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Reply to reviewer #2

Sarah Shannon et al.

Author comment on "A snow and glacier hydrological model for large catchments – case study for the Naryn River, central Asia" by Sarah Shannon et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2022-51-AC2, 2022

We would like to thank the reviewer #2 for providing comments on the manuscript. Please find our replies below.

The paper is dedicated to an acute problem of development of glacio-hydrological models for the prediction of future changes in river runoff due to deglaciation. The presented study aims to develop a computationally efficient hydrological model that can be applied to large glaciated and snow-fed catchments. The paper is overall well-written and provides interesting results. However, there are few major and several minor recommendations to the authors, stated bellow:

The description of the DECIPHeR model needs to be extended: what hydrological processes are taken into account, how the water is routed, number of conceptual storages etc.

We have extended the description of DECIPHeR in Section 2.2 as follows:

"DECIPHeR simulates water storage, hydrologic partitioning, and surface/subsurface flow for steeper shallow soils and/or groundwater-dominated watersheds. The model structure (as implemented in Coxon et al, 2019) consists of three stores defining the soil profile (root zone, unsaturated and saturated storage), which are implemented as lumped stores for each HRU. Moisture is added to the soil root zone by rainfall input and removed only by evapotranspiration. Any excess precipitation is added to the unsaturated zone where it is either routed directly as overland flow or added to the saturated zone. Changes to storage deficits in the saturated zone are dependent on this recharge from the unsaturated zone, fluxes from upslope HRUs and downslope flow out of each HRU. Subsurface flows for each HRU are distributed according to a flux distribution matrix based on accumulated area and slope. Channel flow routing is modelled using a set of time delay histograms. For more detailed discussion of the original DECIPHeR model structure please see Coxon et al, (2019).

While DECIPHeR has been applied catchments in the UK (Coxon et al., 2019; Lane et al.,2021), it has not been used in a glaciated or snow-fed regions because these processes have not yet been included in the model. …."

A clearer parameters calibration scheme should be added to the methods

section. What is the initial and resulting range of the parameters? It is mentioned that degree day factor varies daily in the introduction – it gives the first impression that the values are calibrated for each day separately.

We have added an extra table to the Supplementary Material (Table S3) which lists the initial and calibrated parameter ranges for each sub-catchment. The table also lists the parameter values for the overall best simulations. We reference Table S3 in Section 3.2.2. The updated Supplementary Material is in the zip file attached to the replies to reviewer #1.

We removed reference to the degree day factor varying daily in the introduction (L130), so as not to mislead the reader. The calculation of the degree day as a function of day number is described in Equation 3.

The 3.1 section provides information on the evaluation and validation period. It seems that for the evaluation the same period as for the calibration was used? It is not quite common. Authors should comment on that.

We replaced instances of "evaluation" with "calibration" to make clear that the period to which we refer to, is the calibration period (1951-1970).

It is mentioned on P16 L 337 that the Nash–Sutcliffe efficiency (NSE) is used to evaluate high flows and the timing of peak discharge. Just below that a formula for mean monthly discharges evaluation using NSE metric is given

To clarify the point, we are using the NSE calculated from all monthly values as a metric to evaluate high flows and the timing of peak discharge. High NSE values will be found if the discharge predicts the monthly peak flows and timing of the monthly discharge well. We are not calculating NSE using the high flow values only (i.e. a subset of the monthly data).

Analysis of model performance using the MSC method compared to ISC method for other sub-catchments should be included as well in 3.2.2

We added table S2 to the supplementary material which lists the ranges of values for precipitation lapse rate and sublimation correction factors for the 10 best performing experiments for the individual sub-catchments.

The text in section 3.2.2 is edited.

