Journal of Hydrology 521 (2015) 482–497

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Characterization of snowmelt flux and groundwater storage in an alpine headwater basin

Jaime L. Hood [a,b], Masaki Hayashi [a,*]

[a] Department of Geoscience, University of Calgary, Calgary, Alberta, Canada
[b] Crux Consulting, Canmore, Alberta, Canada

ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form 15 December 2014
Accepted 16 December 2014
Available online 27 December 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief

Keywords:
Mountain hydrology
Alpine aquifer
Talus
Proglacial moraine
Snow energy balance

SUMMARY

Snowmelt recharge of groundwater and its delayed release is considered an important mechanism for sustaining the baseflow of alpine streams, but relatively little is known about groundwater storage capacity in alpine regions. The goal of this study is to quantify the storage capacity and the timing of recharge and discharge in a partially glaciated, first-order watershed in the Canadian Rockies using detailed measurements of hydrological input and output fluxes. We computed daily input fluxes from direct measurements of snow accumulation at 1300 points within the watershed near the peak accumulation date, time-lapse photography during the melt season, and high-resolution (25 m) snowmelt simulation using a field-validated snowmelt energy balance model; and estimated the amount and timing of water storage within the watershed from the water balance. The peak storage amount was on the order of 60–100 mm averaged over the watershed, which was relatively small compared to the pre-melt snow water equivalent in the watershed (500–640 mm), but significant in comparison to the fall and winter baseflow ($<0.5\ \mathrm{mm\ d^{-1}}$) sustaining the aquatic ecosystem. This is an important finding demonstrating the critical role of groundwater storage and delayed release in alpine environments, which generally have little soil water storage.

1. Introduction

Mountainous regions are an important source of water for downstream regions. The hydrologic regime of mountains is dominated by seasonal and inter-annual storage of water in the snowpack and in glaciers, which is slowly released to rivers throughout the melt season (Viviroli et al., 2007). These processes are subject to changes resulting from climate variability (Barnett et al., 2005; Stewart et al., 2005), and these changes may affect the water supply of downstream communities (Finger et al., 2012), as well as the conditions of alpine stream habitats (Brown, 2006). Despite the importance of understanding alpine hydrological processes (Bales et al., 2006), field-based research has been limited due to difficulties with access and instrumentation in alpine environments and research is often focused on one aspect of the hydrologic cycle, such as glacier mass balance or snow accumulation and melt. Comprehensive field studies that address all components of the hydrologic cycle, including groundwater, are still relatively rare in alpine environments.

Recent studies have found that groundwater storage and flow in alpine regions may be more important than previously thought. Analysis of daily precipitation and discharge records in a Himalayan region showed that deep groundwater contributes as much as 20% to stream flow (Andermann et al., 2012). Studies in the Colorado Rocky Mountains in the USA have ascertained that subsurface flows contributed as much as 60% of water, even during early snowmelt times (Liu et al., 2004), with groundwater being important at a range of watershed scales (Frisbee et al., 2011). A study in the Sierra Nevada in the USA using chemical and isotopic tracers showed that the majority of flow in a mountain headwater stream was provided by shallow groundwater sources (Shaw et al., 2014). Understanding the storage and pathways of groundwater will help us understand how groundwater may or may not buffer the effects of climate variability on mountain rivers (Tague et al., 2008).

Conditions of alpine aquifers have not been well documented, and will likely vary from watershed to watershed. Factors that play a role in subsurface water storage include soil depth and distribution (Soulsby et al., 2006), sub-glacial and pro-glacial aquifers (Ward et al., 1999), and geological (Katsuyama et al., 2010) and

---

* Corresponding author at: Department of Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada. Tel.: +1 (403)220 2794; fax: +1 (403)284 0074.

E-mail address: hayashi@ucalgary.ca (M. Hayashi).

http://dx.doi.org/10.1016/j.jhydrol.2014.12.041
0022-1694/

geomorphological characteristics of the watershed (Zecharias and Brutsaert, 1988; Fujimoto et al., 2008). Hydrological characteristics of overburden materials such as talus and moraine have been evaluated in several different environments (Davinroy, 2000; Caballero et al., 2002; Baraer et al., 2009; Muir et al., 2011; Langston et al., 2013). Clow et al. (2003) concluded that talus slopes in a Colorado Front Range watershed were capable of storing the equivalent to the annual total discharge in the study watershed. However, despite large storage potential, water is quickly transmitted through talus slopes and some studies have determined that baseflow is likely sustained from water transmitted through fractured bedrock (Clow and Sueker, 2000; Liu et al., 2004). Analysis of stream chemistry indicates that residence times in alpine meadows are much longer than in talus (Clow and Sueker, 2000). Yet other studies have concluded that bedrock storage and transmission likely dominates subsurface flow (Katsuyama et al., 2010).

Tague and Grant (2009) note a scarcity of data on drainage efficiencies and groundwater flow parameters, which makes it difficult to represent groundwater processes in hydrological models of alpine watersheds (Flerchinger et al., 1996; Fang et al., 2013). Given the heterogeneous alpine environment, it is important to examine catchment organization and structure (McDonnell et al., 2007) across the diverseness of alpine watersheds in order to determine the key organizational variables that control subsurface flow. The insights gained from small alpine research watersheds are a necessary prerequisite to understanding how processes upscale to larger regions.

