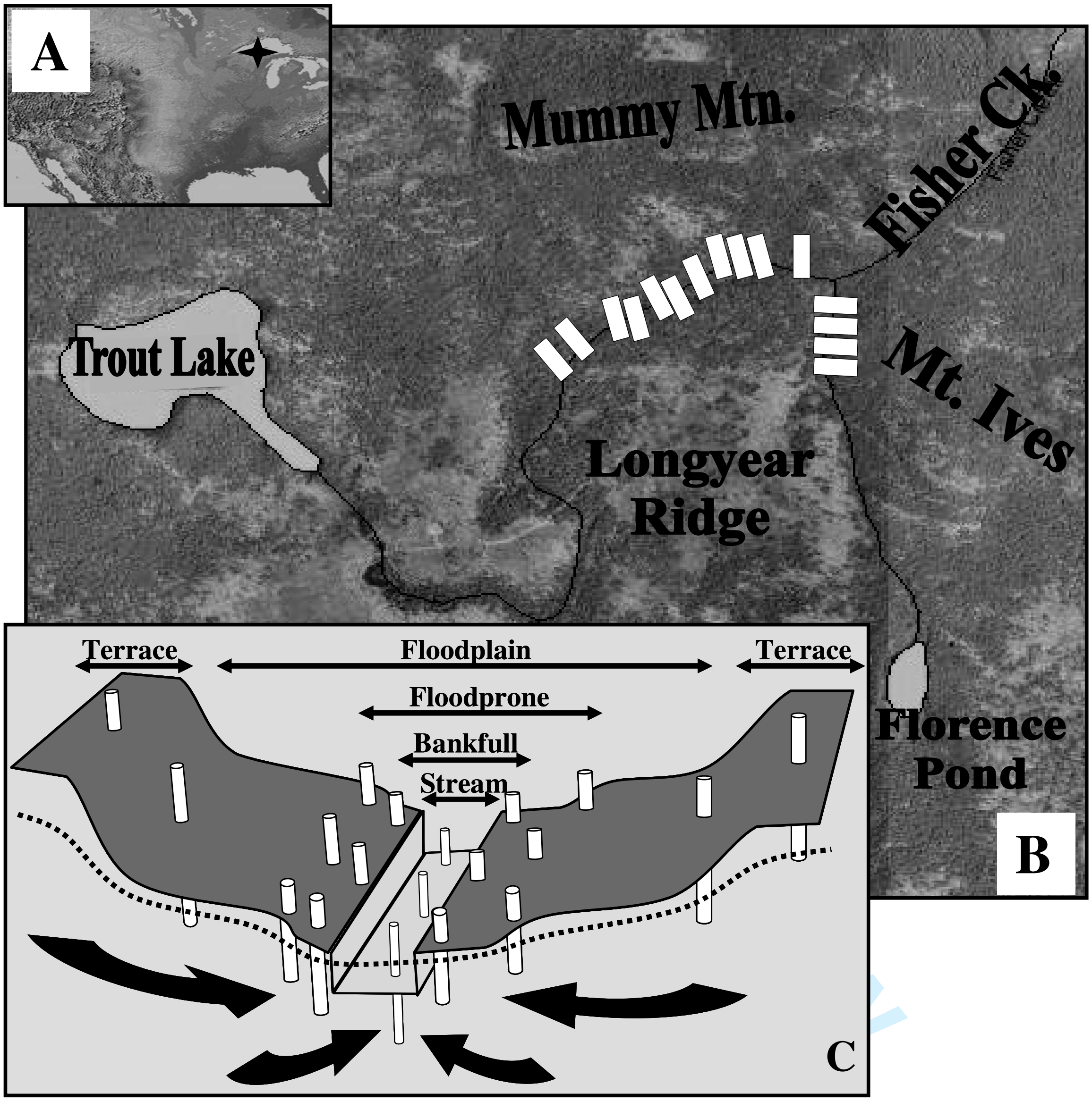
Figure 1. Location of Huron Mountains, MI, USA (A), and locations of plots (rectangles in B) along the middle section of Fisher Creek and lower section of Florence Pond's Drain, within the Huron Mountain Reserve. A reference diagram (C) is provided that describes the relative position of well and in-stream piezometer placement within the riparian plots; the dotted line represents the groundwater elevation, while bold arrows represent possible upwelling flowpaths.

