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Bedrock infiltration estimates from a catchment water storage-based modeling approach in the rain snow transition zone

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SUMMARY

Estimates of bedrock infiltration from mountain catchments in the western U.S. are essential to water resource managers because they provide an estimate of mountain block recharge to regional aquifers. On smaller scales, bedrock infiltration is an important term in water mass balance studies, which attempt to estimate hydrologic states and fluxes in watersheds with fractured or transmissive bedrock. We estimate the a daily time series of bedrock infiltration in a small catchment in the rain snow transition zone in southwest Idaho, using the difference between measured stream discharge and modeled soil drainage. The accuracy of spatial patterns in soil water storage are optimized, rather than the more common approach of minimizing error in integrated quantities such as streamflow. Bedrock infiltration is estimated to be 289 mm ± 50 mm for the 2011 water year, which is 34% ± 12% of the precipitation (95% confidence). Soils on the southwest facing slope drain more often throughout the snow season, but the northeast facing slope contributes more total soil drainage for the water year. Peaks in catchment soil drainage and bedrock infiltration coincide with rain on snow events.

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1. Introduction

Bedrock infiltration (BI) from mountain catchments, defined as water that leaves the catchment boundaries through subsurface drainage, is important from both catchment and groundwater perspectives. The typically thin soils in mountain catchments transmit water to the soil bedrock interface where water can travel laterally towards a stream or valley bottom, or infiltrate into underlying bedrock. From the catchment perspective, BI can be an important loss term in the water balance (Bales et al., 2011; Flerchinger and Cooley, 2000; Graham et al., 2010; Han et al., 2012; Kelleners et al., 2010). Small headwater catchments have been reported to lose up to 40% of annual precipitation to BI (Aishlin and McNamara, 2011), which can discharge down-gradient within larger catchments (Katsuyama et al., 2010) or enter regional groundwater systems (Thoma et al., 2011). The interaction of catchment surface water with bedrock groundwater can have significant controls on rainfall–runoff relationships (Katsuyama et al., 2010; Tromp-van Meerveld et al., 2007). From the groundwater perspective, BI can be an important source of mountain block recharge (Hogan et al., 2004; Thoma et al., 2011; Wilson and Guan, 2004). For example, most of the groundwater recharge in the Great Basin region occurs in the mountainous divides between basins (Flint et al., 2004; Hevesi et al., 2003; Scanlon et al., 2006). However, estimation of BI is difficult and hydrologic modeling studies often ignore this flux.

Quantifying the flux of water across the soil bedrock interface is challenging for many reasons. The hydraulic properties of bedrock are generally unknown, heterogeneous, and difficult to measure. The heterogeneity of overlying soils create variable propagation and storage of water in the soil profile even under uniform rainfall, and the soil bedrock interface may not be a sharp transition, but can be complicated by thick, variably weathered materials (e.g.,

Abbreviations: BI, bedrock infiltration; ROS, rain on snow; DR, drainage to the soil bedrock interface; SWI, surface water inputs; NE, northeast-facing; SW, southwest-facing.

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Notation

Units

l	length
t	time
m	mass
K	temperature
e	energy
A	catchment area (l^2)
A_p	area of polygon p (l^2)
$ATran$	actual transpiration (l)
BI_{WC}	whole catchment bedrock infiltration (l)
C	LAI shape factor 1 (unitless)
D	LAI shape factor 2 (unitless)
DOY	day of year at time t (unitless)
DR	drainage from the bottom of a soil layer (l)
DR_p	drainage to the soil bedrock interface from polygon p (l)
DR_t	whole catchment drainage to the soil bedrock interface at time t (l)
$DR_{x,y}$	drainage to the soil bedrock interface at location x, y at time t (l)
dS_t	whole catchment change is soil water storage at time t (l)
E	evaporation (l)
E_{el}	energy limited soil evaporation (l)
ET_t	whole catchment evapotranspiration at time t (l)
FC_i	field capacity of soil layer i ($l^3\,l^{-3}$)
GS_{pk}	day of year of peak growing season when LAI_{max} occurs (unitless)
GS_{st}	growing season start day of year (unitless)
LAI_{max}	maximum leaf area index ($l^2\,l^{-2}$)
LAI_t	leaf area index at time t ($l^2\,l^{-2}$)
$maxratio$	water availability of the wettest soil layer (unitless)
p	index for polygon summation (unitless)
P	total number of Thiessen Polygons in the catchment (unitless)
PEL	plant extraction limit ($l^3\,l^{-3}$)
PET	potential evapotranspiration (l)
$PTran$	potential transpiration (l)
Q_t	stream discharge at time t (l)
R_n	average daily net radiation (e $l^{-2}\,t^{-1}$)
RDK	soil water redistribution constant (t^{-1})
RDT	soil water redistribution time (t)
S_t	soil water storage (l)
SWI_t	whole catchment surface water input at time t (l)
T	time duration to be integrated over (t)
tb	beginning time step of summation (unitless)
te	ending time step of summation (unitless)
t_{swi}	time from last water input event (unitless)
$\varDelta$	slope of the saturated vapor pressure vs. air temperature line (m $l^{-1}\,t^{-2}\,K^{-1}$)
Δt	time interval for soil water balance calculation (t)
Δz	soil layer thickness (l)
z_i	thickness of soil layer i (l)
γ	psychrometric constant (m $l^{-1}\,t^{-2}\,K^{-1}$)
λ_v	latent heat of vaporization (e m^{-1})
θ	volumetric soil water content at the end of the time interval Δt ($l^3\,l^{-3}$)
θ_i	volumetric soil water content of soil layer i ($l^3\,l^{-3}$)
θ_0	initial volumetric soil water content at the time interval Δt ($l^3\,l^{-3}$)

