Impact of glacier loss and vegetation succession on annual basin water yields

Evan Carnahan, Jason M. Amundson, and Eran Hood
Department of Natural Sciences, University of Alaska Southeast, Juneau, AK, USA

Correspondence: Evan Carnahan (elcarnahan@alaska.edu)

Abstract. We couple a glacier flow model to a simplified landscape use a simplified glacier-landscape model to investigate the effects of glacier dynamics, climate-degree to which basin topography, climate regime, and vegetation succession on annual impact centennial variations in basin runoff during glacier retreat. Basin In all simulations, annual basin runoff initially increases as water is released from glacier storage but eventually ultimately decreases to below preretreat levels due to increases in evapotranspiration and altitudinal losses in precipitation. Peak basin runoff and decreases in orographic precipitation. We characterize the long-term (>200 years) annual basin runoff curves with four metrics: the magnitude and timing of peak basin runoff, the time to peak basin runoff primarily determined by glacier dynamics, with shallow sloping continental glaciers experiencing the largest increases in basin runoff(up to 62%) and longest time until preretreat basin runoff, and the magnitude of end basin runoff. We find that basin slope and climate regime have strong impacts on the magnitude and timing of peak basin runoff(up to 142 years), compared to 14% and 54 years for steep maritime glaciers subjected to the same rate of climate change. These differences in. Shallow sloping basins exhibit a later and larger peak basin runoff than steep basins and, similarly, continental glaciers produce later and larger peak basin runoff compared to maritime glaciers. Vegetation succession following glacier loss has little impact on the peak basin runoff and time to but becomes increasingly important as time progresses, with more rapid and extensive vegetation leading to shorter times to preretreat basin runoff and lower levels of end basin runoff. We suggest that differences in the magnitude and timing of peak basin runoff can be characterized by the glacier response time in our simulations can largely be attributed to glacier dynamics: glaciers with long response times (i.e., those that respond slowly to climate change) are pushed farther out of equilibrium for a given climate forcing and produce larger variations in basin runoff than glaciers with short response times. After peak basin runoff is reached, vegetation plays an increasingly important role, with basin runoff decreasing considerably faster for heavily vegetated landscapes than for rocky landscapes and ultimately reaching values that are over 50% lower than preretreat levels. Our Overall, our results demonstrate that glacier dynamics and landscape evolution vegetation succession should receive roughly equal attention when assessing the impacts of glacier mass loss on water resources.

1 Introduction

Glacier runoff is a dominant control on the timing and magnitude of runoff from glacierized watersheds (Hock, 2005). Short term water storage within glaciers impacts the diurnal characteristics of runoff, while intermediate term storage influences the
seasonality of runoff by heavily concentrating runoff in summer months (Jansson et al., 2003) when glaciers can provide a substantial portion of streamflow even at very low levels of catchment glacierization (Stahl and Moore, 2006; Nolin et al., 2010; Huss, 2011). On annual time scales, basin runoff water yields from glacierized watersheds can be more than double that of comparable nonglacierized watersheds (Hood and Scott, 2008).

Globally, more than a billion people live in watersheds that receive runoff from glaciers (Kaser et al., 2010). Within these watersheds, glacier runoff provides supports a wide variety of ecosystem services, including agricultural and municipal water supplies, hydroelectric power generation, stream temperature modulation, biodiversity, and fisheries (Milner et al., 2017; Cheesbrough et al., 2009; Gaudard et al., 2016; Fellman et al., 2014; Dorava and Milner, 2000). Moreover, changes in runoff from glaciers have wide ranging implications for the ecological structure and function of downstream aquatic ecosystems (Milner et al., 2009; Jacobsen et al., 2012). As a result, developing a quantitative understanding of how runoff from glaciers and their watersheds will be altered as glaciers continue to thin and recede is critical for predicting how the ecosystem services associated with glacier runoff will change in the future. Glacier runoff is controlled by the energy balance at the glacier surface, and as a result it is thus highly vulnerable to future climate warming compared to other components of the terrestrial water budget, lends urgency to this task.

As watersheds undergo deglacierization, annual water yields are deglaciate, annual basin runoff is hypothesized to show a transient increase followed by a decrease to a new, lower baseline value as glaciers are lost (e.g. Jansson et al., 2003; Moore et al., 2009). (e.g., Jansson et al., 2003; Moore et al., 2009). The magnitude of this change in basin water output can be substantial. For example, annual runoff from the Hofsjökull and southern Vatnajökull ice caps in Iceland is expected to increase by roughly 50 percent by the end of the 21st century (Aðalgeirsdóttir et al., 2006). In contrast, late summer water yields basin runoff in glacierized basins in British Columbia demonstrate widespread negative trends in recent decades (Stahl and Moore, 2006). The direction of the glacier runoff driven change in water yields basin runoff is roughly a function of watershed glacier coverage with increasing water yields basin runoff in heavily glacierized basins and decreasing water yields basin runoff in catchments with diminished glacier coverage (<10%; Casassa et al., 2009). On a global scale, this trend is reflected in the fact that projections of regional glacier runoff is projected to decrease sharply: Russian and Canadian high Arctic and a sharp decrease in lower latitude mountain basins in Asia, Europe, and South America where glacier coverage is lower (Bliss et al., 2014).

While valuable, these case studies do not elucidate the broader geomorphological and glaciological controls that govern the hydrological responses of watersheds to ongoing glacier recession. A number of studies have also focused on glacier runoff (e.g. Bliss et al., 2014), the amount of discharge from the receding glacier terminus, rather than basin runoff from a fixed gauging station. The latter is critical from a water resources standpoint because of the static nature of hydroelectric and water collection infrastructure. Efforts to understand how glacier change will impact streamflow at the basin scale are also confounded by the fact that recently deglaciated landscapes are eco-hydrologically dynamic as a result of changes in evapo-
Here, we couple a glacier flow model to a simplified landscape model in order to build on previous work by using a simple glacier-landscape model to systematically evaluate how glacier recession and subsequent vegetation succession will impact the timing and magnitude of variations in annual basin runoff from glacierized watersheds. To investigate how differences in the morphology and climate of glacierized basins influence hydrological responses to glacier loss, we vary a variety of parameters within our model including simulations including: climate regime (maritime vs. continental), rate of climate change, basin slope, vegetation rates, and vegetation types. Our findings provide insight into the fundamental controls on the decision to focus on these parameters is guided by (i) the theoretical glaciology, which indicates that glacier response to climate change depends most strongly on climate regime, rate of climate change, and basin slope (e.g., Harrison et al., 2001), and (ii) the lack of consistent relationships between climate, basin characteristics, and vegetation succession (in other words, we consider a wide range of vegetation rates and vegetation types regardless of climate regime or basin slope). We investigate the effects of each of these parameters on the long-term annual basin runoff curves, whose shapes we characterize with the following hydrological metrics: peak basin runoff, time to peak basin runoff, time to preretreat basin runoff, and end basin runoff (Fig. 1). Our findings provide insights into the hydrologic response of glacierized basins to a changing climate.

2 Methods

Assuming that non-glacier nonglacier changes in water storage within a basin are negligible on annual timescales, the annual basin runoff at the watershed outlet, $Q_s$, is given by

$$Q_s = Q_g + Q_n = (P_g - Q_b) + (P_n - ET),$$

(1)

where $Q_g$ and $Q_n$ are the glacier runoff (definition #5 in O’Neil et al., 2014) (i.e., the total runoff from the glacier surface; O’Neil et al., 2014), $P_g$ and $P_n$ are the precipitation fluxes (solid plus liquid) into the glaciated and nonglaciated portions of the basin, $Q_b$ is the glacier-wide mass balance flux (accumulation minus ablation), and $ET$ is the evapotranspiration flux. For consistency, all fluxes are expressed in water equivalent units. The precipitation fluxes include solid and liquid precipitation because, over annual time scales, solid precipitation either melts and contributes to basin runoff or is retained and contributes to the glacier mass balance. Note that the precipitation flux can be decomposed into rain and snow, and similarly the mass balance flux can be decomposed into accumulation (which equals snowfall) and melt. Consequently, the glacier runoff that we calculate using Equation (1) is identical to the sum of rain on the glacier plus glacier melt, i.e., $P_g - Q_b = P_{rain} + Q_{melt}$.

We calculate the runoff components in Equation (1) with a depth-integrated glacier flow model and a simplified landscape model. The use of a dynamic glacier model has been shown to give more accurate results for the glacier melt contribution to...
Figure 1. Conceptual model of Jansson et al. (2003) and Moore et al. (2009) that hypothesizes that, in response to climate warming, basin runoff will undergo a transient increase due to loss of glacier storage and a subsequent decrease past preretreat levels due to decreased glacier volume contribution and increased basin evapotranspiration.

runoff than static models of glacier ice (Naz et al., 2014). We assume that the precipitation and mass balance rates depend on elevation and that the evapotranspiration rates are a function of time since deglaciation. The glacier flow model adjusts the elevation and length/surface area of the glacier in response to the glacier’s mass balance, and the landscape model tracks the evolution of the deglaciated landscape.

The model domain consists of a parallel-sided valley that has a constant width of 4000 m and a constant downvalley slope, with the bedrock reaching a peak elevation of 2000 m (Fig. 2a). The glacier is assumed to flow from an ice divide at the upper reaches of the valley, to span the width of the valley at all times, and to initially fill the entire length of the valley. Thus, the model results tend to overemphasize the relative importance impact of glacier runoff on basin runoff because (i) glaciers are typically wider in their accumulation areas than in their ablation areas, which damps their response to climate change, and (ii) glaciers rarely fill an entire valley, and therefore the starting glacier runoff is generally less than the basin runoff. While simplified, the model is fast, making it possible to run numerous long-term simulations for various parameter combinations. In particular, we explore the effect that slope, vegetation rates, and vegetation types have on basin runoff over decadal time-scales under two different climate types (maritime vs. continental) and two different climate change scenarios.
Figure 2. (a) Glacier thickness profiles at various stages of glacier recession with a 2° basin slope, continental climate, and RCP8.5 climate change scenario. The dotted vertical line demarcates the basin extent. (b) Precipitation rate with altitude, which is held constant throughout glacier retreat. (c) Specific mass balance rate with altitude at various times during glacier recession. The ELA occurs where the mass balance rate equals 0.

2.1 Precipitation

Precipitation rates are needed for calculating both the glacier and nonglacier runoff ($P_g$ and $P_n$; Sections 2.2 and 2.3). We assume that precipitation varies linearly with altitude, such that

$$\dot{P}(z) = \dot{P}_0 + \frac{d\dot{P}}{dz} z,$$

where $\dot{P}$ is the width-averaged precipitation rate and $\dot{P}_0$ is the precipitation rate at sea level (Fig. 2b). For all simulations we set $d\dot{P}/dz = 0.001$ a$^{-1}$ (Immerzeel et al., 2015). The precipitation rate at sea level is chosen to ensure that the precipitation at elevation always exceeds glacier accumulation rates specific mass balance rate never exceeds the precipitation rate (see Section 2.4).

2.2 Glacier model and glacier runoff

Glacier runoff is calculated by integrating the precipitation and specific surface mass balance rates over the glacier surface, i.e.,

$$Q_g = P_g - Q_b = \int_{\Omega_g} \left( \dot{P} - \frac{\rho_i}{\rho_w} \dot{B} \right) d\Omega_g,$$

(3)
where \( \rho_i = 917 \text{ kg m}^{-3} \) and \( \rho_w = 1000 \text{ kg m}^{-3} \) are the densities of ice and water, \( \dot{B} \) is the width-averaged specific surface mass balance rate (in units of ice equivalent) and \( \Omega_g \) is the glacier surface area (in map view). The precipitation rate is given in Equation (2), and the balance rate is prescribed by using a constant mass balance gradient and imposing a maximum balance rate \( \tau \dot{B}_{\text{max}} \) (as is commonly observed; e.g., Van Beusekom et al., 2010). In other words,

\[
\dot{B}(z) = \min \left( \frac{d\dot{B}}{dz} (z - \text{ELA}), \dot{B}_{\text{max}} \right),
\]

where \( \text{ELA} \) is the elevation of the equilibrium line altitude (ELA; Fig. 2c). We use an initial ELA of 1500 m, consistent with high and mid-latitude glaciers (Huss and Hock, 2015). In our simulations, we vary the climate type by adjusting the balance gradient and the maximum balance rate (e.g., maritime glaciers have high balance gradients and high accumulation rates) and parameterize climate change by varying the ELA (see Section 2.4).