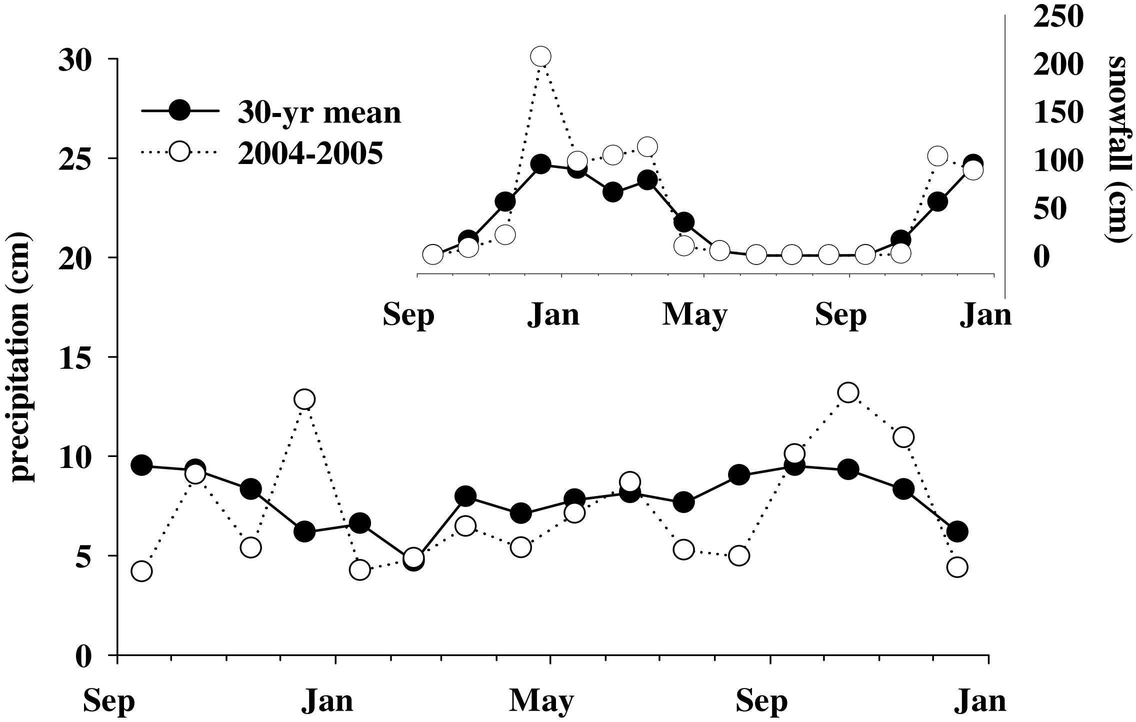
Figure 2. Monthly precipitation and snowfall data for nearby Marquette, MI.

Figure 3. Groundwater discharge of Florence Pond Drain (FPD) and Fisher Creek (FC), along with the Huron Mountain Reserve's rain precipitation inputs for 2005 (gray shaded area). Notice the difference in scale (log) for discharge between reaches.

Figure 4. Local Meteoric Water Line (LMWL; solid line) of δ^2H (‰) and $\delta^{18}O$ (‰) for all precipitation (snow and rain) collected within the Fisher Creek Watershed, 2005; along with the regressed local evaporation line (LEL; dashed line) for all ground- and surface-waters collected.

Figure 5. $\delta^{18}O$ (‰) for select waters of the Fisher Creek Watershed, 2005. The snowmelt signature was elevated +4‰ from the snowpack signature to account for enrichment processes (estimated from Talyor et al., 2002) used in mixing model analyses. Error bars are present, but hidden under most symbols.


A
Mummy Mtn.
Fisher Ck.
Trout Lake
Mt. Ives
Longyear
Ridge
Florence
Pond
B
Terrace
Floodplain
Terrace
Floodprone
Bankfull
Stream
C


