ESTIMATED RESIDENCE TIME OF TWO SNOWMELT DOMINATED CATCHMENTS, BOULDER CREEK WATERSHED, COLORADO

Rory Cowie[1], Mark Williams[1], Nel Caine[1], and Robert Michel[2]

ABSTRACT

$\delta^{18}O$ and ^{3}H (tritium) measurements of precipitation and stream waters from 2002 to 2009 were used as isotopic tracers to investigate residence times in two headwater catchments within the Boulder Creek Watershed in the Front Range of Colorado. The 225--ha Green Lake 4 alpine catchment and the adjacent 664--ha Como Creek subalpine catchment are established research sites for both the Niwot Ridge Long Term Ecological Research Network and Boulder Creek Critical Zone Observatory Network. The Green Lake 4 catchment had a mean residence time of 1.12 years while the Como Creek catchment had a mean residence time of 1.8 years. Tritium levels in Green Lake 4 were consistently similar to that of incoming precipitation indicating little exponential decay and indicative of shallow flowpaths and short residence times. Como Creek tritium levels were also close to incoming precipitation during spring and summer snowmelt with elevated levels appearing during baseflow indicating some contribution of "bomb Spike" waters likely being delivered from deeper flowpaths with longer residence times. These results indicate that headwater catchments within Boulder Creek Watershed have relatively short mean groundwater residence times with the potential for older groundwater contributions during low flow conditions in the sub-alpine. (KEYWORDS: isotopic tracers, residence time, flowpaths, groundwater, Niwot Ridge)

INTRODUCTION

The hydrology of the western United States and many other semi-arid regions of the world is dominated by snowmelt runoff (Serreze et al., 1999). In general, the western United States is predicted to face warmer temperatures, more frequent and prolonged droughts, and more precipitation falling in intense storms (Doherty et al., 2009). When these factors combine we can expect to see a decrease in annual snowpack, earlier onset of snowmelt, and increased evaporation (Clow, 2010; Pielke et al., 2005). Understanding changes in streamflow generation, and surface groundwater interactions, under these changing climatic conditions will become increasingly important as water availability becomes limiting for domestic, municipal, and agricultural uses. An outstanding question for snowmelt-dominated watersheds of the western US is the role groundwater plays in streamflow generation. We know little about mountain aquifers because they commonly involve structurally complicated rocks, extreme head gradients (ground slope angles 10-40°), and dramatically fluctuating recharge driven by seasonal snow-melt (Liu et al., 2004; Manning & Caine, 2007).

Recent studies have shown that groundwater plays a much more important role in the surface hydrology of high-elevation catchments than previously thought (Liu et al., 2004; Manning & Caine, 2007). The goal of this research is to estimate the mean residence time of surface waters in snowmelt-dominated alpine and subalpine catchments of the Colorado Front Range. Residence times will be estimated using a lumped parameter transit time model parameterized using $\delta^{18}O$ in precipitation and surface waters. Additionally, tritium (^{3}H) values will be used to constrain these calculated residence times.

SITE DESCRIPTIONS AND METHODS

The upper extent of the Green Lake 4 catchment is the continental divide at an elevation slightly above 4,000 m and drains an area of 225--ha at the outlet of the lake at an elevation of 3515 m (figure 1). The catchment is dominated by steep rock walls above talus slopes and rock glaciers with a valley floor of glacially scoured bedrock. All of the catchment is above treelike with about 20% of the catchment covered by alpine vegetation growing on well developed soils, most of which is located in the valley bottom (Liu *et al*., 2004).

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[1] Department of Geography and Institute of Arctic and Alpine Research, Univ. of Colorado, Boulder, CO 80302
[2] U.S. Geological Survey, Menlo Park, California 94025