saprolite). Although unique conditions may exist in some locations to allow direct measurement of BI, such as caves underlying catchments in karst terrain (Sheffer et al., 2011; Taucer et al., 2008), direct measurements are rarely possible due to the diffuse and inaccessible location of BI occurrence. Methods to quantify BI are generally indirect (Sammis et al., 1982) and include residual estimates from detailed mass balance studies of water or conservative solutes (Aishlin and McNamara, 2011; Graham et al., 2010), numerical modeling at a lower soil boundary (Dijksma et al., 2011; Guan et al., 2010; Kelleners et al., 2009, 2010; Selle et al., 2011; Wang et al., 2011), and using storage–discharge relationships (Ajami et al., 2011).

Annual mass balance approaches calculate BI as a residual, which includes the additive errors of all other mass balance components. Generally, these approaches cannot be used to assess the sub-annual timing of BI. Solute balance approaches also require multiple years of data to overcome inherent assumptions, and even then may only be correct when averaging over the period of record (Aishlin and McNamara, 2011; Wood, 1999). Numerical modeling of BI is hindered by a general lack of knowledge of the transmissive properties of underlying bedrock, which makes model parameterization challenging (Nolan et al., 2007; Sorensen et al., 2014; Sutanudjaja et al., 2011). Storage–discharge relationships (Brutsaert and Nieber, 1977; Kirchner, 2009) have been used to assess mountain block recharge by recognizing that changes in groundwater storage are related to both streamflow and recharge (Ajami et al., 2011). Inherent in this approach is the assumption that streamflow incorporates all drainage from catchment groundwater storage. In "leaky" catchments, however, streamflow does not represent all drainage. Rather, drainage is the sum of streamflow and BI. When BI is significant, traditional storage–discharge methods are not appropriate.

While many studies have estimated the magnitude of annual BI over catchments or regions (Jie et al., 2011; Ragab et al., 1997; Simmers, 1998; Van der Lee and Gehrels, 1997), few studies have estimated the timing of BI on sub-annual timescales. The timing and magnitude of BI is complicated by rain on snow (ROS) events in the climatically sensitive rain snow transition zones of the mountainous western U.S. The rain snow transition zone is the elevation zone where the dominant winter precipitation phase changes from rain at lower elevations to snow at higher elevations. The elevation of this zone varies from sea level at high latitudes (Feiccabrino et al., 2012) to over 2000 m at lower latitudes (Cayan et al., 2001). This zone typically occurs between 1500 m and 1800 m in the interior Pacific Northwestern U.S. and covers approximately 9200 km^2 (Nolin and Daly, 2006). The dominant phase of precipitation in the rain snow transition zone is expected to change from snow to rain as climate warming trends continue (Cuo et al., 2011; Lutz et al., 2012; Mote et al., 2005; Nayak et al., 2010) and the incidence of winter ROS events is expected to increase (Lettenmaier and Gan, 1990). Although ROS events are known to generate large amounts of runoff (McCabe et al., 2007), there is a general lack of knowledge about how much BI they produce at event and annual timescales.

The goal of this study is to quantify the magnitude and sub-annual timing of BI in a semiarid mountain catchment in the rain snow transition zone north of Boise, Idaho, USA (Fig. 1). A water balance approach at the soil bedrock interface is employed that assumes water draining to the soil bedrock interface, DR, is either routed laterally to streamflow, or vertically to bedrock infiltration.