EGUsphere, author comment AC2
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Reply on RC2

Lena Katharina Schmidt et al.

Author comment on "Reconstructing five decades of sediment export from two glacierized high-alpine catchments in Tyrol, Austria, using nonparametric regression" by Lena Katharina Schmidt et al., EGUsphere, https://doi.org/10.5194/egusphere-2022-616-AC2, 2022

RC2: 'Comment on egusphere-2022-616', Anonymous Referee #2, 18 Nov 2022

Dear anonymous Referee #2,

We would like to thank you for the very thoughtful and detailed comments, questions and suggestions. Below, we provide our response as direct answers to each comment and hope that our suggestions will be to your satisfaction. We also provide figures and a table in the attached pdf for better understanding.

Best,
Lena Katharina Schmidt on behalf of all authors

I appreciate the opportunity to review the manuscript, entitled 'Reconstructing five decades of sediment export from two glaciated high-alpine catchments in Tyrol, Austria, using nonparametric regression'. The topic is study is of great importance to not only the earth and environmental science community but also the policymakers and practitioners such as hydropower companies and water resource managers. This study presents an attempt to reconstruct the long-term suspended sediment export in alpine glacierized basins based on the available shorter records and machine learning. Despite some limitations, the proposed method is capable of reconstructing the sediment yield over the past decades with satisfactory performance.

Major comment 1: Based on modelling scheme in Figure 2, the model validation should target SSC, which is very reasonable and necessary. While, in the results section, the authors only validate the performance of sediment discharge and sediment yield, which are the product of discharge and SSC. In your model (Quantile Regression Forest), discharge is also one of the model input variables and important predictors. The high validation coefficients (NSE and BE) could be only part of the story and maybe just because discharge appears in both input and output variables. Thus, I would kindly suggest the authors try to re-validate the model performance using SSC and replace both Qsed and sSSY in Figure 3-5 with SSC as shown in figure 2 if possible.

Answer: *Thank you for this comment. Indeed, we need to state more clearly, that e.g. the tuning of the models is performed on daily/hourly SSC (not daily Qsed). However, the quantity that we are ultimately interested in is (annual) sediment yield, as we want to understand whether the amount of sediment transported from the catchments changed over time. Adding to this, we find that yields are a more meaningful way to aggregate to annual resolution than mean annual SSC, because of the skewed nature of the concentration distribution. In mean annual SSC, low concentrations on days at the beginning and end of the season are given the same weight as high concentrations during the glacier melt season when discharge is also high – so actually, most of the sediment export happens during the glacier melt period. We believe that this can be captured better using sediment discharge and annual yields.*
Thus, we suggest to add NSE and BE calculated on SSC to the text. As you can see below, the values do not change substantially, if we use SSC instead of Qsed in validation A (hourly vs. daily model resolution at gauge Vernagt, figure 3a):
Hourly model: NSE(Qsed) = 0.98, NSE(SSC) = 0.97
BE(Qsed) = 0.97, BE(SSC) = 0.95

Daily model: NSE(Qsed) = 0.89, NSE(SSC) = 0.82
BE(Qsed) = 0.84, BE(SSC) = 0.73

In validation B (model trained on 2019/20 and validated against 2000/01 at gauge Vernagt), the NSE = 0.51 and BE = 0.33 still represent a satisfactory model performance (Moriasi et al., 2007; Pilz et al., 2019)*, as does model performance at gauge Vent (comparing SSC from turbidity to out-of-bag model estimates) with NSE = 0.6 and BE = 0.43. For mean annual SSC at gauge Vent, the NSE is even as high as for annual yields (NSE(SSC) = 0.825 vs. NSE(SSY) = 0.832).*

In the introduction, the authors say that "Quantile regression forests (QRF) (Meinshausen, 2006) are a multivariate non-parametric regression technique based on random forests, that have performed favorably to sediment rating curves" (paragraph 95). Although it is proven in other publications, I think this statement still needs to be tested and evaluated in this study. If possible, I would suggest the authors compare the SSC simulations by QRF model and SSC simulations by sediment rating curves and explicitly demonstrate how much improvement can be done by the QRF model than sediment rating curves.