From Equation (3) it is clear that glacier runoff depends on glacier hypsometry (surface elevation and area), which evolves in response to the glacier mass balance, mass balance and glacier dynamics. To model the evolution of glacier hypsometry changes in glacier geometry, we invoke a commonly used one-dimensional, depth- and width-integrated flow model (see Fig. 2a for example longitudinal cross-section; Nick et al., 2009; Enderlin et al., 2013) (Nick et al., 2009; Enderlin et al., 2013)(see Fig. 2a for example longitudinal cross-sections). The model is based on conservation of momentum, which requires that the glaciological driving stress is balanced by gradients in longitudinal stress, lateral drag, and basal drag (van der Veen, 2013), such that

\[
2 \frac{\partial}{\partial x} \left( H \nu \frac{\partial U}{\partial x} \right) - \frac{H}{W} \left( \frac{5U}{2AW} \right)^{1/3} - \tau_b = \rho_i g H \frac{\partial h}{\partial x},
\]

where \( H \) is ice thickness, \( \nu \) is the depth- and width-averaged viscosity, \( U \) is the depth- and width-averaged velocity, \( W \) is glacier width, \( A \) is the flow rate factor, \( g \) is gravitational acceleration, and \( \tau_b \) is the basal shear stress, and \( h \) is the glacier surface elevation. The viscosity depends on the strain rate:

\[
\nu = A^{-1/3} \left| \frac{\partial U}{\partial x} \right|^{2/3}.
\]

We assume a constant flow rate factor of \( A = 2.4 \times 10^{-24} \text{ Pa}^{-3} \text{s}^{-1} \{\text{Paas is commonly observed beneath valley glaciers (e.g., Brædstrup et al., 2016). Thus In other words, we assume that the basal shear stress is at the yield stress for ice (Cuffey and Paterson, 2010). A velocity of } U = 0 \text{ is prescribed at the ice divide } (x = 0), \text{ and a velocity gradient is applied at the terminus by inserting the depth-averaged deviatoric stress into Glen’s Flow Law. The latter is necessary because in the model the ice must maintain some finite thickness at the terminus. Finally, after At each time step the (} \Delta t = 0.8 \text{ a) Equation (5) is solved for the velocity, and then the glacier surface is updated with a depth- and width-integrated mass continuity equation (van der Veen, 2013), in which}

\[
\frac{\partial H}{\partial t} = \dot{B} - \frac{1}{W} \frac{\partial (UHW)}{\partial x},
\]

and the glacier length is updated by removing any ice from the terminus that is thinner than 0.1 m.
2.3 Landscape model and nonglacier runoff

The nonglacier runoff is calculated by assuming that the evapotranspiration rate is some fraction of the precipitation rate, such that

$$Q_n = P_n - ET = \int_{\Omega_n} C \hat{P} \, d\Omega_n,$$  \hspace{1cm} (8)

where $0 \leq C \leq 1$ is the local annual runoff ratio (the ratio of precipitation to runoff) and $\Omega_n$ is the area of the deglaciated landscape. The runoff ratio of a particular deglaciated area will vary based on the time since deglaciation. Thus, in order to calculate the nonglacier runoff, our landscape model tracks the area exposed during glacier retreat as well as changes in the surface cover as it transitions through progressively more vegetated surface types (Crocker and Major, 1955; Burga et al., 2010; Chapin et al., 1994). The landscape model is based on two simple assumptions. First, we assume that the catchment becomes increasingly vegetated following deglaciation and that the type of vegetation only depends on within a basin depends only on the time since deglaciation. Second, the assumption is based on the time since deglaciation being highly correlated with vegetation types, biomass, and cover (Crocker and Major, 1955; Burga et al., 2010; Chapin et al., 1994; Klaar et al., 2015; Whelan and Bach, 2017; Fickert et al., 2017) and does not account for the effect that altitude has on vegetation levels (Cowie et al., 2014; Whelan and Bach, 2017). However, in some cases succession rates during glacier recession are comparable at different altitudes because changes in air temperature with altitude can be offset by climate warming (Fickert et al., 2017). Second, we assume that areas of the catchment become colonized, the rate at which water is evapotranspired and vegetation biomass increases, the evapotranspiration rate increases until reaching a maximum value representative of the climax vegetation state. This assumption is based on a general understanding of the processes that are expected to increase evapotranspiration, including increases in vegetation biomass, type, percentage cover, and temperature (Jaramillo et al., 2018; Andréassian, 2004; Barnett et al., 2005), although we note that there are few studies on changes in evapotranspiration throughout vegetation succession following deglaciation. Overall, results for non-glaciated paired watershed studies show increased biomass and reforestation lead to higher levels of evapotranspiration and decreased annual basin runoff (Sun et al., 2010; Klaar et al., 2015; Jaramillo et al., 2018; Bosch and Hewlett, 1982; Andréassian, 2004).

We choose to model evapotranspiration as monotonically increasing in a stepwise manner throughout vegetation succession for the following reasons. First, we are attempting to study general basin characteristics so exceptions to general rules that may cause non-monotonic increases in evapotranspiration during the transition to climax state (e.g., during the growth of eucalyptus trees; Andréassian, 2004) are of less importance. Second, the stepwise increase in evapotranspiration allows us to focus on specific stages of vegetation and not the exact transition between stages, which is less well understood compared to the change between initial vegetation and climax vegetation. We do not account for climate-driven increases in evapotranspiration because this process is attenuated in snowmelt-dominated regions (Barnett et al., 2005).

We express the change in landscape cover that occurs during plant colonization through a stepwise parameterization of the runoff ratio. Runoff ratios range from 0.5 (forest) to close to 1 (ice or rocky alpine...
terrain with no vegetation) and depend on the vegetation type (Zhang et al., 2001; Filoso et al., 2017) (Andréassian, 2004; Filoso et al., 2017).

We parameterize vegetation type using four runoff ratios, such that

\[
C_i = \begin{cases} 
C_1 & 0 \leq t \leq T_1 \\
C_2 & T_1 < t \leq T_2 \\
C_3 & T_2 < t \leq T_3 \\
C_4 & t > T_3 
\end{cases},
\]

where \( C_i \) is the runoff ratio associated with the vegetation type \( i \), \( t = 0 \) is the time at which a portion of the catchment is deglaciated, and \( T_i \) indicates the time at which there is a transition in surface type. Thus, the runoff ratio is a function of time but varies spatially, and consequently Equation (8) can alternatively be expressed as

\[
Q_n = \sum_{i=1}^{4} C_i \int_{\Omega_{ni}} \dot{P} \, d\Omega_{ni},
\]

where \( \Omega_{ni} \) represents the nonglacier surface area that has runoff ratio \( C_i \).

2.4 Simulations

We use our model to test the effect that bed slope, vegetation type, and vegetation rates have on basin runoff for two different climate types and two different climate change scenarios by considering a range of parameter values. We varied the bed slope of the basin (including beneath the glacier) from shallow (2°) to steep (10°) and used six different sets of four runoff ratios, \( C = \{C_1, C_2, C_3, C_4\} \), and six different sets of three vegetation timings, \( T = \{T_1, T_2, T_3\} \) (see Eq. 9). The runoff ratios ranged from a rocky-high elevation or high latitude environment with no vegetation, \( C = \{1, 1, 1, 1\} \), to a low elevation or low latitude environment with heavy substantial vegetation, \( C = \{0.95, 0.8, 0.7, 0.5\} \), and the vegetation rate ranged from rapid, \( T = (5 \text{ a}, 10 \text{ a}, 25 \text{ a}) \), to slow, \( T = (50 \text{ a}, 100 \text{ a}, 250 \text{ a}) \). With the exception of the no vegetation scenario, the runoff ratio always decreased with time since deglaciation, consistent with increased evapotranspiration associated with the assumption of monotonically increasing evapotranspiration due to vegetation succession. Consequently, the runoff ratio decreases in the downvalley direction until the landscape has reached climax vegetation. Our model vegetation types and their corresponding runoff ratios span the range of reported values for the process of vegetation succession following glacier retreat, which can be highly spatially variable even within a given climate (e.g., Crocker and Major, 1955; Burga et al., 2010; Chapin et al., 1994).

The two climate types that we define are designed to roughly mimic the climates that are experienced by maritime and continental glaciers. The climates are defined by a glacier’s surface mass balance gradient and maximum surface mass balance (Eq. 4) and by the precipitation rate at sea level (Eq. 2). For the maritime climate, we set \( \dot{B}/dz = 0.01 \text{ a}^{-1}, \dot{B}_{\text{max}} = 4 \text{ m a}^{-1} \), and \( \dot{P} = 2.4 \text{ m a}^{-1} \), whereas for the continental climate these values are \( \dot{B}/dz = 0.005 \text{ a}^{-1}, \dot{B}_{\text{max}} = 2 \text{ m a}^{-1} \), and \( \dot{P} = 0.55 \text{ m a}^{-1} \) (see Cuffey and Paterson, 2010, for example mass balance curves); note that the mass balance curves are defined in units of ice equivalent while the precipitation curves are defined in units of water equivalent.
In each simulation, a constant climate is used to spinup the model to a steady-state, defined as being reached when the rate of terminus advance or retreat is less than 2 m a \(^{-1}\). After reaching steady-state, the climate is changed by steadily raising the ELA (e.g., Fig. 2c). We consider two climate change scenarios that are roughly based on expected changes in ELA (Huss and Hock, 2015) under two different Representative Concentration Pathways (RCP2.6 and RCP8.5, which correspond to increases in radiative forcing of 2.6 and 8.5 W/m\(^2\)). In the RCP2.6 scenario we prescribe the ELA (in meters) according to

\[
ELA_{\text{RCP2.6}} = 1500 + 158(1 - e^{-t/28}),
\]

where \(t\) is the time in years, resulting in an asymptotic increase in the ELA of about 150 m over a 100 year period. In contrast, during the RCP8.5 scenario we raise the ELA linearly with time:

\[
ELA_{\text{RCP8.5}} = 1500 + 5t.
\]

We hold the climate constant for the first 10 years of the model run before initializing changes in the ELA according to Equations 11 and 12. Note that we neglect any climate warming scenario includes decadal fluctuations in climate that may complicate the simplified retreat scenario. Thus we neglect temporal variations in precipitation and assume that changes in glacier mass balance are primarily due to warming (Fig. 2c; Van de Wal and Wild, 2001). Climate-driven changes in precipitation from snow-to-rain have equivocal effects on basin runoff, which are not included in our modeling (Neal et al., 2002; Tague and Dugger, 2010; Berghuijs et al., 2014).

During the simulations the basin is initially filled with ice (i.e., the length of the basin is defined as the initial steady-state length of the glacier and thus the basins do not have the same lengths, which depends on climate type and basin slope). As the glacier recedes, the portion of vegetated area increases and previously exposed portions mature, moving through progressive vegetation types. The simulations continue until the glacier has reached a new steady-state or disappeared altogether and the newly exposed landscape has reached the final vegetation state.