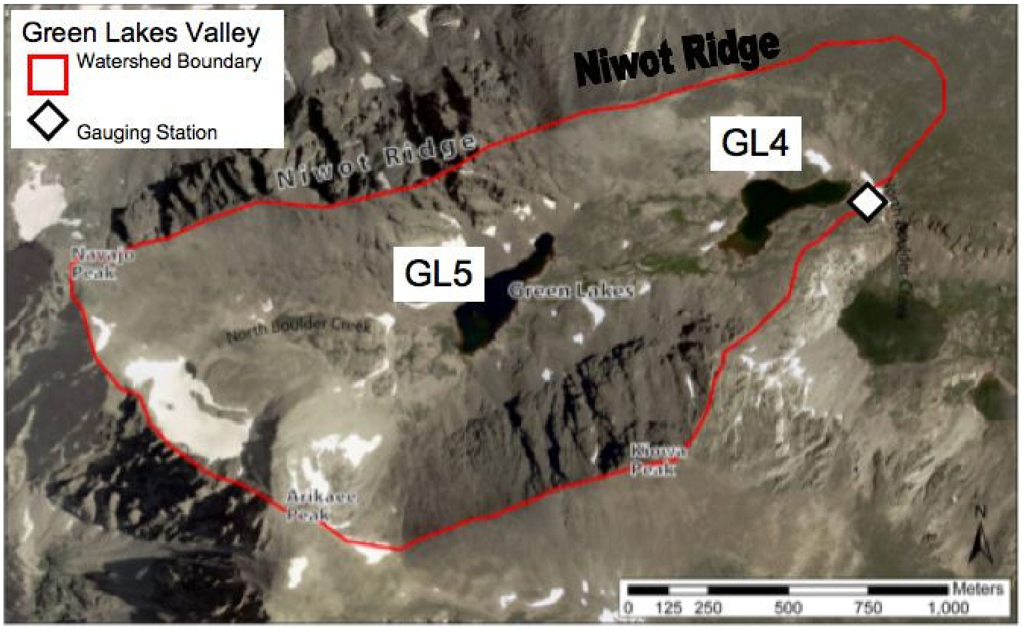

Figure 1. Aerial photograph of Green Lakes Valley with the Green Lake 4 watershed outlined. Precipitation collection occurred at the Saddle site on Niwot Ridge along the northern boundry of the watershed and surface waters were collected at the outlet gauging station on North Boulder Creek just east of Green Lake 4 (GL4).

Como Creek originates just to the North and East of Green Lakes valley on the southeast flank of Niwot Ridge approximately 8 km east of the Continental Divide and 26 km west of Boulder, CO (Figure 2). The catchment falls within the Niwot Ridge Biosphere Reserve, has an area of 664--ha, and ranges in elevation from 2900 m to 3560 m. Approximately 80% of the catchment is below treelike (Lewis & Grant, 1979b) (Figure 2). The Saddle site (3528 m) is located in alpine tundra with research infrastructure including an aerometrics wet-chemistry

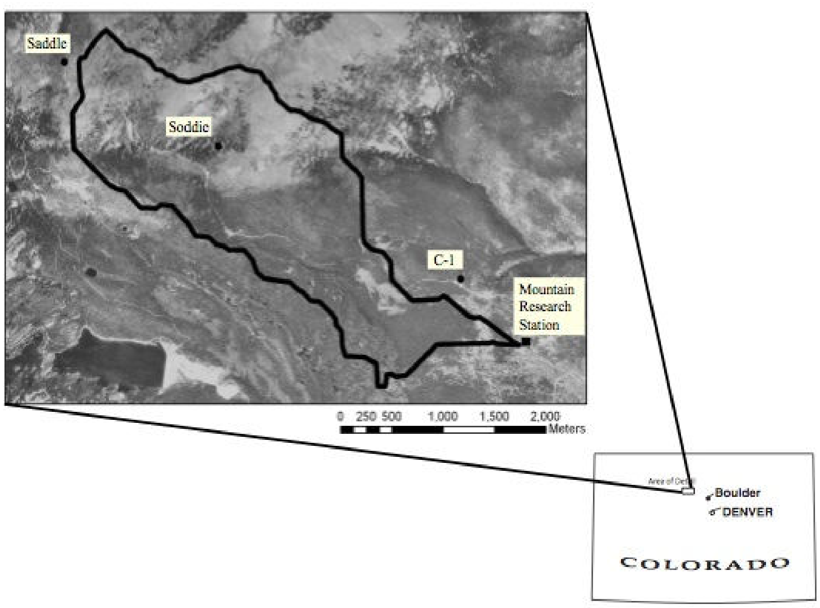

Figure 2. The Como Creek watershed which resides just below and east of the Green Lake 4 watershed in Figure 1. The Saddle sampling site for Green Lakes valley is labled along with the Soddie site where precipitation was collected for Como Creek watershed. Surface waters were collected at the outlet flume, located at the Mountain Research Satation.

precipitation collector, which is part of the National Atmospheric Deposition Program (NADP) (site CO02). The Soddie site (3345 m) is located in the treelike ecotone within the Como Creek catchment. This site also has an aerometrics wet-chemistry precipitation collector that is sampled simultaneously with the NADP sites but is not part of the official NADP program.

