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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Modeling the effect of glacier recession on streamflow response using a coupled glacio-hydrological model" *by* B. S. Naz et al.

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Modeling the effect of glacier recession on streamflow response using a coupled glacio-hydrological model

by B. S. Naz, C. D. Frans, G. K. C. Clarke, P. Burns and D. P. Lettenmaier

Summary of the manuscript: This manuscript presents the application of a dynamically coupled, spatially distributed hydrologic model (DHSVM-MODEL) and a dynamic glacier model (SIA-MODEL) to a glaciated Canadian study site (Upper Bow River). The model was calibrated by identifying five key model parameters (conductivity, exp.

decrease, snow roughness, P-laps rate and T-laps rate) and adjusting them "one at a time" to observational datasets for all odd-years between 1979 and 2007. Model outputs were evaluated with observed discharge, SWE at two locations, glacier mass balances and glacier extent during even years between 1979 and 2007. The model results are used to quantify the effects of glacier retreat during the investigated modeling period on discharge patterns. Furthermore, contribution of glacier melt, snow melt and precipitation to the total runoff is estimated. The study concludes by assessing glacier melt contribution to total flow in the Bow River, quantifying temporal trends in the total runoff and identifying that glacier contribution is not yet decreasing due to retreating glaciers.

The manuscript convincingly presents model set up, calibration and validation. In particular the mutli-variable validation can be highlighted, as discharge, SWE, mass balances and glacier extents are reproduced adequately by the model. While the presented topic has been discussed by many authors in recent years, I see two fundamental new contributions to the ongoing discussion of glacier retreat effects on runoff: i) a glacier dynamic model has been dynamically coupled (or integrated) in a fully distributed hydrological model which improves model performance and ii) the assessment of glacier contribution to runoff is of major importance as it may generate social, ecological and economic impacts in the downstream dry areas. Accordingly, I do think that this study is suitable for publication in HESS, following revisions addressing the specific points listed thereafter. Also, referring to the comment posted by reviewer 1, I also think that additional information is needed to clarify some modeling approach.

Major comments: 1) This may be one of the first studies where a dynamic glacier model has been coupled dynamically to a physically based hydrological model. In order to demonstrate the added value of this technique the results have to be compared to the results of a hydrological model with static glaciers and periodic updates of the glacier extents. In accordance with reviewer 1 and Dr. Schäfli, I also believe that a comparison without glacier model is of little interest, as the effects are obvious. The interesting question is: What is the added value of the dynamic coupling of the two models compared to a model where glacier extents are updated periodically?

2) In the introduction it is briefly mentioned that discharge from glaciated catchments provide crucial water resources to the dry downstream areas in Canada. This statement is certainly true, but it could be discussed in more detail and the results of the study should be put into the context of potentially declining water resources in the downstream dry areas. What can be learned from the simulations? And is the model accuracy high enough to assess impacts on water availability for the downstream areas?

3) Structure of the manuscript: calibration and validation is a method, accordingly it should not be in the study site section; validation performance is a result, accordingly it should be in the result section. Although structure is a question of style, I would like to recommend the following structures: 1) Introduction, 2) Study site and data (incl. Fig. 2, 3, 4, 5), 3) Methods: incl. model setup, glacier thickness estimation, calibration and validation method (incl. Fig 1, 6 evt. 7) 4) Results: incl. model performance for calibration and validation (Fig. 8 - 12), 5) discussion and 6) conclusion.

4) The model uncertainty should be assessed. The authors used a "one at a time" calibration technique (more information on the calibration proceeding would be nice). The approach is adequate; all observational datasets are reproduced adequately. However, is this the only adequate optimum? Are there other adequate parameter sets leading to similar performance, but revealing different conclusions? Model uncertainty should be addressed. Especially when several datasets are used to calibrate a model, parameter sets can be adjusted to increase performance of one or another dataset leading to different optimums (e.g. see Finger et al. 2011, 2012).

I believe that if the four points mentioned above are addressed adequately, the study would improve significantly, making it a substantial contribution to the ongoing discussion about glacier retreat and its impacts on downstream water resources. Accordingly,

I would also suggest a more focused title, e.g: Assessing the effects of glacier retreat on downstream water resources using a dynamic glacio-hydrologic model.