"Simulations that perform well in the sub-catchments (Figs. S10-S15) favour higher values for the precipitation lapse rates, in contrast to the global catchment parameters which range from 1%100m−1 – 10%100m^{-1} (Fig. S9). This is visible in Table S2 which summarises the range of precipitation lapse rates for the 10 best performing simulations for each sub-catchment. The upper values for the precipitation lapse varies between 16 and 24%100m^{-1} depending on the sub-catchment, which is higher than the global catchment upper bound of 10%100m^{-1}. Simulations also perform better in the sub-catchments when higher values for the sublimation factor E_{sub} are used, in contrast to the global values (0.005 - 0.2). The 10 best E_{sub} parameter ranges are also listed in Table S2. The upper bound values for E_{sub} vary between 0.6 - 1.0, depending on the sub-catchment, which is higher than 0.2 predicted by the global catchment values. E_{sub} controls the reduction in PET over snow and ice surfaces. "

Compare the range in glaciated area prediction with the observed glaciated area

We added this at L445

"The model produces a large range of estimates for the glaciated area (680km^2 – 1, 196km^2) (5th -95th percentile limits) at the end of the simulation period. This range is larger than the observed uncertainty range of 903 - 948 km^2. The uncertainty range in the model is 516 km^2 (in 2007) which is more than 10 times greater than the uncertainty in the observed glaciated area (46 km^2)"

The positive trend in snow melt and negative trend in rainfall component seems to be consistent over the territory that could be better emphasized in the text.

We added this "Small positive trends in the snow melt fraction are consistent across the catchment and are likely driven by warming temperatures. There are small negative trends in the rainfall fraction of less than 1% per decade which is associated with a small decrease in the APHRODITE precipitation. "

Discussion should be extended covering following aspects: 1) the 95th percentile simulations in all cases show an asymmetrically larger contribution of the rainfall compared to 5th and 50th percentile,

We add the following text at L501

"The discharge components are calculated using the 0.5% best calibration parameters for the Uch-Kurgan station located the outlet of the catchment. "

Added at L507

" Figure 10 shows that the rainfall component is larger at the 95th percentile simulations than at the 5th and 50th percentile simulations. This is because the lapse rate at the 95th percentile simulations is higher (22%100m^{-1}) than at the 5th (1%100m^{-1}) and the 50th (6%100m^{-1}) percentile simulations. "

2)analysis of the importance of including new calibration parameters in the DECIPHeR model. As the model performance seems to be not very sensitive to most of the calibration parameters values (FigS15),

We have added this into the discussion on the section on improving the evaluation to include additional observations (L605) as follows:

"This highlights the importance of including ancillary observations, such as glacier mass balance, snow depth or snow extent, in the evaluation to help constrain the predictions and parameter values. Currently, the model performance is not sensitive to many of the calibration parameter values (Fig S15). It is possible that some parameter combinations compensate each other. For example, a high snowfall correction factor may be compensated for by a lower precipitation lapse rate. More analysis needs to be conducted on the sensitivity of the new snow and ice parameters added to DECIPHeR as part of this study, both in time and space, and the types of data that may help to constrain these parameters. Remote sensing snow products have been used to evaluate models and studies indicated that the integration of data such as MODIS snow cover into hydrological models can improve the simulated snow cover while maintaining model performance with respect to runoff (Parajka and Bloschl, 2008)."

3) comparison of derived contributions of snow melt, glacier melt, rainfall with previous studies

We added this to the discussion at L529

"We used the model to calculate the relative contributions of snow, rain and glacier melt to the annual runoff. We found spatial variability in the relative contributions of each of the components. For the entire catchment (gauging station at Uch-Kurgan) the 50th percentile contributions are snow (89%), rain (9%) and glacier melting (2%). These estimates are broadly consistent with Armstrong et al. (2019) who used MODIS imagery and degree day melt modelling to partition the runoff components in the Syr Darya river. Armstrong et al. (2019) found the runoff comprised of snow (74%), rain (23%) and glacier melting (2%). Our estimates are slightly higher for the snow melt contribution; however, our study focuses on the upper reaches of the Syr Darya river where the snow melt is more likely to dominate the runoff.

Snow melting is the dominate component of the runoff at the six gauging stations. Throughout the Tien Shan long-term hydrological records of the former USSR show that snow melt is the dominant source of runoff (Aizen et al., 1995). Further upstream in the Naryn sub-catchment the glacial melt contribution to the annual runoff is higher (4% - 15%) than at Uch-Kurgan. Our upper estimate (15%) is slightly lower than a study by Saks et al. (2022) who calculated that 23% of the runoff originates from glacier melting in upper Naryn river. A possible explanation for why our estimate is lower, is that our simulation period starts 30 years earlier (1951) than the study by Saks et al. (2022) which started in 1981."