Precipitation and Surface Water Sampling

Precipitation samples were collected in conjunction with the Niwot Ridge LTER site participation in the National Atmospheric Deposition Program, which operates about 200 wet precipitation collectors throughout the continental United States. Samples were collected weekly and analyzed using the same protocols, so that precipitation chemistry may be compared among sites. This research analyzed splits of the NADP samples collected at the Saddle site (CO02) for precipitation entering the Green Lake 4 catchment and from splits of the NADP samples collected at the soddie site for precipitation entering the Como Creek catchment. All samples were analyzed for δ^{18}O and δD from 2002 to 2009. Current levels of ^{3}H (tritium) in snow and rain were obtained from previous research conducted in Leadville, CO (Wireman, 2006).

Surface water samples for isotopic analyses were collected weekly from 2002 to 2009 as grab samples from gauging sites at the Green Lake 4 outlet and Como Creek as part of the Niwot Ridge LTER program and Boulder Creek CZO. Sampling procedure followed the protocols presented in Williams et al. (2006). Water samples for isotopic analysis were collected un-filtered in cleaned, 25-mL, borosilicate bottles with no-headspace lids to avoid any evaporation or fractionation. Samples were collected about 10-cm below the water surface in turbulent areas where the water column was well-mixed.

Analytical Methods

All samples were analyzed at the Kiowa wet chemistry laboratory operated by the Niwot Ridge LTER program, following the protocols presented in Williams et al. (2006). Samples were analyzed for δD and δ^{18}O using a Picarro L1102-i Isotopic Liquid Water Analyzer developed by Picarro Incorporated. The analyzer is based on Picarro's unique Wavelength- Scanned Cavity Ring Down Spectroscopy (WS-CRDS), which is a time-based measurement using near-infrared laser to quantify spectral features of molecules in a gas contained in an optical measurement cavity. All isotopic results were measured relative to the Vienna Standard Mean Ocean Water (V-SMOW) standard and given in units per mil (‰). A select set of surface and groundwater samples were also collected as grab samples in 1L HDPE bottles and analyzed for tritium at the USGS Menlo Park Stable Isotope and Tritium Lab. Tritium concentrations were measured using a distillation and electrolysis technique with an analytical precision of +/- 0.3 TU (Tritium Units). A tritium unit is defined as 1 tritium atom for every 1×10^{18} hydrogen atoms making up the water molecules in a given sample.

Residence Times

Average residence time for subsurface flow can be calculated by comparing the smoothing of the δ^{18}O input (precipitation) and output (streamflow) using a convolution algorithm (Maloszewski et al., 1983; Pearce et al., 1986). The time series of incoming precipitation δ^{18}O values can be approximated as a sinusoidal function:

$$\delta out\,(t) = A\,sin(wt) + M$$

Where A is the amplitude of δ^{18}O variation in precipitation, w is the period, and M is the mean of the $\delta^{18}O$ variation. Similarly the isotopic variation of streamflow can be characterized by:

$$\delta out\,(t) = B\,sin(wt + \varphi) + M$$

Where B is the amplitude of δ^{18}O variation in streamflow, and φ is the phase shift. By assuming a well mixed and exponential flow system, and knowing the amplitude of variation in precipitation and surface waters, the convolution integral can be solved for mean residence time. This isotope-based age estimate includes the groundwater age, mixing, and transit time in the unsaturated zone (Plummer et al., (2001)). The convolution also assumes an exponential mixing model, which was introduced to hydrology by Eriksson (1958) who made the assumption that the distribution of transit times of water in the outflow of a system is exponential and corresponds to a probable situation of permeability decreasing with aquifer depth. Given the structural complexity and general lack of detailed investigations of mountain aquifers it is difficult to confirm or reject this assumption but it is recognized that deviations from this situation, such as preferential flow through fractures, are not specifically accounted for when using the convolution algorithm.