### 3 Results

#### 3.1 Basin runoff

Following the initiation onset of climate change in our simulations, glaciers retreat and thin steadily until either disappearing completely (for the RCP8.5 scenarios) or reaching a new steady-state (for the RCP2.6 scenarios). Glaciers in the RCP2.6 climate scenario lose between 16–25\% of their area and 19–26\% of their volume before reaching a new steady state, with steep glaciers showing higher fractional volume and area losses. For a given Regardless of slope, fractional volume and area changes are similar (within \(\sim 1\%\)) between continental and maritime climates.

As glaciers retreat, basin runoff in the maritime climate under the RCP8.5 scenario experiences a transient increase of about 10–40\% over a time period of 20–100 years (Fig. 3), with shallow sloping basins experiencing substantially higher and later peak basin runoff than steep basins (Fig. 3). Basin runoff subsequently decreases over the next 100–200 years.
Figure 3. Variations in basin runoff (a) without vegetation and (b) with vegetation. For both (a) and (b) we use a maritime climate and the RCP8.5 climate change scenario. In (b) we set the vegetation timing and type as \( T = \{20, 50, 100\} \) and \( C = \{1, 0.9, 0.8, 0.6\} \), respectively.

For simulations that include no vegetation, end basin runoff (the final steady-state runoff) is slightly below preretreat levels due to orographic losses in precipitation since glacier volume loss results in the loss of orographic precipitation associated with the decrease in basin elevation (Fig. 3a). This result is more pronounced for shallow basins than for steep basins (-14% vs -1% for the RCP8.5 scenario) because shallow sloped sloping basins contain longer, thicker glaciers that undergo more surface lowering. When vegetation is included, end basin runoff can fall below 50% of the preretreat basin runoff (e.g., Fig. 4). Increases in evapotranspiration during glacier retreat partially offset increases in basin runoff driven by glacier volume loss, although this effect is small compared to the impact of vegetation on end basin runoff (Fig. 4). Vegetation rate has Rates of vegetation have no impact on the magnitude of end basin runoff because the vegetation eventually reaches a mature climax state regardless of the rate of change (Fig. 5). Overall, the magnitude and timing of peak basin runoffs as well as the magnitude of the time to preretreat basin runoff, and the end basin runoff are smallest minimized when vegetation occurs rapidly and progresses to a heavily forested vegetated state (low runoff ratio).

Variations in annual basin runoff also depend on climate type. Continental basins, i.e., those with low precipitation rates and mass balance gradients, experience peak basin runoffs that are about 10–20% higher and 10–20 years later during RCP8.5 (with a greater difference for shallow basins) than comparable maritime basins, regardless of the vegetation type (Fig. 4) or vegetation rate (Fig. 5). Changing from a maritime basin to a continental basin under Differences between maritime and continental basins in the RCP2.6 has a similar trend in effect as during scenario are similar to, but smaller than, those in the RCP8.5, except with smaller changes in magnitude and timing. Continental basins have a peak runoff that is ~3% higher peak basin runoff and that occurs 7–15 years later than for comparable maritime basins during the RCP2.6 (data not shown). Thus, changing
Figure 4. Variations in basin runoff for differing types of catchment vegetation as expressed by runoff ratios in (a) maritime and (b) continental climates. The basin slope ($5^\circ$), climate change scenario (RCP8.5), and vegetation timing ($T = \{15\,\text{a}, 30\,\text{a}, 50\,\text{a}\}$) are the same in both panels.

Figure 5. Variations in basin runoff for differing rates of catchment vegetation in (a) maritime and (b) continental climates. The basin slope ($5^\circ$), climate change scenario (RCP8.5), and vegetation type ($C = \{1, 0.95, 0.85, 0.8\}$) are the same in both panels.
from a maritime climate to a continental climate has a comparable effect to decreasing the slope of a basin in that it leads to a higher and later peak in basin runoff. The dependence of peak basin runoff on slope and climate type is related to the glacier response to climate change, which we discuss in Section 4.

To further quantify the effects of model parameters on basin runoff, we characterize the impacts of glacier recession on basin runoff with four key metrics: peak basin runoff, time to peak basin runoff, time to preretreat basin runoff, and end basin runoff. We evaluate the relative effect that each parameter has on basin runoff by selecting a canonical set of parameters, and then varying each parameter individually around that parameter set. For the canonical set we use a maritime climate, basin slope of 5°, vegetation type of $C = \{1, 0.9, 0.8, 0.6\}$, and vegetation timing of $T = \{15 \text{ a}, 30 \text{ a}, 50 \text{ a}\}$.

Influence of catchment vegetation and basin slope on four key basin hydrologic metrics: (a) peak basin runoff, (b) end basin runoff, (c) time to peak basin runoff, and (d) time to preretreat basin runoff. The line within each box represents the value for the canonical simulation (maritime climate, basin slope of 5°, $C = \{1, 0.9, 0.8, 0.6\}$, and $T = \{15 \text{ a}, 30 \text{ a}, 50 \text{ a}\}$). Boxes represent the range of influence for change in an individual parameter, and the direction of change for vegetation rate (slow to fast), vegetation type (unvegetated/rocky to forest), and basin bed slope (shallow to steep) are noted for each box.

Within a given climate regime, the magnitude and timing of peak basin runoff is most strongly influenced by basin slope (Fig. 6a, b). In the RCP8.5 scenario, peak basin runoff from shallow basins—a shallow basin (2° slope) is ~30% higher and occurs 70 years later than for steep basins—a steep basin (10° slope). The timing and extent of catchment vegetation have minimal impact on peak basin runoff timing and magnitude, due to the limited amount of newly vegetated land that is present at peak basin runoff, regardless of the vegetation scenario. The vegetation type and vegetation rate become increasingly important rate exert an increasingly strong impact on basin runoff as time progresses. The end basin runoff is almost entirely dependent on the runoff ratio of the final vegetation state (Fig. 6b). The time to preretreat basin runoff is affected almost equally by slope and vegetation type, with vegetation rate playing a smaller but still substantial role (Fig. 6c). The end basin runoff is almost entirely dependent on the runoff ratio of the final vegetation state (Fig. 6d).

Variations in model parameters consistently have a smaller impact on model output in the RCP2.6 scenario than in the RCP8.5 scenario but exhibit similar trends. This is consistent with the fact that the due to the complete loss of glacier ice in the RCP8.5 scenario, which has a larger range of hydrologic impacts compared to the partial loss of glacier ice associated with the RCP2.6 scenario. One exception is the effect of varying slope on end basin runoff, which has the opposite trend for the RCP8.5 scenario than for the RCP2.6 scenario (Fig. 6b). In all simulations, glacier thinning causes a decrease in orographic precipitation that is most pronounced in shallow basins. In the RCP8.5 simulations where glaciers disappear completely, this process determines the impact of slope on end basin runoff. The situation is different for the RCP2.6 simulations because the glaciers do not disappear. There, the steep glaciers experience a larger fractional retreat than the shallow sloping glaciers, which exposes more land for vegetation and ultimately results in a slightly lower end basin runoff than for shallow basins.

Overall, peak basin runoff, time to peak basin runoff, and time to preretreat basin runoff are all smaller in the RCP2.6 scenario than in the RCP8.5 scenario. Of the four key hydrologic metrics, only the end basin runoff is higher in the RCP2.6 scenario, and this occurs because the basins do not fully deglaciate in that climate scenario. The results are similar for a continental climate, but with slightly longer times to peak and preretreat basin runoff and larger peak basin runoff (data not shown).
Figure 6. Influence of catchment vegetation and basin slope on our hydrologic metrics: (a) peak basin runoff, (b) end basin runoff, (c) time to peak basin runoff, and (d) time to preretreat basin runoff. We varied vegetation rate (slow to fast), vegetation type (rocky/unvegetated to forest), and slope (shallow to steep) across the ranges shown in the legends of Figures (3)–(5). The boxes represent the timing and relative magnitude of basin runoff associated with varying each parameter, and the lines within each box represents the value for the canonical simulation (maritime climate, basin slope of 5°, \( C = \{1, 0.9, 0.8, 0.6\} \), and \( T = \{15 \text{ a}, 30 \text{ a}, 50 \text{ a}\} \)).
3.2 Glacier and nonglacier runoff

In our simulations, peak basin runoff and time to peak basin runoff are most strongly influenced by basin slope and climate type (Fig. 6a, c), whereas landscape evolution plays an increasingly important role in the later stages of retreat (Fig. 6b, d). The largest possible contribution of nonglacier runoff to total basin runoff occurs when vegetation and associated evapotranspiration are assumed to be negligible ($C = \{1, 1, 1, 1\}$). Under these conditions, nonglacier runoff contributes 10–20% (RCP8.5; Fig. 7a) and 1–5% (RCP2.6; Fig. 7b), of the basin runoff during peak basin runoff. By the time that basin runoff has returned to preretreat levels, the contribution from nonglacier runoff has increased to 70–95% and 9–22%, for RCP8.5 and RCP2.6 respectively (lower bounds of peak basin runoff and preretreat basin runoff, note that lower bounds are from the continental simulations and are not shown in Fig. 7). The smaller contributions of nonglacier runoff in the RCP2.6 scenario reflect the smaller amount of glacier retreat that occurred during those simulations.

Basin runoff is clearly controlled by variations in glacier runoff during the early stages of retreat. Glacier runoff, $Q_g$ (Eq. 1), undergoes a transient increase followed by a decrease to below preretreat levels (Fig. 8). This pattern is consistent for all glacier geometries and climate variations. Glaciers with steep basin (bed) slopes experience lower fractional peaks in glacier runoff compared to glaciers on shallow basin slopes, with variations in slope eliciting a 35% difference in peak fractional glacier runoff for the RCP8.5 scenario (Fig. 8a) and an 8% difference in peak fractional glacier runoff for the RCP2.6 scenario (Fig. 8b). The smaller peak glacier runoff of glaciers in steep basins is also associated with an earlier peak glacier runoff. For example, in a continental climate glaciers in steep basins experience peak glacier runoff roughly 80 and 30 years before shallow sloping glaciers for the RCP8.5 and RCP2.6 scenarios, respectively. Furthermore,
continental glaciers have higher peak glacier runoff, reach peak glacier runoff later, and exhibit greater variations in glacier runoff between low and high slope basins than maritime glaciers. Peak glacier runoff occurs before peak basin runoff due to decreases in precipitation on glaciated area. The impacts of basin slope and climate type on the magnitude and timing of peak glacier runoff timing and magnitude are similar to those observed for basin runoff, and are discussed in more detail in Section 4.2.

4 Discussion

4.1 Glacier-driven hydrological change

Our projections of the long term impacts of glacier volume loss on annual basin runoff agree closely with previous conceptual models suggesting that basin runoff will increase sharply at the onset of glacier recession, peak as glacier coverage in the basin diminishes, and then return to a steady state below the preretreat basin runoff level when the basin becomes deglacierized (Jansson et al., 2003; Moore et al., 2009). Moreover, our model results provide insights into how climate and basin characteristics influence variability in the timing and magnitude of the hydrologic response among glacierized basins basin characteristics (slope, vegetation, and climatic setting) can influence the shape of this hydrologic response curve among basins with retreating glaciers. In particular, glacier basin slope exerts a strong control on the timing and magnitude of annual basin runoff, with steeper glaciers having a shorter time to peak basin runoff and a lower peak basin runoff compared to shallower sloping glaciers. Unlike peak basin runoff, final steady state basin runoff following glacial recession is strongly influenced by the rate and type of vegetation that colonize ice-free landscapes within a basin.
Our model results also suggest that climate regime is also an important control on basin hydrological response to glacier loss, with basins in continental climates experiencing a later and proportionally larger peak in annual basin runoff response to glacier volume loss. This finding is in agreement with field measurements from a paired basin study in Alaska showing, which showed that glacier volume change has a strong impact on annual basin water yield in a continental environment in part because of the fact that glacier volume change accounts for a larger proportion of annual streamflow in interior mountain ranges (O’Neill et al., 2014). The rate of climate warming in a basin can similarly impact the hydrological response. In particular, applying the RCP8.5 climate scenario to our model elicited a stronger and more variable response in annual basin runoff compared to the more moderate RCP2.6 climate scenario. Much of the difference in response is due to the fact that the glacier completely disappears from the basin in the RCP8.5 scenario, resulting in a longer response time to peak basin runoff, a higher peak in annual basin runoff, and a substantially lower end basin runoff regardless of individual basin characteristics.

