

Anonymous Referee #2

Received and published: 5 November 2018

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 Q_g 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).
- 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).
- 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 the mass balance rate then there is some summer melt. We have slightly reworded this sentence.

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 Ω_g) is used to calculate the glacier part of the total basin runoff (and how it influences Ω_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 (B_{max})? 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.

Additional comments:

- “(z)” should be included in equation (4); thanks for catching this.
- “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.
- We replaced glacier hypsometry with “glacier geometry (surface elevation and extent)”.
- Little ‘h’ is the surface elevation and is now indicated as such.
- Equation 5 is solved for the velocity, which is then used to calculate changes thickness via Equation 7. This has been clarified.

Van Beusekom, A. E., O’Neel, S. R., March, R. S., Sass, L. C., and Cox, L. H.: Re-analysis of Alaska benchmark glacier mass-balance data using the index method, USGS Scientific Investigations Report 2010-5247, 16 p., 2010.

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.

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.

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.

- – *“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.

- – *“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”.

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 bed slope.

- *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:

$$dQ_s/dt = dQ_g/dt + dQ_n/dt$$

When the glacier runoff is at a peak, $dQ_g/dt = 0$ and therefore $dQ_s/dt = dQ_n/dt$. 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).

- *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.

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."

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.
- 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.
- 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.
- 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 dominant 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).

Specific remarks

L7 P1: “rate of climate change” – what does rate mean here? Scenario might be more clear

Changed to “climate change scenario”.

P1 abstract: “Peak basin runoff” – use magnitude of peak basin runoff as in rest of paper to be more clear

Added “magnitude” to improve clarity.

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 effect 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.

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 deglaciated 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.

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”.

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 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.

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%.

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.

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.

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. Changed to “Precipitation at any elevation”, but we are specifically talking about precipitation in the accumulation area.

L8 P5: “timestep” – indicate that timestep is one year

The time step is .08 of a year and this has been clarified.

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.

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)”.

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.

L8 P7: “As the glacier recedes”, add comma

Comma added.

L3 P9: “on slope and climate type and is related to the glacier response” – remove “and” or is another variable forgotten here?

Removed “and”

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.

L9 P11: “slightly longer times” – longer times of what?

Added “to peak and preretreat basin runoff” to clarify.

L5 P12: “for all glacier geometries”- what is meant here? Slope?
Changed “geometries” to “bed slopes”.

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.

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

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)

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.

- 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.

- 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.

- 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).