Additionally, the residence time estimates can be constrained by measuring the amount of tritium, a radioactive isotope of hydrogen, found in surface and groundwater. Tritium enters the groundwater system through recharge waters derived from precipitation. An analysis of tritium concentrations in groundwater and surface water samples can provide information concerning the time since the water was isolated from the surface (i.e. recharge date). The activity of tritium greatly exceeded natural levels due to above-ground nuclear weapons testing in the 1950's and early 1960's. Tritium is a radioactive atom with a half-life of 12.33 years (Maloszewski et al., 1983) and thus is an ideal tracer for identifying relatively young groundwater. Since tritium is a part of the water molecule it does not undergo any substantial chemical reactions once the water has entered the subsurface and thus is an ideal hydrological tracer (Rose, 1996).

RESULTS

Residence Times

Table 1 shows the yearly amplitudes of the $\delta^{18}O$ values measured in incoming precipitation and outgoing surface waters, along with the corresponding residence time calculations for Green Lake 4 and Como Creek watersheds. The Saddle precipitation and Soddie precipitation show similar amplitudes in $\delta^{18}O$ values with the Saddle having an annual average range of 23.65 ‰ around a volume weighted mean of -18.89 ‰ and the Soddie having an annual range of 24.65 ‰ around a volume weighted mean of -18.67 ‰. Green Lake 4 surface waters had an average range of 3.3‰ around a weighted mean of -15.5 ‰, while Como Creek surface waters had an average range of 2.17 ‰ around a weighted mean of -16.88 ‰. Figure 3 show time series data from 2002 to 2009 that details the variations in the amplitude of precipitation compared to the dampened amplitude in surface waters for Green Lake 4 and Como Creek. The calculated residence times using each year's data for Green Lake 4 ranged from 1.0 to 1.9 years. Using the average amplitudes from all available data (2002-2009) the mean residence time for Green Lake 4 is 1.12 years (Table 1). For Como Creek residence times were calculated using data from each individual year (2002-2009) and using the averaged amplitudes for years 2002-2004, 2002-2006, and 2002-2009 to test the sensitivity of the residence time calculations to the length of the data set. Residence times calculated from individual years of data ranged from 1.11 to 2.41 years while residence times using 3, 5, and 7 years of data only ranged from 1.72 to 1.88 years. The mean residence time for Como Creek calculated from all data was 1.8 years (Table 1).

Table 1: Annual $\delta^{18}O$ values and corresponding residence time estimates for Green Lake 4 and Como Creek.

Green Lake 4				**Como Creek**			
Year	Precip. Range ($\delta^{18}O$ ‰)	Stream Range ($\delta^{18}O$ ‰)	Residence time (Years)	Year	Precip. Range ($\delta^{18}O$ ‰)	Stream Range ($\delta^{18}O$ ‰)	Residence time (Years)
2002	27.8	2.93	1.50	2002	22.6	2.60	1.38
2003	26.9	4.22	1.00	2003	28.5	1.99	2.28
2004	26.8	4.11	1.02	2004	25.8	1.92	2.14
2005	20.4	2.16	1.49	2005	27.5	2.13	2.05
2006	16.9	3.61	0.72	2006	19.4	2.77	1.11
2007	23.7	3.45	1.08	2007	22.0	1.90	1.84
2008	20.2	3.87	1.47	2008	23.0	2.16	1.69
2009	26.3	2.18	1.90	2009	28.1	1.85	2.41
2002-2009	32.3	3.32	**1.12**	2002-2004	25.6	2.17	1.88
				2002-2006	24.8	2.28	1.72
				2002-2009	24.6	2.17	**1.80**