It is difficult to directly validate our model results because of a lack of discharge data for glacierized watersheds that span timescales comparable to those that we modeled. However, comparisons to studies from individual glacier basins previous studies provide insight into whether the timing and magnitude of changes in annual runoff that we modeled are consistent with previous runoff projections from individual glacierized basins across a range of climate conditions. At the Hofsjökull ice cap in Iceland, basin runoff is projected to peak in about a century at 50% above current basin runoff levels (Aðalgeirsdóttir et al., 2006), which agrees well with our model results indicating that they indicate that shallow sloping maritime glaciers reach a peak basin runoff of $43\pm13\%$ after 110 years of climate warming under RCP8.5. In Alaska, increases in summer basin runoff of $15\text{–}25\%$ in continental and maritime glacierized catchments over a 30+ year period (O’Neill et al., 2014) are similar in magnitude to our model results for annual basin runoff with increases in basin runoff on the order of $15\text{–}25\%$ (O’Neill et al., 2014).

Our model results for annual basin runoff are generally lower than both Aðalgeirsdóttir et al. (2006) and O’Neill et al. (2014), possibly because both of these studies account for long term increases in precipitation that are not included in our more general modeling we did not include in our model.

In the Pacific Northwest of North America, Nolin et al. (2010) modeled the relationship between changes in glacier extent and end-glacier runoff for Eliot Glacier and found that end-glacier runoff was reduced by 0.9% for every 1% decrease in glacier area. This finding ratio is highly consistent with our simulations for maritime glaciers during RCP 2.6, which showed that glacier area losses of $16\text{–}24\%$ corresponded with decreases in end-glacier runoff of $14\text{–}22\%$. Model predictions for changes in basin runoff in Peru’s Cordillera Blanca show that end-basin runoff after glaciers fully disappear decreases $\sim30\%$ from present day values (Baraer et al., 2012). Present day values for nearly all given that nearly all of the basins in Baraer et al. (2012) are past peak discharge ($\sim30\text{–}40$ years). Their model results for decreases in present day basin runoff to end basin runoff fall within, their model results are consistent with the range of values that we predict for decreases we modelled for the decrease from peak basin runoff to end basin runoff after a basin is deglacierized for glaciers that fully disappear (RCP8.5) in a continental climate for all slopes and vegetation scenarios, $\sim20\text{–}90\%$.

In a global scale analysis of future basin runoff in 56 large-scale glacier basins, the increase in basin runoff to peak basin runoff averaged 26% for the RCP2.6 scenario and 36% for the RCP8.5 scenario (Huss and Hock, 2018), which is in broad agreement with our results. Moreover, the findings of Huss and Hock (2018) suggest that (i) there is a significant positive
correlation between glacier area (shallow sloped glaciers in our study) and time to peak basin runoff and (ii) increases in the strength of the warming scenario result in a later and higher peak basin runoff. The similarity in our findings across a wide range of basin characteristics provides confidence in the trends elucidated by our model results. The delay in peak basin runoff evident in basins with larger glaciers and basins that undergo stronger warming scenarios highlights the roles of glacier surface area and overall melt rates for determining the long term hydrological response in basins that contain glacier ice.

In many regions, glaciers have receded to the point where glacier and basin runoff have passed the peak basin runoff tipping points and are exhibiting declines in annual water output (Stahl and Moore, 2006; Bliss et al., 2014; Huss and Hock, 2018). In these basins, the variation in glacier response will no longer be the major driver of variation in basin runoff and further examination of the ecohydrological impact of vegetation colonization is warranted. In glacierized basins with declining annual runoff, increased evapotranspiration and canopy interception resulting from by vegetation will become an increasingly important driver of long-term variation in annual basin runoff. This finding suggests that decreases in annual basin water yields associated with glacier loss may be especially pronounced in regions such as Patagonia, New Zealand, and coastal Alaska where productive forests can rapidly recolonize newly exposed landscapes following the loss of glacier ice (e.g. Crocker and Major, 1955; Chapin et al., 1994).

We acknowledge that our study focused on annual basin runoff and did not explore climate-driven changes in the seasonality of basin runoff, which may be substantial even in basins where annual runoff remains largely unchanged. In particular, discharge data and model results from glacierized basins suggest that late summer basin runoff may decrease substantially with the continued loss of glacier ice (Huss and Hock, 2018; Kaser et al., 2010; Stahl and Moore, 2006; Nolin et al., 2010). Nevertheless, understanding future changes in annual basin runoff is useful for understanding the overall hydrologic response of glacierized basins and how the wide range of ecosystem services these basins provide (e.g. Milner et al., 2017) may respond to future warming. Our findings suggest that changes in annual basin runoff with glacier loss may vary on regional scales as a result of differences in climate regime (maritime vs. continental) and regional differences in the strength of the climate warming signal. However, sub-regional variation in the hydrologic response may also be considerable as a result of catchment-scale differences in aspect, elevation, slope, and latitude, all of which influence rates of glacier ice loss and subsequent colonization.

4.2 Glacier response times

Our results indicate that the initial hydrological responses to glacier recession are dominated by variations in glacier runoff, which are themselves a result of glacier dynamic feedbacks. Thus, the peak basin runoff and time to peak basin runoff can be understood in terms of the time that it takes a glacier to respond to climate change. Theoretical work (Harrison et al., 2001) suggests that the glacier volume response time, $\tau_v$, is given by

$$\tau_v = \frac{1}{-b_e/H^* - G_e},$$

(13)
where \( \dot{b}_e \) is the effective specific mass balance rate in the vicinity of the terminus, \( \dot{G}_e \) is the effective gradient of the specific mass balance rate with elevation, and \( H^* = \frac{dV}{d\Omega_G} \) is a thickness scale in which \( V \) is volume and recalling that \( \Omega_G \) is glacier surface area. The volume glacier response time is the e-folding time for the volume of a glacier to evolve from one steady-state to another following a step change in climate. Equation 13 is derived from mass continuity arguments and characterizes both the timing and magnitude of the volume response of a glacier (longer response times result in larger changes in volume; Harrison et al., 2001), but depends on the assumption that \( H^* \) is constant and therefore that changes in volume \( \Delta \text{climate} \) are small. Nonetheless, the glacier response time is a useful tool for understanding how glacier volume and glacier runoff might be expected to evolve in a changing climate. In particular, Equation 13 indicates that glacier response times will be largest for thick glaciers (i.e., those that occur on shallow slopes) in a continental climate. The first term in the denominator, \( -\dot{b}_e/H^* \), will always be positive, and the larger this value the shorter the response time. Glaciers in continental climates typically have relatively small values of \( -\dot{b}_e \) and thus this term tends to be small (indicating long response times). The second term in the denominator, \( \dot{G}_e \), is positive and acts to increase the response time by accounting for the impact of climate on mass redistribution from high elevations to low elevations. Mass balance gradients are smaller in continental climates than in maritime climates. However, the \( -\dot{b}_e/H^* \) term is significantly smaller in continental climates, and thus the denominator is about half as small (i.e., the glacier response time is twice as long) for continental glaciers than it is for similarly sloped maritime glaciers.

Our modeling results do not follow the assumption of small changes in climate volume, but nonetheless they are broadly consistent with the notion of glacier response time. We calculate the glacier response time using the initial balance rate at
the terminus, the balance gradient for the respective climate, and the thickness scale $H^*$ by calculating an average value of $dV/d\Omega_g = -dV/d\Omega_n$ during the first quarter of each simulation. We find that peak glacier runoff is highest and occurs latest for shallow sloping glaciers in a continental climate (i.e., those that have long response times; Fig. 9). Similarly, because variations in basin runoff are strongly influenced by glacier runoff in the early stages of retreat (Fig. 7), glacier response time is also a useful predictor of peak basin runoff and time to both the magnitude and timing of peak basin runoff. We find nearly linear relationships between response time and both peak runoff and time to peak runoff for small response times (for both glacier runoff and basin runoff; Fig. 9). The relationships deviate from linear because the response time calculation (i) does not directly indicate when the rate of volume loss is at a maximum, (ii) does not account for changes in basin/glacier runoff due to precipitation (it is only a statement about glacier evolution), and (iii) is based on the assumption that changes in volume are small and therefore that $H^*$ is a constant, which breaks down as the response time increases. In this context, a key result is that peak basin runoff and time to peak basin runoff are largest for basins containing glaciers that have long response times (Fig. 9), likely because glaciers with long response times are not able to evolve in step with climate (i.e., they have greater disequilibrium; Christian et al., 2018).

Two additional, important observations from our simulations are that (i) fractional increases in basin runoff exceed fractional increases in glacier runoff and (ii) peak basin runoff lags peak glacier runoff (Fig. 9). Although we are unable to provide precise explanations for these differences due to nonlinear relationships between glacier volume change and associated changes in precipitation, mass balance, and vegetation rates, we can explain the trends through simple analysis of the terms affecting the basin runoff (Equation 1). First, the basin runoff and glacier runoff are both normalized by the initial basin runoff, which is equal to the initial glacier runoff, $Q^0_g$, in our simulations. The normalized basin runoff is given as

$$\frac{Q_s}{Q^0_g} = \frac{Q_g}{Q^0_g} + \frac{Q_n}{Q^0_g}.$$  \hfill (14)

The terms on the right hand side are the normalized glacier and nonglacier runoffs, respectively. Both the glacier and nonglacier runoffs increase during the early stages of retreat, and therefore the peak basin runoff must exceed the peak glacier runoff (in both absolute and relative terms). Second, the rate of change of basin runoff is

$$\frac{dQ_s}{dt} = \frac{dQ_g}{dt} + \frac{dQ_n}{dt}.$$  \hfill (15)

When glacier runoff reaches a peak, $dQ_g/dt = 0$ and consequently $dQ_s/dt = dQ_n/dt$. Peak glacier runoff occurs at a time that glacier retreat is rapidly exposing bedrock, implying that the nonglacier runoff — and by extension, basin runoff — are increasing. Thus, peak basin runoff must occur after peak glacier runoff.

5 Conclusions

Basin runoff varies during glacier recession due to release of water from glacier storage and subsequent colonization of deglaciated land. Rapid glacier mass loss during the early stages of retreat drives an increase in basin runoff, which eventually decreases as a glacier shrinks and the landscape becomes increasingly vegetated. Peak basin runoff and time to peak
basin runoff are largely driven by glacier response to climate change due to the major contribution of glacier runoff to basin runoff during the initial stages of retreat. Basins with glaciers that have fast response times (i.e., steep and maritime) have lower and earlier peak basin runoff because those glaciers respond rapidly to climate warming. Slow responding glaciers (i.e., shallow sloping and continental) are unable to stay in step with climate variations and consequently experience high sustained rates of volume loss well after the initiation of climate warming, resulting in high and late higher and later peak basin runoff. In the later stages of retreat, nonglacier runoff becomes an increasingly significant contributor to basin runoff. The time at which basin runoff falls below preretreat levels is heavily influenced by the colonisation of the basinrate of vegetation following the loss of glacier ice. Basins with fast and high levels of vegetation have earlier and lower peak basin runoff and reach preretreat levels of basin runoff substantially earlier than those with low levels of vegetation. Basin runoff in the late stages of glacier recession is primarily determined by the vegetation in extent of vegetation within the basin because the glacier runoff becomes small or negligible (depending on the degree of climate warming that has occurred) evapotranspiration becomes an increasingly important term in the basin water budget compared to glacier runoff. 