30-yr mean
2004-2005
precipitation (cm)
0
5
10
15
20
25
30
Sep
Jan
May
Sep
Jan
snowfall (cm)
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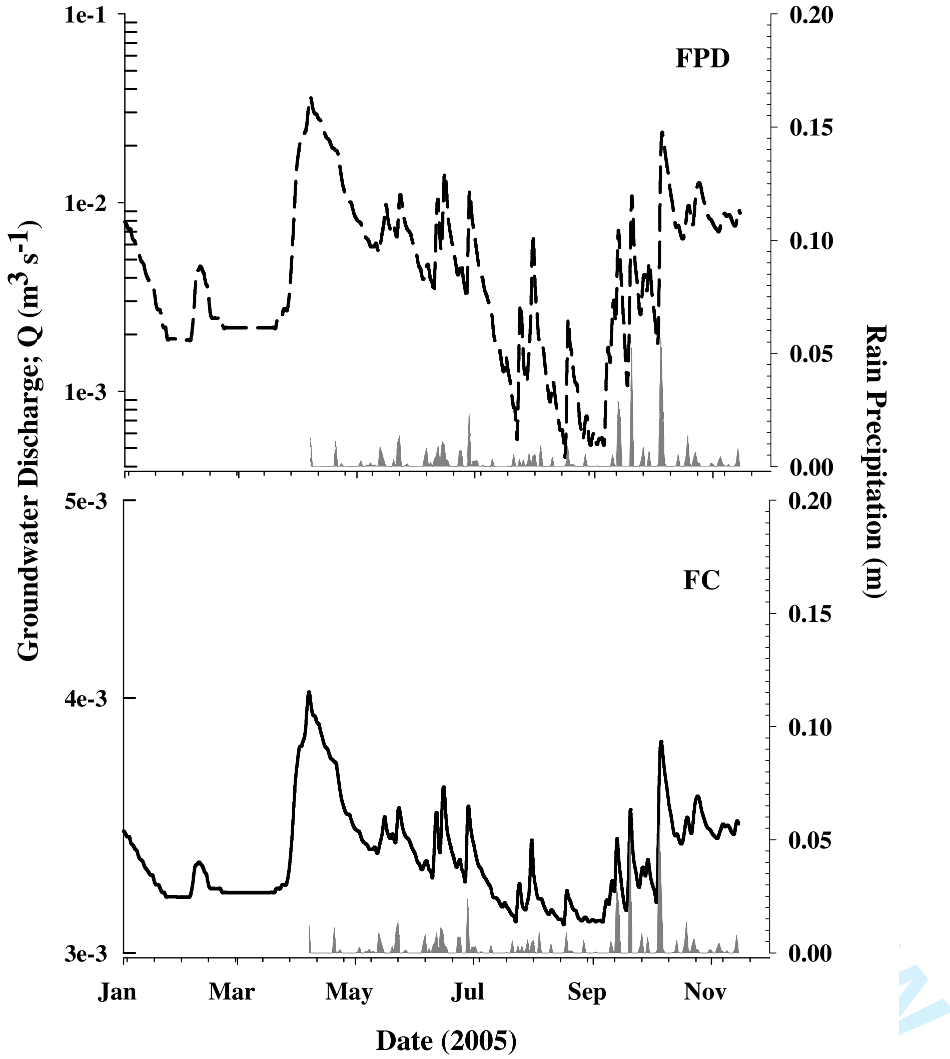
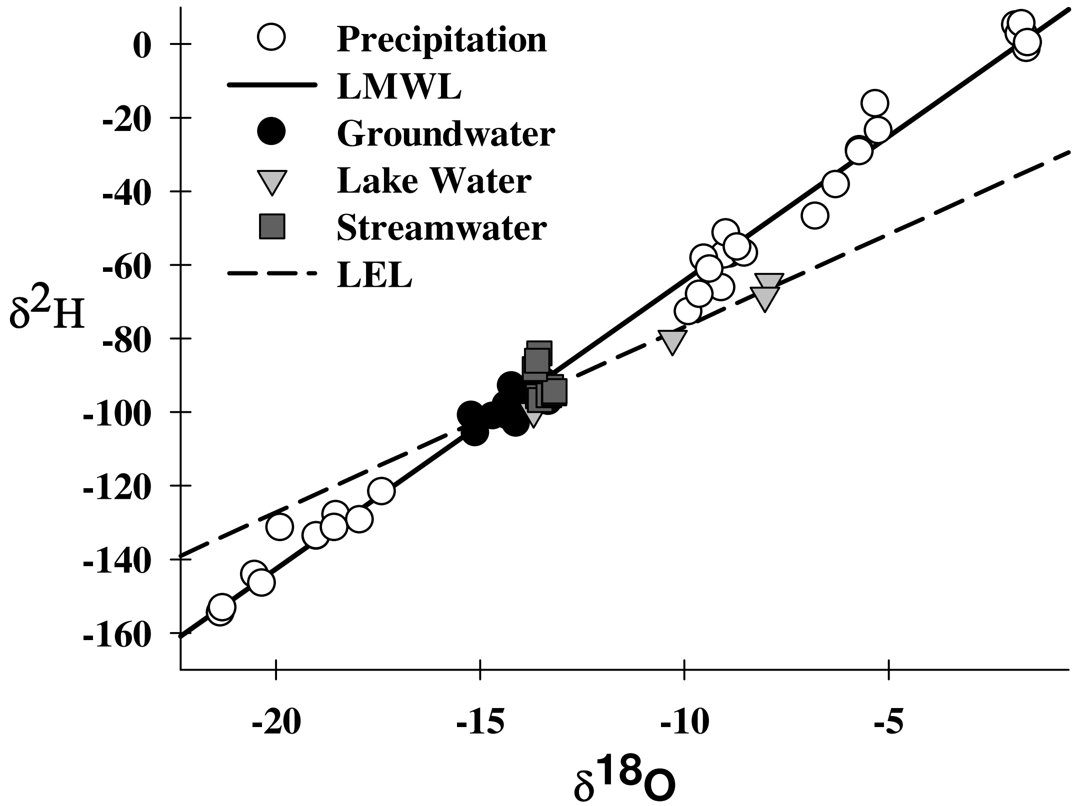
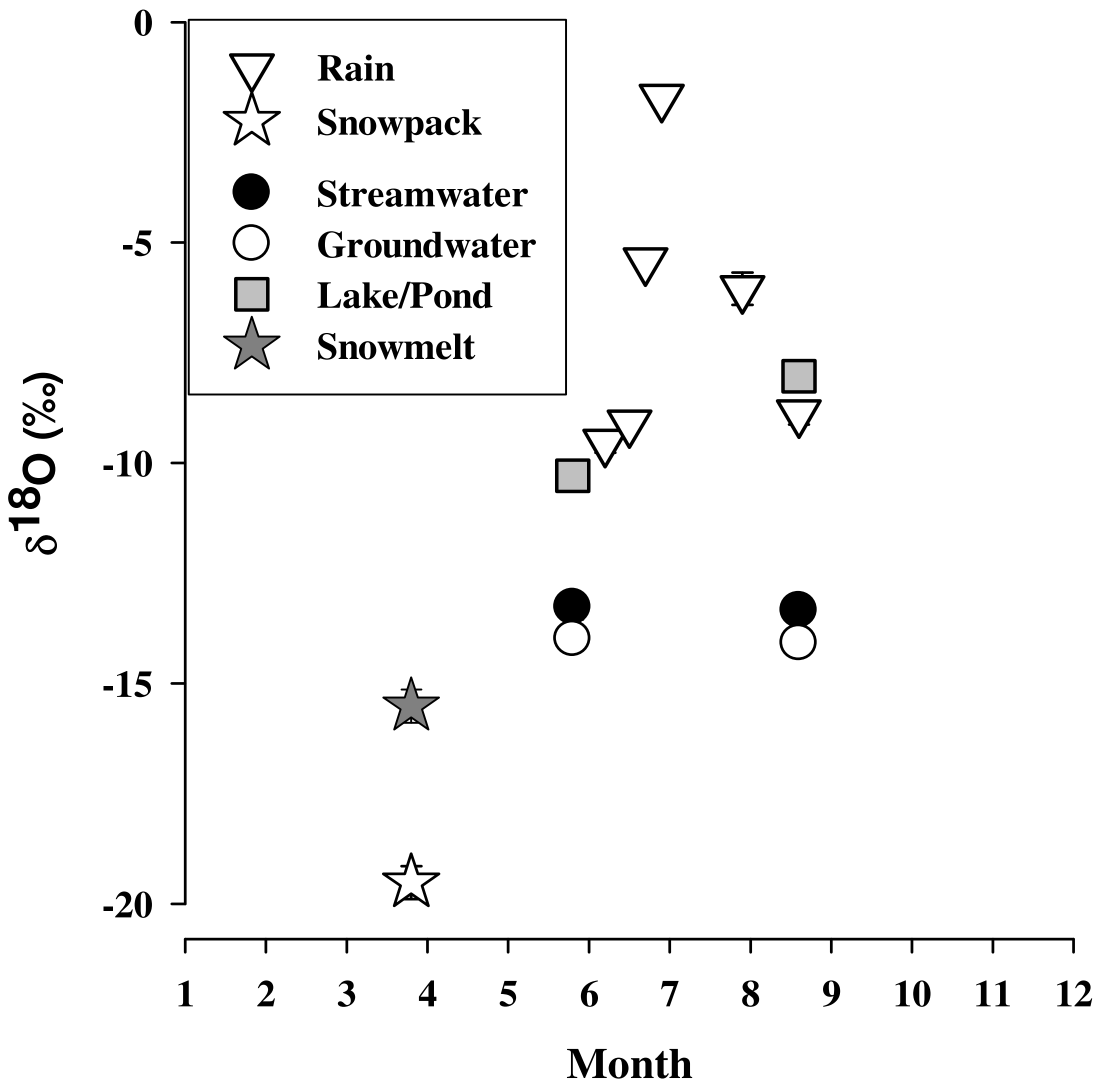
50
100
150
200
250
Sep
Jan
May
Sep
Jan


FPD
FC
Groundwater Discharge; Q (m3 s-1)
Rain Precipitation (m)
1e-1
1e-2
1e-3
5e-3
4e-3
3e-3
0.20
0.15
0.10
0.05
0.00
Jan
Mar
May
Jul
Sep
Nov
Date (2005)


Precipitation
LMWL
Groundwater
Lake Water
Streamwater
LEL
0
-20
-40
-60
-80
-100
-120
-140
-160
δ2H
-20
-15
-10
-5
δ18O


Rain
Snowpack
Streamwater
Groundwater
Lake/Pond
Snowmelt
0
-5
-10
-15
-20
δ18O (‰)
1
2
3
4
5
6
7
8
9
10
11
12
Month