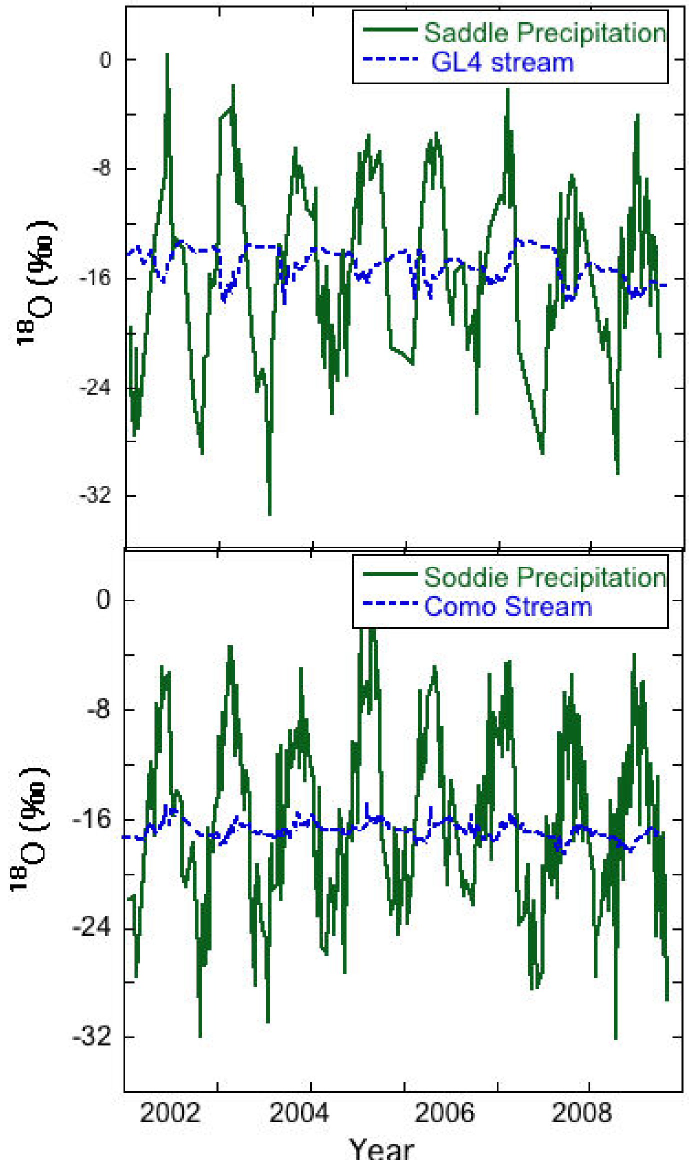

Figure 3: Time series of $\delta^{18}O$ values in precipitation and surface waters for Green Lake 4 and Como Creek Watersheds.

Tritium Analysis

Figure 4 shows the levels of tritium found in surface waters throughout 2009. Also plotted are the estimated current levels of atmospheric tritium entering the catchments through precipitation based on values from a previous study near Leadville, Colorado in 2006 (Wireman, 2006). The incoming precipitation is estimated to be between a low of 10 TU in snow and a high of 11.5 TU during summer rains. During mid-winter baseflow conditions Como Creek tritium levels are at a high of 13.6 TU and then return to levels close to incoming precipitation during the spring and summer snowmelt runoff season. The surface waters at Green Lake 4 show little change in tritium concentration and remains bracketed by the estimated incoming amounts in precipitation throughout the entire year.