The model simulations that we performed in order to explore variations in basin runoff were highly idealized and aimed at elucidating the fundamental controls on basin runoff over annual time scales and longer. In particular, we assumed constant glacier width, uniform basin slope, and simplified parameterizations of climate, climate change, and vegetation succession. We also note that we began all simulations with 100% glacier cover and a glacier in a near steady-state, and consequently our simulations tend to overemphasize the impacts of glacier recession on basin runoff. Future work should explore in more detail the effect of basin hypsometry. A number of processes and parameters that we either did not account for or accounted for in a simplified way have the potential to modify the shape of the annual basin runoff curves we modeled, and should be considered in future work. In particular: 

- Bedrock topography, including variations in valley width and slope, will modify retreat rates, with retreat tending to be slowest when ice flows through narrow, steep constrictions.

- The formation of proglacial lakes will accelerate retreat (Larsen et al., 2007; Moyer et al., 2016) and modify basin evapotranspiration rates.

- Interannual variability in climate can create significant interannual variations in runoff that are superposed on the long-term basin runoff curves (O’Neel et al., 2014). In addition, interannual climate variability can push a glacier out of equilibrium with long-term climate trends (Christian et al., 2018), resulting in unexpectedly large fluctuations in runoff in subsequent years.

- In basins that have lower starting glacier cover, the effect of glacier recession on basin runoff and also incorporate more sophisticated climate and hydrological models will be dampened.
Vegetation succession within a specific basin may differ from the simple framework we used in our model (see Section 2.3).

We did not include groundwater storage in our model and, in some basins, the loss of glacier runoff to groundwater may be substantial (Liljedahl et al., 2017) and modify basin runoff on seasonal and annual timescales.

Increased model complexity would will be required to address the full impact of climate change on the timing of runoff on seasonal and shorter time scales, which is critical for water resource management since glacier runoff tends to be highly focused and highly variable during the summer months. magnitude and timing of basin runoff from glacierized basins, and some variability between basins will depend on site specific factors such as bedrock topography and erodibility. The simulations that we presented here focused on what we feel are the fundamental controls on basin runoff, and as such the results provide key context for subsequent studies.

*Competing interests.* The authors have no competing interests.

*Acknowledgements.* This project was supported in part by the U.S. National Science Foundation (OPP-1504288). We thank Shad O’Neel, Brian Buma, and Christian Kienholz for discussions that led to and improved this paper.
References


General comments
This paper proposes to analyze the joint effect of glacier retreat and revegetation (due to climate warming) on the overall water balance of glacier-covered catchments for long term evolution (up to 500 years into the future). It does so with a simplified model whose possible outcomes are studied for different glacier retreat and revegetation scenarios, for two different climate types. The studied climates are continental and maritime climates, which are emulated by adjusting the glacier mass balance rate with elevation according to observed rates in these climates. No actual data is used in the presented study but the model parameters are selected in light of known /reasonable values for existing glacier catchments.

The idea of studying the possible evolution of catchment-scale water balance resulting from climate warming with a simplified model is appealing: it has the potential to explain in simple terms the possible outcomes (temporal increase of total basin runoff, overall decrease on the long run) without obscuring the involved mechanisms by a complex input-output model. In its current form, the results of the analysis are however hardly surprising and essentially say that "with more vegetation we get less runoff", which corresponds to an oversimplification of high alpine hydrology.

Thank you for your comments and careful review. Although some of the results may not be surprising, we feel that previous literature has not systematically analyzed the parameters influencing annual runoff, and thus our results provide a simple framework for understanding variations in runoff that should be relevant to a broad range of researchers and resource managers. As pointed out in this review and in the other reviews, additional complexity could be added to the model that would produce positive and/or negative feedbacks, but that would not change the general results from this study. In the introduction, we highlight that we are trying to understand (1) how a suite of fundamental parameters (glacier slope, climate regime, etc.) control the shape of the long-term annual runoff curves and (2) how sensitive the runoff curves are to changes in these parameters. (P2 L28 -- P3 L4)

I am a hydrologist by training, with little knowledge in ice flow modelling. From my perspective, the used one-dimensional, depth- and width-integrated flow model, combined with different glacier mass balance rates seems to be a reasonable approach
to generate different glacier retreat scenarios under climate warming. I find it, however, surprising that the authors choose an approach that does not allow to study the effect of the actual glacier shape (here a simple rectangle has been chosen) and that this aspect is not further discussed.

The rate of glacier volume change, which drives variations in glacier runoff over secular time-scales, is governed by two feedbacks: a negative feedback with glacier length and a positive feedback with glacier surface elevation. These feedbacks are well captured by simple flow line models, although it is correct that spatial variations in glacier width will modify the glacier evolution. We tested the model sensitivity to glacier width by using a trapezoidal basin (in map view) whose width varies from the ice divide to the terminus by ± 5 degrees. These variations have limited effect on peak runoff (~1%) and changes in time to peak and end runoff were easy to predict. Essentially, all other things equal, glaciers with large accumulation areas have higher end runoffs due to the smaller fractional area change and a slower decrease to end runoff. The large accumulation areas provide some buffer against climate warming as long as the glacier does not fully disappear. In the manuscript we now motivate our choice of using a parallel-sided valley and discuss how variable glacier width might affect the variations in runoff. (P4 L13--15, P19 L4--5)

Regarding the hydrological side of the study, I have to admit that as I hydrologist I can only warn against the use of such oversimplified assumptions without sufficient discussion of the implications. To actually study the fundamental controls on the high alpine water balance, these fundamental controls and what we know thereof should be reviewed in detail before building a model.

My critic is the following: The parameterization of the effect of colonization is summarized by two simple assumptions: “First, we assume that the catchment becomes increasingly vegetated following deglaciation and that the type of vegetation only depends on time since deglaciation. Second, as areas of the catchment become colonized, the rate at which water is evapotranspired increases until reaching a maximum value representative of the climax vegetation state.” While the first assumption seems reasonable (some references would certainly be useful), ...

The first assumption is based on the time since deglaciation being highly correlated with vegetation types, biomass, and cover (Crocker and Major, 1955; Burga et al., 2010; Chapin et al., 1994; Klaar et al., 2015; Whelan and Bach, 2017; Fickert et al., 2017; Wietrzyk et al., 2018). The assumption does not include any variations in vegetation regrowth with altitude, which have been shown to affect vegetation growth rates
primarily through its influence on air temperature (Cowie et al., 2014; Whelan and Bach, 2017). Yet, succession rates have been shown to be comparable at different altitudes throughout glacier recession as changes in air temperature with altitude are offset by climate warming (Fickert et al., 2017). We have added the following citations to the manuscript, and thank you for the suggestion. (P6 L23--29)


Wietrzyk, P., Rola, K., Osyczka, P., Nicia, P., Szyman´ski, W., and We,grzyn, M.: The relationships between soil chemical properties and vegetation succession in the aspect of changes of distance from the glacier forehead and time elapsed after glacier retreat in the Irenebreen foreland (NW
Thus, rates basin and decreases state evapotranspiration establishment decrease following few in variety of runoff vegetation. The project description here: http://gepris.dfg.de/gepris/projekt/318089487?language=en).

... the second assumption omits an important body of hydrological literature of the effect of vegetation on the water balance, and in particular the effect of forest (e.g. Andréassian, 2004). Forests show typically increased ET fluxes during younger states as compared to the climax state.

Whether the typical vegetation succession to be expected in glacier catchments leads to a continuous ET increase with vegetation cover increase, remains to be demonstrated. I am not aware of literature on this topic (but it might well exist of course). In general the evolution of hydrological / geomorphological / pedological processes in moraines (and related runoff processes) can be assumed to be still largely unknown (see an ongoing project description here: http://gepris.dfg.de/gepris/projekt/318089487?language=en).

The second assumption is that as areas of the catchment become colonized and vegetation biomass increases, the amount of precipitation that does not contribute to runoff on an annual scale, ET, increases until reaching a maximum value representative of the climax vegetation state. The assumption is based on a general understanding of the relationship between biomass, vegetation cover and decreased basin runoff. A variety of processes are expected to cause annual ET to increase including: increases in vegetation biomass, type, percentage cover, and temperature (Jaramillo et al., 2018; Andréassian, 2004; Barnett et al., 2005), yet as the reviewer rightly points out there are few studies on changes in evapotranspiration throughout vegetation succession following deglaciation. Results for non-glaciated paired watershed studies show a clear decrease in annual basin runoff moving from the time of initial reforestation to the establishment of climax forest (Andréassian, 2004; Filoso et al., 2017). Changes in evapotranspiration rates through the transition period from initial reforestation to climax state in non-glaciated basins is variable. Some studies show approximately monotonic decreases in annual basin runoff from reforestation to climax forest (Andréassian, 2004, and references within; see there Fig. 8). However, others show a non-linear decrease in basin runoff after deforestation, with younger states having higher evapotranspiration rates than climax state (Andréassian (2004), and references within; see there Fig. 9). Thus, there are two scenarios and the debate between them continues, either
Evapotranspiration on newly revegetated land is lowest at first and progressively increases until climax state or evapotranspiration is initially lowest and increases rapidly before decreasing and stabilizing above deforestation levels at climax state. These conflicting results have been explained as particular to different species of tree with the latter, non-linear increase in evapotranspiration, measured primarily for eucalyptus trees (Andréassian, 2004).

Our modeling is of plant growth in a previously deglaciated basin, where transitions in evapotranspiration have yet to be extensively studied. However, based on evidence for the first assumption we can assume that vegetation biomass, types, and cover are all increasing with time since deglaciation. There are multiple studies showing that increased biomass and reforestation leads to higher levels of evapotranspiration and decreased annual basin runoff (Sun et al., 2010; Klaar et al., 2015; Jaramillo et al., 2018; Bosch and Hewlett, 1982; Andréassian, 2004). In our general modeling we choose to model evapotranspiration as monotonically increasing in a stepwise manner throughout vegetation growth for the following reasons. First, we are attempting to study general basin characteristics so exceptions to general rules (e.g., eucalyptus trees) are of less importance. Second, the step wise increase in ET allows us to focus on specific stages of vegetation and not the exact transition between stages which is less well understood; most studies show an eventual increase in ET and interception after vegetation reaches a climax state (Andréassian, 2004). These two assumptions provide the basis for our landscape modeling throughout glacier recession. We have more clearly delineated the justification for these assumptions in the methods. (P2 L34--P3 L1, P6 L29--P7 L13, P19 L15--16)


The hydrological assumptions should however be a bit more elaborate, including good references for glacier catchments and a detailed review of what we know today about the evolution of the water balance of newly vegetated areas in such catchments. If no sufficient literature can be found, possible hypotheses should be discussed in detail. This literature review should also include the important ongoing discussion what the effect of decreases in snow to rainfall ratios has on the catchment-scale water balance (Berghuijs et al., 2014). The relative decrease of snowfall might significantly contribute to the reduce of basin-scale runoff (add to the effect of vegetation).

We have found equivocal studies on the impact of changes from snow to rainfall on annual streamflow. Basins in southeast Alaska show strong seasonal changes but no discernible trend in annual streamflow from moving from snow-dominated to rain-dominated climate regimes over 20 year climate oscillations (Neal et al., 2002). A review of studies in the western United States found no clear trend in how mean annual streamflow responded to changes in precipitation phase across different basins (Tague and Dugger, 2010). Finally, a study of non-glaciated basins across North America suggests that a change in phase of precipitation from snow to rainfall results in larger interannual variability, and lower mean annual streamflow (Berghuijs et al., 2014). These differing results do not allow for the determination of a simple modeling parameter to include for changes in annual runoff associated with changing precipitation regime in a glaciated basin. We briefly justify why we choose to not include the effect of changing from snow to rain in our modelling of annual runoff for glaciated basins. We also mention the possible effect of the alternative hypothesis and how it affects our results. (P8 L26–27)
Similarly, a topic that should be discussed (even if not included in the analysis) is the interaction between glacier retreat and groundwater recharge. Not much is known so far about this topic but glacier retreat might change the relative amount of water that is available to vegetation in the non-glaciated part.