Other minor suggestions and technical corrections:

P 1 L12 The model reproduces the spatial extent in seasonal snow cover well, capturing 86% of the snow extent on average (2001-2007) for the median ensemble member of the best 0.5% evaluation simulations, when evaluated against MODIS snow extent. Better divide the sentence in 2-3 sentences to make the message clearer.

Rewritten as

"The model reproduces the spatial extent in seasonal snow cover well, when evaluated against MODIS snow extent. 86% of the snow extent is captured (mean 2001-2007) for the median ensemble member of the best 0.5% evaluation simulations."

L18 At all stations snow melting is the largest component, followed by the rainfall and the glacier melt component. Please provide estimation of shares

Added values "Snow melting is the largest component of the annual discharge (89%), followed by the rainfall (9%) and the glacier melt component (2%), where the values refer to the 50th percentile estimates at the catchment outlet gauging station Uch-Kurgan. "

P2 L30 Sry Darya – Syr Darya

Typo corrected

L32 semi-arid lows lands – semi-arid low lands

Typo corrected

P3 L78-79 Section 3 describes the evaluation and validation of discharge. The evaluation and validation of modelled runoff?

We are calibrating and validating against discharge observations.

Section 4 describes the validation of snow extent against MODIS observations of modelled snow extent?

Changed section heading from “Validation of snow extent against MODIS observations”

to “Validation of modelled snow extent against MODIS observations”

P4 L96-98 A high resolution irrigation map of the catchment derived from normalized difference vegetation index (NDVI) (Meier et al., 2018) shows that the irrigated area is low, in contrast to the Ferghana valley downstream. (Fig. S1). It would be better to add the numerical estimation to the comparison

We calculated that 3% of the catchment is irrigated and added this to the text.

“A high-resolution irrigation map of the catchment derived from normalized difference vegetation index (NDVI) (Meier et al., 2018) shows that the irrigated area is low (3% area is irrigated), in contrast to the Ferghana valley downstream. (Fig. S1).”

P8 L163 “d” symbol doesn’t seem the best choice for the day of the year. As it is hard to distinguish from the first site in a formula abundant with letters d

Changed “d” to “j”

P26 L428 The dotty plots show… –> The dotty plots (see Fig.S9) show..

Edited as suggested.

Figure 3. Please add the transcription of the used indexes either in the caption or in the text.

We added a table containing the definitions of the symbols in Figure 3. The table is included in an appendix (inserted at the end of the paper)

Table 7. The addition of p-values would probably contribute to the informativeness of the table

This would perhaps make the table a bit messy. The p-Values < 0.05 are indicated by the bold font.

S1 The colors need to be explained

We edited the figure to include a legend.

S2 The color ramp is evidently different for the left and right half of the picture

The line visible at approximately 77.75^{o}E longitude is because the HRUs share a common climate grid, rather than an error in the colormap. The pattern is visible because the HRUs share the same climate input grid (APHRODITE and ERA5 data).

S3-S4 Glacier thickness seems to differ a lot between the pictures, though the corrections only for two glaciers are mentioned.

We have replotted these figures with a consistent colour ramp. The thickness is the same except for the corrected regions at the two glacier snouts.

Additional references

Aizen, V. B., Aizen, E. M., and Melack, J. M. (1995). Climate, Snow Cover, Glaciers, and Runoff in the Tien Shan, central Asia. JAWRA J. Am. Water Resources. Assoc. 31.

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Saks, T., Pohl, E., Machguth, H., Dehecq, A., Barandun, M., Kenzhebaev, R., Kalashnikova, O., and Hoelzle, M.: Glacier Runoff Variation Since 1981 in the Upper Naryn River Catchments, Central Tien Shan, Frontiers in Environmental Science, 9, https://doi.org/10.3389/fenvs.2021.780466, https://www.frontiersin.org/articles/10.3389/fenvs.2021.780466, 2022