This study investigates the role of groundwater storage and release in an alpine watershed in the Canadian Rockies. The key study objectives are: (1) quantify the groundwater storage capacity from the detailed water balance of the watershed, (2) assess the importance of groundwater in regulating peak flows and sustaining baseflow, and (3) examine the sensitivity of snowmelt flux calculations to the spatial resolution of input data. The last objective is important for the other study objectives, as the accuracy of groundwater storage estimates is highly dependent on the accuracy of input flux estimates.

2. Study site

The study was conducted in the 4.7-km^2 Opabin watershed, located within the Lake O'Hara watershed (51.35°N, 116.33°W) in Yoho National Park, British Columbia, Canada (Fig. 1). The Opabin watershed was fully glaciated during the last glacial maximum (Osborn and Luckman, 1988) and still has a small pocket glacier (Opabin Glacier, 0.17 km^2) that has an extensive pro-glacial moraine. The terrain is comprised of exposed bedrock (53%), talus (11%), moraine (17%), sub-alpine vegetation (14%), lakes and tarns (1%) and glacier (4%) (Fig. 1). The Opabin watershed has rugged topography with elevations ranging from 2000 to 3500 m. Bedrock in this region is composed primarily of thickly bedded quartzite and quartzose sandstone, separated by thin layers of siltstone, sandstone and grey shale of the Cambrian Gog Group. Carbonate rocks of Mt. Whyte, Cathedral, Stephen and Eldon Formations are present in the moraine and talus material (Price et al., 1980; Lickorish and Simony, 1995) which is present in the upper elevations of mountain peaks in the area. Mean annual precipitation in the Opabin watershed is 1000–1200 mm depending on the elevation, and mean monthly temperature is −9.6 °C in January and 10.4 °C in July, with daily average temperatures ranging from −31 to 18 °C (Hood, 2013). Most of the Opabin watershed is snow-covered for 9–10 months of the year.

Previous studies in the Opabin watershed have delineated an extensive groundwater flow system below the Opabin moraine (Langston et al., 2011; McClymont et al., 2012), which discharges at a large spring complex located at the toe of the moraine (Roy and Hayashi, 2009; McClymont et al., 2011) (LS in Fig. 1). The spring complex provides the majority (70–80%) of water to the Opabin Creek, which flows year around. Talus deposits at the base of cliffs also serve as aquifers (Muir et al., 2011). These aquifers provide water input to the alpine meadows that are typically located in bedrock depressions down-gradient from talus slopes (McClymont et al., 2010). Derived from weathering-resistant quartzite bedrock, moraine and talus deposits consist of coarse and blocky materials ranging from boulders to sands with hydraulic conductivity in the order of 10^{-4} to 10^{-3} m s^{-1} for moraine (Langston et al., 2013) and 10^{-2} m s^{-1} for talus (Muir et al., 2011).

3. Field methods

The primary objective of this study was to determine the groundwater storage capacity of the watershed from the water balance by measuring or estimating all major water balance components. Snowmelt is the largest term in the water balance and it is highly variable in the complex alpine terrain, both spatially and temporally. Therefore, a major effort was made to characterize the spatial and temporal distribution of snowmelt flux using various field and modelling techniques. The details of field methods are described in this section and the modelling approaches are described in the next section. Data collection occurred from April to October of 2007 and 2008. Limited additional data from 2005 and 2006 were used to supplement the 2007–2008 data for model validation purposes.

3.1. Meteorological measurements

Two semi-permanent automatic weather stations (AWS) are located in the Lake O'Hara watershed at 2230 m (Opabin) (Fig. 1) and at 2000 m (O'Hara, 650 m northwest of stream gauging station G5 in Fig. 1). The Opabin AWS is equipped with a four-component radiometer (Kipp & Zonen, CNR-1), temperature and relative humidity sensor (Vaisala, HMP45), snow depth sensor (Campbell Scientific, SR50), anemometer (RM Young, 05103), weighing precipitation gauge with an Alter shield (Geonor, T200B) and a tipping bucket rain gauge (Hydrological Services, CS700). Solid precipitation data were corrected for wind-induced catch deficiency using the method of Smith (2007, Eq. 4). The O'Hara AWS has the same instrumentation with the exception that the four component radiometer is replaced with a net radiometer (Kipp & Zonen, NR-Lite). At the Opabin AWS, measurements were taken every 5 min and recorded (averaged or summed) every 30 min, and data at the O'Hara AWS were averaged or summed hourly. Three other temporary AWS (Babylon, Tarn, Glacier in Fig. 1) equipped with four-component radiometers (Kipp & Zonen, CNR-1) were deployed during the summer of 2008 to validate radiation models (see Appendix A and B). The four-component radiometers were cross-referenced to each other over 14-day periods to check and correct for instrumental bias, which was of small magnitude (<3.6%).

The AWS data, in conjunction with four temperature and relative humidity sensors (Veriteq, VL2000) placed along an elevation transect in the Opabin watershed (Fig. 1) were used to establish temperature and relative humidity lapse rates, based on monthly mean temperature and relative humidity at each data site derived over the period of 2005–2008. A precipitation multiplier with elevation was calculated from the difference between the two weighing precipitation gauges at O'Hara and Opabin AWS, again over the period of 2005–2008.