Thank you for this suggestion. Reviewer 3 also pointed out a number of processes that we neglected in our model. In response to those comments, we briefly discuss how processes such as groundwater recharge might modify our model results for annual basin runoff. We note that changes in glacier mass balance have been shown to affect groundwater recharge, however the impact to basin runoff is seen more strongly at seasonal rather than the annual timescales we are modeling (e.g., Liljedahl et al., 2017). (P3 L6, P19 L17--18)


To summarize, to increase the value of this study, I suggest a good literature review of the impact of glacier retreat and the associated reduction of snow-to-rainfall ratio on the water balance of high alpine catchments. Based on this, key processes and their synergy and possible unknowns should be identified. Based on this, the hydrological model can either be kept as is (but with more realistic future scenarios) or be refined. At the very least, the hydrological simplifications should be more explicitly discussed.

We acknowledge that there are limitations to the assumptions that we made for both the landscape and glacier models. These assumptions were made due to either a desire to understand a few fundamental parameters that influence basin runoff or a lack of consensus on various processes. We prefer not to add additional model complexity at this point and chose to focus on the key processes/parameters. In the revised manuscript we added justification for our chosen model parameters and also discuss
how some of the parameters identified by the reviewer that were not included in our model, such as the snowfall to rainfall ratio and changes in ET, may affect trends in runoff (see also response to reviewer #3). (P2 L28--P3 L4, P6 L23--P7 L13, P8 L26--27, P19 L4--18)

**Detail comments:**

- Regarding the future ET fluxes, the reference to a paper that studied forest versus crop/pasture across the globe in non-mountain environments (Zhang et al., 2001) is probably not adequate.

This issue was also raised by reviewer #3, who suggested a number of additional studies that we have now included in the paper. (P6 L25-27)

- The concept of “runoff ratio” is an engineering concept that was developed to separate precipitation into surface runoff and infiltration at the event scale (e.g. for the application of the so-called rational formula). What is used in this model is the “annual runoff ratio”, which is the ratio between total basin runoff and the total incoming precipitation. The total basin runoff is the sum of direct surface runoff and fast and slow subsurface runoff processes (and not the "runoff over an area of land"); the latter are the result of soil–vegetation interactions and groundwater recharge/release processes. This should be clear to avoid confusion for non-hydrologists.

Thanks. We have clarified this in our revision. (P6 L18--19)

- the conclusion should give clear indications about what should be explored on the hydrological side (not just the glaciological side)

We agree, and we have addressed model limitations in more detail in the manuscript (discussed above and in response to reviewer #3). (P19 L6--7, P19 L15--18)
Summary
In this study the basin (glacier) peak water trajectory, following glacier retreat, is modelled using a glacier flow model in combination with some parameterizations, to simulate glacier retreat and changing vegetation in the non-glacierized areas of the basin. The effects of basin slope, climate type (maritime and continental), vegetation rate and type, and climate change scenario (RCP2.6 RCP8.5) on this trajectory are tested. The results show that slope and climate type influence the magnitude and timing of peak water, and this is related to the glacier response time. A continental climate and shallow slopes cause a higher increase in basin runoff and a later time of peak runoff, compared to a maritime climate and steep basin slopes. The effect is more pronounced in the RCP8.5 scenario. Vegetation rate and type is influencing how fast runoff levels decrease after peak water to pre- peak water runoff levels and vegetation type determines how much runoff drops after peak runoff compared to initial runoff levels.

The modelling approach is rather mathematical, in contrast to many other glacio-hydrological studies published in HESS. This allows to perform an interesting sensitivity study, which is of interest for the HESS community. However, the more glaciological way of describing a glacierized hydrological system as presented in this study, requires more clarity, explanation and discussion when publishing in a hydrology journal (HESS). Please find my explanation, together with some other concerns below. Apart from that, the manuscript is generally well written and the figures are nicely presented.

Thank you for this feedback. Our goal with this paper was to write it in a way that would be of interest to both glaciologists and hydrologists, and we have therefore made a concerted effort to revise the model description to make it more accessible to non-glaciologists.

Major issues
1. Modelling framework
The study uses a simple glacier flow model in combination with parameterizations of runoff ratios to model vegetation succession in the non-glacierized parts of the basins. Together with some climate “input”, this is coupled to calculate basin runoff, glacierized runoff and nonglacier runoff over time. However, the problem is that the description of the model in the different equations and sections is not well connected (e.g. how the modelling of glacier dynamics is connected to the calculation of Qg or in which
Equations parameters are changing (apart from C and T)). This is important to better understand and interpret the results.

Equation 1 gives a good overview of the main modelling framework. However, from the other equations given in the methods section it is not always clear how they fit the calculation of the total basin runoff. The description of the precipitation input is sometimes a bit confusing. Why is it a separate section? And why is there written that it includes the solid and liquid fluxes? This is a bit confusing since there is no temperature input involved. Maybe it should be also made clear that precipitation “input” is constant every year. Precipitation is in this study also not a real input to e.g. the glacier, because the mass balance is another parameter partly independent of precipitation. Please clarify the sentence “precipitation at sea level is chosen to ensure that the precipitation at elevation exceeds glacier accumulation rates”. Does it mean that precipitation should fit the mass balance rates above zero? And what is the exceeding precipitation assumed to be? Can this be indicated in Figure 1?

In response to these questions:

- The precipitation parameterization is input as a separate section because it is needed for both the glacier and non-glacier components of the model (in the subsequent sections, which we now refer to when presenting the precipitation parameterization). (P4 L21)

- The precipitation parameterization describes the total precipitation flux, and therefore includes both solid and liquid precipitation. This is important to note because snow that falls in winter melts and runs off in the summer and therefore contributes to the annual basin runoff. The exception is in the glacier accumulation area, where not all of the snow will melt during the summer. This is accounted for through the mass balance parameterization; in the accumulation area, the mass balance rate is positive, and therefore the amount of runoff generated at a specific location is less than the precipitation flux. Lower on the glacier, the mass balance is negative, and thus the runoff produced exceeds the precipitation flux. We have added a few sentences to the methods to clarify why the precipitation flux includes both solid and liquid precipitation and to indicate that our method for calculating glacier runoff is identical to calculating the sum of rain plus glacier melt (without the need of a climate model that calculates those terms independently). (P4 L2-4)

- We require the precipitation at elevation to exceed the glacier mass balance rate because the amount of snow that accumulates on the glacier can’t be more than the amount of snow that falls on the glacier. If the precipitation rate equals the mass balance rate then there is no summer melt; if the precipitation rate exceeds
In the section about the glacier runoff and the glacier model, it might be more clear when the section starts with the description of the glacier model and then show that the output of this glacier model (surface area of the glacier \( \Omega \ g \)) is used to calculate the glacier part of the total basin runoff (and how it influences \( \Omega \ n \) in the next section). Why is \( P(z) \) written in equation 2, but is \( (z) \) left out in equation 4? What does “min” indicate in equation 4? And why is there a maximum mass balance (Bmax)? Why can \( P \) increase with height but \( B \) not? What is meant with glacier hypsometry (L21 P4)? If it refers to equation 3 it only indicates length changes (since the width is constant), or does it also include the glacier thickness due to “z” in \( P \) and \( B \)? What does small \( h \) mean in equation 5? Is this the slope? What is solved from equation 5? And how does it relate to equation 7? I think some more explanation here would be beneficial.

We prefer to start this section with the equation describing glacier runoff (equation 3) because for non-glaciologists this is the only equation that really matters. Everything that follows are basically details about the glacier model. To help clarify, though, we have added a statement that indicates that equation 3 changes with each time step because of changes in glacier surface elevation and extent, which we account for with a glacier flow model. (P5 L10--13)

Additional comments:
- “(z)” should be included in equation (4); thanks for catching this. (P5 L5)
- “min” refers to the minimum of two numbers i.e. the balance rate increases with elevation until reaching a maximum value, B_max.
- The mass balance profiles, which reach a maximum value at high elevations, are based on field observations from many glaciers. We have now added a reference to Van Beusekom et al. (2010) that demonstrates this phenomenon for both maritime and continental glaciers. The leveling off of the balance rate at high elevations is probably due to several processes, including things like refreezing of meltwater that percolates into firn and the length of the melt season, but it can also be understood in terms of changes in precipitation type (solid vs. liquid) with elevation. At high elevations precipitation occurs mainly as snow, and since ablation rates scale with temperature (and therefore elevation), the difference between accumulation and ablation is linear --- and observations suggest that the difference between these two is roughly constant at high elevations. At low elevations, a larger fraction of the precipitation falls as rain and does not contribute to the glacier’s mass balance; thus the mass balance profile is more
strongly affected by ablation processes there, resulting in a bending of (or kink in) the mass balance profile. (P5 L4)
- We replaced glacier hypsometry with “glacier geometry (surface elevation and extent)”. (P5 L10)
- Little ‘h’ is the surface elevation and is now indicated as such. (P5 L2)
- Equation 5 is solved for the velocity, which is then used to calculate changes thickness via Equation 7. This has been clarified. (P6 L10)


The “t=0” in L1 P6 is a bit confusing with the later explanations that the climate in the model is kept constant during the first 10 years. What is t(0) in this case? Start of the simulations or when a portion of the catchment is deglaciated? Related to that it is also confusing that it is written that the climate is kept constant (for each climate type?) to reach a steady state (spin-up) and is then changed by changing the ELA, but then the climate is held constant for 10 years (no change in ELA)? Please reorder. Also the definition of “constant climate” (L25 P6) only becomes clear later in the text when it is explained that climate change is modelled by changing the ELA. The last sentence of the methods also requires some more explanation, that the simulations continue until the glacier have reached a new steady-state. How can the glacier reach a steady state when the ELA is increasing every timestep, especially in the RCP8.5 scenario? Is there a maximum ELA?

We have changed our graphs so that t=0 is the time that the climate starts to change, and we removed the text about holding the climate constant for the first 10 years of each simulation. (see figures 3--5, 7--8)

The last sentence states that the simulations are run until the glaciers reach a new steady-state or completely disappear, the latter of which happens in the RCP8.5 scenarios.

Apart from the methods model description also other parts of the manuscript sometimes lack clarity:
- It would help if the key metrics described in the results are indicated in a conceptual figure. Especially the time to pre-retreat basin runoff and end basin runoff would get more clear from such a graph
We agree and think that this is an excellent suggestion. Thanks. We have added a figure and a statement in the introduction about the metrics that we are assessing. (See Fig. 1)

The “Thus” sentences in the manuscript are not always straightforward:

- “thus the basins do not have the same length” (L8 P7) – this depends on climate type (and thus mass balance gradient) but also on slope? It would help if the initial glacier areas/lengths and volumes for all simulations (climate type and slopes) are given, together with their change over time. In that case the fractional volume changes e.g. for steep glaciers and the different climate types could be better interpreted. Why is for example the fractional volume and area change similar for both climate types, but the peak runoff differently – due to a larger volume in the continental climate? It also helps to visualize that there is a limited amount of newly vegetated land at peak runoff. It would be good to indicate/explain differences in glacier geometry due to climate type and slope in the results or methods based on the equations, e.g. why shallow sloped basins contain longer glaciers.