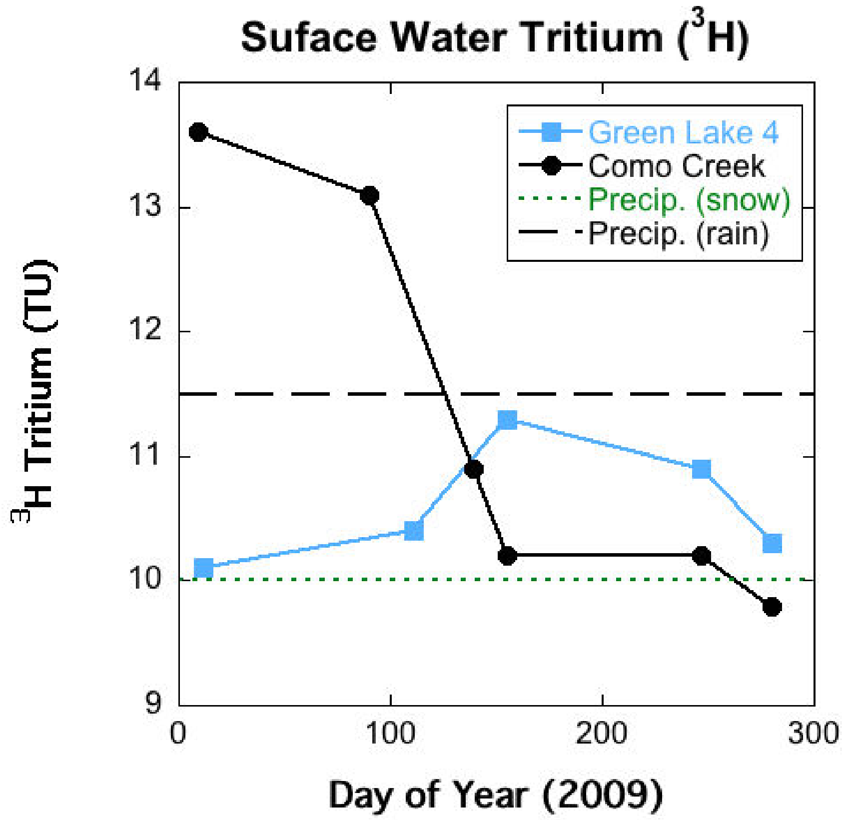

Figure 4: Tritium values in 2009 for Green Lake 4 and Como Creek plotted in reference to estimated current levels in incoming precipitation.

DISCUSSION

Our estimates of residence times are similar in magnitude to that of other mountain catchments using the same technique, with Plummer et al. (2001) reporting 5 years in the Appalachians and McGuire et al. (2005) reporting 0.8 - 3.3 years in the Cascade Mountains. For Green Lakes 4 the relatively short residence time of 1.12 years suggests that the alpine basin do have surface-groundwater interactions but that most of the water is moving through the shallow subsurface and then quickly returning to surface flows. The tritium results for Green lake 4 (Figure 4) also suggest that all water reacting with the sub-surface is traveling along shallow flowpaths with relatively short residence times allowing little time for exponential decay thus producing surface water values very similar to those found in present day precipitation.

For Como Creek, with a slightly longer average residence time of 1.8 years, it could be suggested that the greater the percentage of subalpine area leads to increased residence time and larger groundwater reservoirs when compared to the adjacent alpine catchment. The greater overall residence time may actually be the result of the mixing of predominately young sub-surface water with some amount of significantly older groundwater. This notion is supported by the tritium data that shows elevated levels of tritium during baseflow conditions in Como Creek (figure 4). This result suggests that during baseflow conditions some portion of groundwater contribution is coming from deeper flowpaths with longer residence times and thus containing water that was recharged from bomb spike precipitation containing tritium levels above those found in present day precipitation. It is important to remember that the tritium values represent an average value for all water contributing to streamflow. Therefore the results do not provide a quantitative analysis of the age of groundwater but do provide confidence in the age estimates generated using the lumped parameter transit time approach. Overall the tritium values do constrain the convolution results and suggest that both the alpine and sub-alpine headwater catchments are dominated by relatively young groundwater that follows shallow sub-surface flowpaths. These results also suggest that the lower elevation catchment within the sub-alpine ecosystems may have thicker soils and deeper weathered profiles creating potentially larger groundwater reservoirs, and longer sub-surface residence times than alpine catchments.

In contrast to Campbell et al. (1995), who found that snowmelt infiltration exceeded groundwater supplies and shallow groundwater had short residence times in the Loch Valle watershed in the Northern Front range of Colorado, Como Creek shows larger groundwater reservoirs and longer subsurface residence times. This difference is likely indicative of geomorphic differences between basins and greater soil development within the Como Creek catchment. Also important to note is that the area of the Como Creek watershed (664--ha) is nearly 3 times that of Green Lake 4 watershed (232--ha), which may lead to longer flow paths and increased residence times. However, the recent findings of Rogers et al. (2005) and McGlynn et al. (2003) both suggest that landscape organization rather than catchment area plays a more dominant role as a first-order control on catchment residence times.

Additional geophysical research currently being conducted by the Boulder Creek Critical Zone Observatory will help to better quantify the geomorphic structure and subsurface composition of these headwater catchments. Combining the structural information of the critical zone with the hydrologic and geochemical data will ultimately create a more robust understanding of the flowpaths and residence times of sub-surface water across these headwater catchments. Greater knowledge of sub-surface hydrological processes are necessary because current modeling efforts to predict future hydrologic changes have focused on spatial changes in snow cover and have neglected to address changes in the subsurface hydrological component (Bavay et al., 2009). Ultimately, understanding surface-groundwater interactions under current hydrologic conditions will enhance our ability to predict how future natural and anthropogenic perturbations will impact sub-surface water resources in headwater catchments.

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