

## ***Interactive comment on “Impact of glacier loss on annual basin water yields” by Evan Carnahan et al.***

**Anonymous Referee #2**

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### **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

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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.

## 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

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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 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 ( $B_{max}$ )? 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.

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

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## 2. Clarity

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

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- In the results section: why are results sometimes explained for one of the two climate scenarios only?
- What is meant with glacier geometries? Slope, length, thickness?
- What is the reason that glacier runoff peaks before basin runoff? The decreases in precipitation on glaciated land also influence basin runoff?
- 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).

### 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.

### 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

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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).

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?

### Specific remarks

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

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

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.

L2 P2: “Glacier runoff...water budget” – this sentence does not fit here, move up or connect better

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

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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)

L7 P2: "increase roughly 50 percent by end of century" – compared to what?

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?

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.

L18 P2: what does "also" mean here?, same for "also" in line 21?

L21 P2: reduce the use of "the fact that" throughout the manuscript

L25 P2: "annual basin runoff" is used mostly in the paper, but in title and introduction "water yield" is used – why?

L1 P3: "definition 5" – please explain

L4 P4: notation of variables with an overdot to indicate width average – is overdot usually not used to indicate a derivative?

L7 P3: "precipitation at elevation" – which elevation?

L8 P5: "timestep" – indicate that timestep is one year

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

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?

Eq. 11 and 12 P6 and P7: indicate (e.g. as subscript) that equation is for RCP2.6 and the other for RCP8.5

L8 P7: "As the glacier recedes", add comma

L3 P9: "on slope and climate type and is related to the glacier response" – remove

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"and" or is another variable forgotten here?

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

L9 P11: "slightly longer times" – longer times of what?

L5 P12: "for all glacier geometries"- what is meant here? Slope?

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

L15 P13: "longer response time" – what is response time here?

L29 P13: "end glacier runoff" – what is end glacier runoff?

*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
- 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
- Why is legend in some figures in the right graph and in others in the left graph?
- Please indicate the degree symbol in the "slope" legends
- 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?

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- 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
- Fig. 3 and 4 and 5: why is the basin slope 5 and does figure 2 not show a slope of 5 degrees?
- Fig. 5: Missing in caption, results are only shown for 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

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