This sentence has been re-worded. (P8 L28--29)

- “Thus the model results tend to overemphasize the relative importance of glacier runoff on basin runoff” – because in reality one does not start with 100

This sentence has been re-worded. (P4 L15--16)

- “Thus we assume that the basal shear stress is at the yield stress” – please explain the “thus”

“Thus” has been replaced with “In other words”. (P6 L7)

2. Clarity

- In the results section: why are results sometimes explained for one of the two climate scenarios only?

This is done when the results that are being described are universal, or in other words, that trends are the same for both climate scenarios.

- What is meant with glacier geometries? Slope, length, thickness?
Glacier geometry was replaced with basin slope. (P13 L11--12)

- What is the reason that glacier runoff peaks before basin runoff? The decreases in precipitation on glaciated land also influence basin runoff?

Peak basin runoff lags peak glacier runoff because nonglacier runoff continues to increase when glacier runoff is at a peak. This can be understood through a simple analysis of the basin runoff given in Equation 1:

\[ Q_s = Q_g + Q_n \]

Taking the time derivatives of both sides:

\[ \frac{dQ_s}{dt} = \frac{dQ_g}{dt} + \frac{dQ_n}{dt} \]

When the glacier runoff is at a peak, \( \frac{dQ_g}{dt} = 0 \) and therefore \( \frac{dQ_s}{dt} = \frac{dQ_n}{dt} \). Because the nonglacier runoff is increasing at this time as new bedrock is being exposed, the basin runoff must also be increasing, which implies that it has a later peak. We have added a paragraph to the end of the discussion which explains this and, in addition, explains the observation that peak basin runoff exceeds peak glacier runoff (in both absolute and relative terms). (P17 L18--P18 L12)

- What is magnitude in case of end basin runoff? The magnitude is smallest for peak basin runoff, but largest for end basin runoff in case of a heavily forested state? (P8).

The magnitude of end basin runoff is the amount of basin runoff that occurs when the glacier reaches a new steady state (RCP2.6) or disappears (RCP8.5). P8 L13-14 “Overall… ...(low runoff ratio).” states that the magnitude of end basin runoff is smallest when the vegetation progresses to a heavily forested state. (Now, P10 L1--2)

3. Structure
The introduction section of this manuscript lacks the description of a clear knowledge gap. It should be emphasized more what is new about this study (landscape coupling?) and what we do not yet know. The results section includes quite some interpretation, and even refers to the discussion (glacier response times). The results section also includes text about key metrics that should shift to methods.
We have added a conceptual figure, and associated text, to the introduction to clarify the knowledge gaps and describe what is new in this study. This also allowed us to introduce the metrics that describe the changes in runoff curves. Nonetheless, we do feel that our initial draft did describe the knowledge gaps that we are addressing, particularly in paragraph 4 of the introduction. For example, we wrote “...., these case studies do not elucidate the broader geomorphological and glaciological controls that govern the hydrological responses of watersheds to ongoing glacier recession.” (P2 L28--P3 L4, Fig. 1)

4. Discussion and implication

In the discussion the hydrological changes (changes in annual runoff) are discussed together with their controls and compared to other literature. However, the implication of the quantitative analysis (as presented in the introduction) is lacking. What do the numbers mean and how can they be transferred to glacierized catchments around the world? Some numbers are compared, but it is not always clear which part of the graphs (trajectory) agree with observations. The simulations all start with 100% glacier cover, but what can we learn from that when a catchment has e.g. 50% glacier cover? Will it have the same variations? And what if the glacier hypsometry has not a fixed width? Why has a 1D model been chosen? Has \( t(0) \) been in the past for glacierized catchments and can we expect a similar peak runoff and rate of decline in annual runoff? Is e.g. the size of the glacier modelled in this study representative? Other aspects that could be more emphasized is the drop of annual runoff below pre-retreat levels, which is e.g. not found/modelled in other studies (e.g. Huss Hock, 2018). Also the importance of including vegetation could be more stressed and compared with other studies (where it is often neglected).

Some specific replies to these questions:

- Our goal with this study is not to describe the specific responses of particular glaciers or regions, but rather to develop a theoretical understanding of how variations in annual basin runoff depend on several key parameters. From our study a reader should be able to make an educated guess about how basin runoff will vary for their glacier of interest. More accurate, glacier specific predictions would require designing a coupled glacier-landscape model for a particular region. (P2 L32--P3 L4)

- More detailed comparisons between model results and observations are difficult/impossible owing to a lack of streamflow measurements over decadal-to-centennial time scales.

- The impact of initial glacier coverage on the results was initially explored but had the straightforward effect of adding a constant (the basin runoff from a portion of
the basin with climax vegetation) to any calculation of basin runoff. Thus, having a smaller initial glacier coverage reduces the impact of glacier loss on basin runoff in an easily predictable way, which we now discuss in the manuscript. (P19 L14)
- See response to reviewer #1’s comments regarding the impact of glacier width and the choice of using a 1D model.
- The question of dis(equilibrium) is an interesting one, as glaciers are probably never truly in a steady-state, and the distance from steady-state may have interesting consequences for interannual variability in runoff. We now discuss this in more detail in the conclusions and leave it for future work. (P19 L10--13)
- The drop in annual runoff below preretreat levels is not found in other studies that do not account for vegetation. We emphasize this point in the manuscript.

Also the glacier response time is discussed, as an explanation why slope and climate type influence the hydrological response. Why is peak basin runoff related to the time a glacier needs to respond to climate change? This would only be half way (the time it needs to reach a new steady state)? Can the different simulations for which a response time is calculated also be indicated in Figure 8? The conclusions that are drawn in the text can now not be seen in the Figure. Is the response time – peak runoff relation also influenced because the ELA increases every time step?

Peak basin runoff occurs relatively early during glacier recession, when glacier runoff is a large proportion of total runoff (see Figure 7) and is therefore a dominate control on total runoff. Peak glacier runoff is related to the glacier response time because glaciers with long response times are pushed farther out of equilibrium and take longer to evolve back toward a steady state.

The glacier response times do not vary with any changes in the landscape parameters, and therefore only the peak runoff and time to peak runoff are affected by climate change and vegetation types/rates (in other words, the vertical axes in Figure 8 are affected by vegetation and climate change but the horizontal axes are not). We now clarify what data we are plotting in this figure. Use of a different climate change scenario (e.g., RCP2.6) would change the curves, with slower rates of climate change causing smaller fluctuations in basin runoff (see previous figures). (See caption for Fig. 9, P17 L8, L11)

Specific remarks
L7 P1: “rate of climate change” – what does rate mean here? Scenario might be more clear
This was referring to the climate change scenario. We have re-written the abstract, so this comment no longer applies. (Changed abstract)

P1 abstract: “Peak basin runoff” – use magnitude of peak basin runoff as in rest of paper to be more clear
We have re-written the abstract, so this comment no longer applies. (Changed abstract)

L24 P1: “Moreover, changes in runoff...ecological function of downstream aquatic ecosystems” – The order of the sentences is strange here, because one first reads that changes in glacier runoff only affect the downstream aquatic ecosystems, but on the next page it is described how all the ecosystem services will be affected by changing glacier runoff.
The changes to the structure and function of aquatic ecosystems are an example of how changes in glacier runoff propagate downstream that is separate from the ecosystem services listed previously. We left the order of the sentences as they were originally written.

L2 P2: “Glacier runoff. . ..water budget” – this sentence does not fit here, move up or connect better
We added some text to improve the connection to the previous sentence. (P2 L5--7)

L5 P2: “lower baseline” – only Moore et al. (2009) show a lower baseline, Jansson et al. (2003) not. Also Huss Hock (2018), for example, show no lower baseline. So either explain why there is a lower baseline, or leave it out in the introduction and discuss the differences presented in the literature in the discussion (or discuss in the introduction)
Both the Jansson et al. and Moore et al. papers (cited in this sentence) show a lower baseline. And, while it is true that the Huss and Hock paper (not cited in this sentence) did not show a lower baseline, they explicitly acknowledged that they “do not consider other processes in the gradually growing deglacierized proglacial area, such as evapotranspiration or changes in groundwater recharge and land cover” that are responsible for the lower baseline in annual runoff seen in our study. Thus we left the sentence as written.

L7 P2: “increase roughly 50 percent by end of century” – compared to what?
We changed this to “during the 21st century” to be more precise. (P2 L11)

L11 P2: “On a global scale. . ..South America” – be more explicit here, Arctic, Canada and Russia have higher glacier coverage basins? In Asia, Europe and South America glaciers have retreated and therefore lower glacier coverage?
We added the phrase “where glacier coverage is lower” after “Asia, Europe, and South America”. (P2 L17)

L14 P2: How can “Stahl and Moore (2006)” be both cited as a study on individual catchments and on regions? Nolin et al. (2010) is a study on a specific catchment so why mentioned as a study focused on the regional scale? Huss and Hock (2018) is a global scale study? “case studies” in the next sentence does not fit all of the references mentioned here.

Stahl and Moore 2006 is listed as both an individual catchment and region because it reports data on runoff change in over 100 individual glacierized catchments and uses these results to draw conclusions about changes in glacier runoff across British Columbia, which we consider to be a region. The Nolin reference was misplaced and has been moved earlier in the sentence. This is getting super particular but the Huss and Hock paper models changes in glacier runoff for 56 large basins, which is not all of the glacierized basins world. All but one of of the basins modeled by Huss and Hock are categorized into 4 regions in the paper: Asia, Europe, N. America and S. America. Thus, the paper provides insight into future glacier runoff change in these regions and is appropriate as referenced.

L18 P2: what does “also” mean here?, same for “also” in line 21?
On line 18, we replaced “also” with “in addition”. We did not replace the “also” in line 21 because we feel the meaning should be self-evident to the vast majority of readers. (P2 L24)

L21 P2: reduce the use of “the fact that” throughout the manuscript
This phrase was used 5 times in 18+ pages of text. We reduced our use of the phrase by 40%. (P2 L15--17, P11 L22, P14 L18)

L25 P2: “annual basin runoff” is used mostly in the paper, but in title and introduction “water yield” is used – why?
We now use “annual basin runoff” throughout the paper. (Title, P2 L8,11--12,13,14,18)

L1 P3: “definition 5” – please explain
We have added “total runoff from the glacier surface” to the parenthetical remark, which is the 5th definition for glacier runoff presented in O’Neel et al., 2014. (P3 L9)

L4 P4: notation of variables with an overdot to indicate width average – is overdot usually not used to indicate a derivative?
We use the dot indication to denote a rate, or derivative with time, they just happen to also be width averaged.