Specific recommendations: Abstract: Ln3: add county and state to the study site Ln 7-9: not necessary here, might be deleted Ln 10: SWE of what? Mass balances or snow height? Ln13-14: why is uncertainty reduced? This was not convincingly shown... (see comment 1 above)

Introduction: Ln20: not only in Canada, but worldwide... (e.g. Gardner et al. 2013, Science) Ln23: Why is the discharge crucial? And during which seasons? This should be addressed in more detail. The quantification of the glacier retreat in connection to downstream water availability could be, in my opinion, a main objective of the study. Pg5015, Ln 1: snow is not depleted either, as in some years mass balances are positive Ln2: negative feedback should be explained Ln6-9: needs a citation Ln17: water supply for what? How much is required? Are the observed changes already crucial? Ln19: why is our ability limited? Numerous studies exist... Ln29: Why is the periodic update of the glacier extent a disadvantage? This issue should be addressed better... e.g. model is driven with the same input data. See also recommendations below. Pg5016, Ln2: "on the other hand" needs a "On one hand" Ln14: Why is it important to dynamically couple glacier and runoff models? There are numerous advantages, but they should be discussed... Ln21: repetition of Line 11 Ln 28-29: The updating of ice extend can easily be implemented into any code; this reasoning seems week. Pg 5017, Ln3: is a shorter time step necessary for glacier modeling? Glaciers evolve gradually, what is the added value of smaller time steps? Ln7: why is the integration for the named objective necessary? Others have used periodic updates of the glacier extent. The added value of dynamic coupling should be emphasized in the entire ms. Ln16: please give full name of the model and only thereafter abbreviations. Pg5019, Eq1-4: define index x,y Ln15: m is an "empirical" exponent Pg5020, Ln17: if Jarosch et al. (2013) provided a more robust method, why not use it? Pg5022, Ln2: this relies on the assumption that the glaciers are in steady state; however, the entire study discusses the dynamics of the glaciers; so an argument should be listed why this approach is still valid. Pg5022, Ln1, Eq6: define index i,j,t (also at pg 5019, Ln7) Pg5024, Ln 29: Structure: move description of Fig 4f to the description of the other panels of Fig 4. Pg5025, Ln1-6: why is it realistic to assume that glaciers are steady state under a given climate? I understand that you used this to obtain glacier thickness, but the assumption should be somehow justified. Pg5026, Ln2: Fig 6a and b should come before 6c Pg5026, Ln19: calibration and evaluation is rather method, accordingly it should not be in the study site chapter Pg5027, Ln2: We also used MODIS data to calibrate our models (see Finger et al. 2011), so I am absolutely in favor of this. Nevertheless, the MODIS data are not mentioned again. What happened to the MODIS data? Ln12-17: the calibration procedure needs more details: how was each optimum found? How were the different observational data sets weighted? Or was only the Nash-value optimized? Ln18: How about the melt parameters? Did they not need to be calibrated? Pg5029, Ln14: a NS value of 0.7 may seem low for a glaciated catchment (see comments of reviewer 1), however, given that the model reproduces all other observational datasets well, a NS value of 0.7 seems adequate. We discuss this issue in Finger et al. (2011). Ln16: hydrographs are illustrated in Fig 11! As this is mentioned here for the first time I suggest switching Fig 10 and 11. (see also comments above). Pg5030, Ln 15-19: can you give an estimate of the model uncertainty regarding the glacier contribution? What does this imply for the water availability in the downstream dry areas? Pg5031, Ln9-12: this is what we expect, glaciers must have a significant effect on runoff. But it would be very interesting to compare a static update of the glacier extent with the dynamic coupling? This would provide new insights to modeling effects of glacier retreat on runoff. Pg5032, Ln9-11: Could you estimate how this uncertainty affects uncertainty on glacier contribution to stream flow? Ln22-25: This is indeed very valuable and an important input to the ongoing discussion of glacier contribution to stream flow. Pg5033, Ln 7: better than what? Ln13: average over what period Point2: What is the trend of precipitation? Can you quantify this hypothesis? Point3: This is a very interesting point, which should be linked to downstream socio-ecological impacts. What does this mean

for the dry downstream areas?

Comments to the Figures: Figure 1: a mixture of proceeding steps, data sets, model results and images are presented in a flow chart. This should be made consistent. Suggestion: put only datasets or model products in text boxes, label arrow with proceeding steps; the final results should be at the bottom, not in the center of the figure. Figure 2: make details on the map visible also in black and white printouts. Include river network in the figure. Figure 3: Figure 3 and 10 present the same data; one is redundant. (Figure 10 and 11 are wrongly labeled, see comment above) Figure 4: include in all panels the river network. Figure 5: I would not illustrate mass balances on areas outside the glacier extent; this is confusing; also include key location presented in Fig 1, this helps the reader recognize the study site. Figure 6: add "w.eq" to the units. I suggest using the same extent in figure 5 and 6. Figure 7: a) % of what? Total watershed? b) add "w.eq" to units Figure 8: a) change the scale to = to 650 as SWE never exceeds 650. Figure 10: should be Figure 11 (see comment above) Figure 11: should be Figure 10 (see comment above) Figure 12: include observed flow in plot b and c.

Recommended references: Finger, D., F. Pellicciotti, M. Konz, S. Rimkus, and P. Burlando (2011), The value of glacier mass balance, satellite snow cover images, and hourly discharge for improving the performance of a physically based distributed hydrological model, Water Resources Research, 47, doi: W07519, 10.1029/2010wr009824.

Finger, D., G. Heinrich, A. Gobiet, and A. Bauder (2012), Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century, Water Resources Research, 48, doi: 10.1029/2011wr010733, W02521.

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 5013, 2013.