Anonymous Referee #3

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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.

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.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303 EP –, https://doi.org/10.1038/nature04141, 2005.

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.

Benn, D.I., C.R. Warren, and R.H. Mottram (2007), Calving processes and the dynamics of calving glaciers, *Earth Sci. Rev.*, 82, 143-179.

Larsen, C.F., R.J. Motyka, A.A. Arendt, K.A. Echelmeyer, and P.E. Geissler (2007), Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise, *J. Geophys. Res.*, 112(F01007), doi:10.1029/2006JF000586.

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.

Anderson, L.S. and R.S. Anderson (2016), Modeling debris-covered glaciers: response to steady debris deposition, *Cryosphere*, 10, 1105–1124, doi:10.5194/tc-10-1105-2016.

Kienholz, C., R. Hock, M. Truffer, P. Bieniek, and R. Lader (2017), Mass balance evolution of Black Rapids Glacier, Alaska, 1980–2100, and its implications for surge recurrence, *Front. Earth Sci.*, 5(56), doi:10.3389/feart.2017.00056.

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.

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.

Christian, J.E., M. Koutnik, G. Roe (2018), Committed retreat: controls on glacier disequilibrium in a warming climate, *J. Glaciol.*, 64(146), 675-688, doi:10.1017/jog.2018.57.

O'Neel, S., E. Hood, A. Arendt, and L. Sass (2014), Assessing streamflow sensitivity to variations in glacier mass balance, *Clim. Change*, 123(2), 329-341, doi:10.1007/s10584-013-1042-7.

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.

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).