L7 P3: “precipitation at elevation” – which elevation?
Assuming you mean P4. We re-worded this sentence for clarity. (P4 L25--26)

L8 P5: “timestep” – indicate that timestep is one year
The time step is .08 of a year and this has been clarified. (P6 L10)

L15 P5: “runoff ratio (the ratio of precipitation to runoff over an area of land)” – switch precipitation and runoff -> the ratio of runoff to precipitation
Change has been made. (P6 L18)

L24 P5: “runoff ratios range from 0.5 (forest) to close to 1 (ice)” – on the next page it is written that runoff ratios are 1, and that it represents rocky high elevation environment with no vegetation?
We changed the sentence to “...~1 (ice or rocky alpine terrain with no vegetation)” (P7 L15)

Eq. 11 and 12 P6 and P7: indicate (e.g. as subscript) that equation is for RCP2.6 and the other for RCP8.5
We added the requested subscripts to the equations. (P8 L19, L22)

L8 P7: “As the glacier recedes”, add comma
Comma added. (P8 L29)

L3 P9: “on slope and climate type and is related to the glacier response” – remove “and” or is another variable forgotten here?
Removed “and” (P11 L8--9)

L10 P9: Fig 5a,b – this should be figure 5 a and c – see also other references to Figure 5 in this part of the results
Good catch, the corrections were made. (P11 L14, L19, L20, L25)

L9 P11: “slightly longer times” – longer times of what?
Added “to peak and preretreat basin runoff” to clarify. (P11 L33)

L5 P12: “for all glacier geometries”- what is meant here? Slope?
Changed “geometries” to “basin slopes”. (P13 L12)
L5 P13: “final steady state basin runoff following glacial recession is strongly influenced by the rate and type of vegetation” – do you mean here the final steady state basin runoff or also the timing of the end basin runoff? In the first case, this sentence contradicts the results
We clarified that steady state basin runoff following glacial recession is strongly influenced by the type of vegetation that colonizes ice free areas of the catchment. (P14 L12)

L15 P13: “longer response time” – what is response time here?
Added “to peak runoff” to clarify the reference to response time. (P15 L4)

L29 P13: “end glacier runoff” – what is end glacier runoff?
Deleted “end” so that the term “glacier runoff” is consistent with the terminology in Nolin et al. (2010) (P14 L16--19)

Figures:

- **Fig. 1:**
  - Can you indicate ELA in fig. 1c?
  - For clarity it might help to also plot the lines for a maritime climate and if possible also for the RCP2.6 scenario
We now indicate in the caption that the ELA occurs where the balance rate is 0. We prefer to only plot one climate type and RCP scenario to keep the figure clean. (See caption Fig. 2)

  - It would be helpful to have the same x and y axes in all figures, since for the interpretation of some results one needs to look at several graphs
We have changed our figures to have similar x- and y-scales when presenting basin runoff curves. (See Fig. 3,4, and 5)

  - Why is legend in some figures in the right graph and in others in the left graph?
We have now moved the legends to the left panels.

  - Please indicate the degree symbol in the “slope” legends
We have made this change. (See Fig. 3,7, and 8)
When looking at the figures it is not directly clear what is compared in the left and right graphs, although it is indicated in the figure captions. Could the figures get a title or a label in the graph so it is clear what is compared in both?

Adding a title would be redundant with the caption, so we have left the figures as is.

- **Fig. 2**:
  - Why is y axis starting at 0, but at 70 in figure 4?
  - What determines the length of the (horizontal) line indicating after peak runoff in figure a? I assume glaciers have disappeared and since no vegetation is present in figure 1 no final vegetation state needs to be reached.

We have changed the figures to have the same scales. See above comment.

The horizontal lines arise because the model is required to run through the full vegetation succession, even though the runoff ratio doesn’t change.

- **Fig. 3 and 4 and 5**: Why is the basin slope 5 and does figure 2 not show a slope of 5 degrees?

Figure 2 shows the range of runoff curves, and the curve for slope 5 can be inferred from the curves that are presented in Figure 2.

- **Fig. 5**: Missing in caption, results are only shown for maritime climate?

The caption does indicate that the results are for a maritime climate.

- **Fig. 6**:
  - Add symbols as legend
  - What determines the end of the simulation in both graphs? Compared to Figure 2a the results stop earlier in Fig. 6a. Also for 6b this is not clear.

We use the legend to describe the color of the curves. The meaning of the symbols are indicated in the caption.

In Figures 2a and 6a, the glaciers disappear at the same time (for example, at t=300 years for the dark blue curves). The extra length of the curves in Figure 2a is due to running the landscape model to completion (as described above).
This manuscript addresses the “peak water” concept associated with glacier response to climatic warming. As reviewed in the introduction to the manuscript, this concept was described in two review articles and has been studied empirically in a number of site-specific studies. Although the empirical studies generally confirmed the conceptual model in broad terms, two fundamental questions arise from this body of literature: (1) what is the time scale over which the “peak water” cycle progresses, and (2) does the trajectory ultimately lead to reduced runoff.

To address these questions, the authors combined a numerical model of glacier dynamics with a parameterized model of vegetation succession and its influence on runoff. They applied the model to glaciers within simplified valley geometries for scenarios representing various combinations of bed slope, vegetation type, and rates of vegetation development for two different climate types and two different climate change scenarios.

The simulations confirmed that basin runoff ultimately decreases relative to pre-warming conditions. For scenarios without vegetation development, this decrease results from the surface lowering associated with glacier thinning and retreat, and the subsequent reduction in precipitation. Development of vegetation results in greater reductions in basin runoff. The magnitude of and time to “peak water” were greatest for continental glaciers with shallow bed slopes and lowest for steep maritime glaciers.

Overall, this is an interesting and relevant study. However, the conclusions, at least in qualitative terms, could have been deduced fairly directly from the underlying assumptions and basic knowledge of glacier dynamics. I believe that some further analysis and more detailed consideration of vegetation dynamics and ecohydrology would strengthen the contribution of this work. Some specific comments follow.

Thank you for your careful review of our manuscript and your constructive feedback. It is clear from your review, as well as the other reviews, that we need to better articulate the objectives and scope of our study (particularly in the title and introduction). As you point out below, we have not accounted for several processes that likely affect basin runoff over decadal time scales. We agree that these processes are important and that they should be discussed in the manuscript. However, our goal was to focus on what we feel are the key controls on basin runoff: basin topography, climate, and revegetation.
Work on modeling glacier retreat has indicated that basin topography and climate are key factors determining retreat rates, and the effects of revegetation on basin runoff have not been systematically explored. Instead of incorporating all of the additional processes that affect runoff (which could potentially be papers on their own), we have included brief discussion of these processes and their potential impacts on runoff. In addition, we have more clearly justified our selection of parameters. (P2 L28--P3 L4,P19 L4--18)

1. There are additional processes by which annual runoff would decline in a warming climate that are not accounted for in the model. First, as pointed out by another reviewer, recent literature suggests that a shift from snow to rain results in decreased runoff even with no change in the amount of precipitation. Second, increasing air temperatures would be expected to increase evapotranspiration, subject to soil moisture availability. A third reason that one would expect glacier retreat ultimately to reduce basin runoff is that evaporation/condensation from snow or ice is typically low and often dominated by condensation, whereas an unglaciated surface would lose water by evaporation.

For the first point, please see our response to the first reviewer. To the second point, we assume that the impacts to ET from changes in vegetation communities and biomass far outweigh changes driven by climate warming. This assumption is supported by Barnett et al., 2005, who found that increases in ET associated with climate warming are attenuated in snowmelt-dominated regions of the globe. The third point raised by the reviewer is important, however we feel that we have accounted for this effect as the changing runoff ratios account for net changes in evapotranspiration from moving from glaciated to vegetated terrain and thus include changes in condensation. (P8 L26--27,P7 L12--13)


2. The scenarios represent glacier retreat followed by vegetation succession. However, retreat can also result in formation of lakes, which can accelerate glacier retreat and would ultimately provide an additional mechanism for reduced basin runoff via evaporation (Moyer et al., 2016). While it is likely not feasible to incorporate lakes into the model, this point should be acknowledged.
This is a good point, and indeed lake-calving glaciers are often some of the fastest retreating glaciers (Larsen et al., 2007). Lakes could be incorporated into the model by using basin topography that has overdeepenings and then forcing faster retreat through the overdeepenings, although the processes driving calving retreat are poorly understood (e.g., Benn et al., 2007). Incorporating lakes in a systematic way is challenging, though, because the glacier evolution will depend on the location, depth, and length of the lake(s). Moreover, although evaporation from lakes will tend to reduce basin runoff, the formation of a lake prevents the development of a forest and will tend to increase basin runoff. In other words, evapotranspiration from a forest is being replaced with evaporation from a lake. With that in mind, we briefly mention the potential impact of lakes in the revised paper. (P19 L6--7)


3. The model does not accommodate the development of a supraglacial debris layer, which can reduce meltwater generation and the rate of glacier retreat. See Frans et al. (2016). This point should at least be addressed as a discussion point if not incorporated into the model.

We agree that a supraglacial debris layer can reduce meltwater generation and the rate of retreat, the latter of which has also been nicely demonstrated by Anderson and Anderson (2016) and Kienholz et al. (2017). With respect to our study, the challenge with including debris cover is that it depends strongly on bedrock lithology and therefore adds yet another parameter (erodibility) and would distract from the key questions that we are addressing. While not including it in the model, we have mentioned the potential impacts of debris cover on glacier recession in the revised manuscript. (P19 L8--9)


4. The analysis focuses on annual runoff, and the authors appropriately acknowledge the importance of considering seasonal runoff variations, particularly in late summer. This discussion could be extended by commenting on the relative magnitude of glacier contributions to seasonal and annual runoff (e.g., as a fraction of total runoff). Good references to draw upon are Frans et al. (2016) and Naz et al. (2014), both of which analyzed effects of glacier retreat on seasonal runoff.

Thank you for this suggestion; we acknowledge this issue in the revised manuscript. Figure 6 illustrates how the proportion of (non)glacier runoff varies over decadal time scales with no vegetation. The proportion of glacier runoff on seasonal timescales should follow similar trends because, although the summer runoff from a glacier will increase during glacier retreat, the proportion of the basin that is occupied by glacier ice also decreases. Perhaps more important is the interannual fluctuations that occur and whether large interannual fluctuations occur when the runoff is near “peak water”. We now mention in the introduction that we are modeling the “base flow” upon which seasonal and interannual variations are superposed. See also response to next comment. (P2 L30, P19 L10--13)

5. The climate scenarios do not include decadal fluctuations, which can complicate peak water cycles – e.g., by generating transient periods of glacier advance, at least early in the warming phase. See, for example, Figure 4 in Clarke et al. (2015) and Figures 8 and 9 in Frans et al. (2016). Also, the magnitude of glacier runoff varies interannually, being greater in warm/dry years than in cool/wet years. See, for example, Naz et al. (2014). This compensating effect is an important aspect of glacier contributions to basin runoff that is not captured in the model.

We agree, and in some cases interannual variability in runoff may be more significant than long term trends (e.g. O’Neel et al., 2014). The net effect of interannual and decadal variability is an interesting question. Glacier retreat is primarily controlled by long time-scale fluctuations in climate, but short time-scale fluctuations could produce complex, nonlinear relationships between climate and runoff. For example, a series of cool/wet years may slow down a glacier’s rate of retreat, causing it to be farther from equilibrium with the long time-scale climate trends (e.g., see Christian et al., 2018) and perhaps more susceptible to anomalously high melt rates in subsequent years. We also now mention this issue in the revised manuscript. (P2 L30--31, P8 L23--24, P19 L10--13)


6. The model scenarios are rather abstract, and I would encourage the authors to make a more structured effort to “map” the model scenarios into the real world. The authors should consider how they might synthesize their model results with results from the literature to develop a more nuanced conceptual model than those proposed by Jansson et al. (2003) and Moore et al. (2009).

Thank you for this suggestion. Our model scenarios are indeed abstract, as our goal is to determine what controls the variations in basin runoff and the sensitivity of these variations to bedrock topography, climate, and vegetation rates. The metrics that we focus on (i.e., peak runoff, time to peak runoff, time to preretreat runoff, and end runoff) describe the shape of the hydrographs, and the sensitivity of these metrics to model parameters are what make our model more nuanced than those proposed by Jansson et al. (2003) and Moore et al. (2009). We have clarified this point in the revised manuscript. (P2 L28-- P3 L4)

7. Related to the preceding comment, the analysis does not consider the covariation of vegetation succession, climatic regime and elevation, or their influences on runoff generation. The authors cite only two papers to support the range of runoff ratios and three papers to support the parameterized model of landscape evolution. The authors should review a broader selection of papers to provide a better framing of their vegetation scenarios. A selection from the last five years includes Wietrzyk et al. (2018), Fickert et al. (2017), Whelan and Bach (2017), Eichel et al. (2015), Klaar et al. (2015), Cowie et al. (2014) and Mizuno and Fujita (2014).

We agree and thank the reviewer for the thorough and relevant literature provided. We have included a number of new references that help to frame the hydrological model in the revised manuscript (see also response to reviewer #1). (P2 L34--P3 L2, P6 L23--P7 L13)