Answer: *Thank you for this valuable comment. When comparing daily SSC estimates using sediment rating curves (SRC) to QRF at gauge Vernagt (VF), we find that SRC estimates are in fact slightly better in validation B, i.e. when we train both QRF and SRC solely on SSC from 2019/20 at gauge Vernagt and compare modelled to measured SSC values in 2000/01 (see figure 1 in attached pdf). However, when using the full dataset, SRC performance is worse than QRF performance, even though QRF performance considers out-of-bag estimates only. Thus, SRC performance gets worse with a larger training dataset, which already demonstrates that SRC cannot describe the variability in SSC as well as QRF.*

Likewise, mean daily SSC at gauge Vent is represented better by out-of-bag QRF estimates than by SRC (see figure 2 in attached pdf). Adding to this, compared to gauge VF more years with turbidity measurements are available, so that performance with respect to annual yields can be evaluated (figure 2 c). Here, mean annual SSC estimated through SRC yields a negative NSE, indicating that the mean observed value would be a better predictor (Moriasi et al., 2007)*. In contrast, annual values based on QRF show very good performance.*

Major comment 2: Usually, most of the annual sediment load is contributed by several extreme sediment events and they could cause severe socio-ecological-economic impacts. However, for the daily-scale model, such episodic high Qsed events are always

underestimated, especially for the smaller nested basin Vent. Apart from the insufficient observations as training data as the authors discussed already, can this be also given rise to the different erosion and sediment transport processes during the episodic high-flow events and the threshold effect in sediment transport (see ref below)? If so, is that possible to re-fine such underestimation and consider the different transport mechanisms in Quantile Regression Forest Model? Zhang, T., Li, D., East, A.E. *et al.* Warming-driven erosion and sediment transport in cold regions. *Nat Rev Earth Environ* (2022). https://doi.org/10.1038/s43017-022-00362-0
Answer: *Thank you for this interesting question. Firstly, it is important to note that (unlike in many other fluvial systems), the majority of the annual sediment load in the Ötztal is not transported by several extreme events: on average, only about 21 % of the annual yield is transported by events associated with precipitation (Schmidt et al., 2022). The most extreme event captured in the measurements (i.e. from 2006 to 2020) was in August 2014, where 26 % of the annual yield were transported in 25 h. We assume that this event was associated with mass movements, unfortunately though there are no field data available from this instance. In August 2020, we observed a mass wasting event in the Vent catchment that lead to 13 % of the annual yield being transported at gauge Vent within 30 h. However, these events constitute exceptions.*
Secondly, since QRF is a statistical model, it is not possible to consider different transport mechanisms as such. However, the way the (ancillary) predictors were configured, is assuming that they can be proxies for certain processes; e.g. temperature as a proxy for melting processes or precipitation in time slices before the day to be modelled as a proxy for antecedent moisture conditions (see also (Francke et al., 2008)*). Unfortunately, to our awareness there are no other data available to re-fine the model further (such as thaw depths in permafrost etc., which could potentially describe these processes even better).*
Thus, we do already have some (presumed and observed) mass wasting events within the time series. This provides the opportunity for the model to learn that sediment yields are especially high under certain conditions (e.g. intense precipitation and high temperatures and/or high antecedent moisture conditions) and that precipitation (which translates to other transport mechanisms) might become a more important predictor at these times. This represents an advantage compared to e.g. sediment rating curves, where such threshold effects cannot be described.
Adding to this, it is important to understand that figure 3 a) and 5 a), which we assume you are referring to, show out-of-bag data, i.e. the model prediction for such an extreme event, if this particular event is not part of the training data. So, underestimation is less severe in the full model. We will express this more clearly.

Major comment 3: As the authors introduced in Methods, Quantile Regression Forest Model is driven by discharge, temperature, and precipitation, and only a few years' sediment observations are used for training the model. The reconstructed long-term sediment yield series is highly dependent on the input hydroclimatic predictors. Thus, I guess it's not surprising that the abrupt change in sediment yield coincides with the hydroclimatic abrupt change. Is that possible for the authors to collect any other relevant erosion, sedimentation, or landscape change data to independently prove the abrupt change in sediment transport in this region?
Answer: *Thank you for this question. However, unlike in sediment rating curves, it is not necessarily the case that we would observe an abrupt change in modelled sediment concentrations if there is one in the predictors, because with QRF there is not necessarily a linear or monotonous relationship between input and output. Adding to this, we will state more clearly, that the glacier mass balances were not part of the model predictors, so these already are relevant data that independently show an abrupt change, as you are referring to. We suggest to state this more clearly in the results / figure 7. Beyond that, to our knowledge there are no other long-term data from our catchment that could be used as continuous model drivers in daily resolution.*

Specific comments:

- The abstract can be substantially shortened with at most two paragraphs.
  Answer: *Thank you for this suggestion. We will streamline some parts of the abstract, but suggest to keep the indicated level of detail to provide a meaningful summary of the manuscript.*
- Introduction: there is a lack of acknowledging the existing literature on multi-decadal sediment observations in other high mountain areas and cold regions such as in the Tibetan Plateau, Andes, and the Arctic.
  Answer*: Thank you, we will integrate this.*
- Line 35: Considering the distinct underestimation of high sediment yield events. I would suggest the authors to be careful about the statement and clarify the possible insufficiency: "Our findings demonstrate that QRF performs well in reconstructing past daily sediment export".
  Answer: *Thank you for this suggestion. We will clarify this.*
- Line 50: Impacts of sediment transport on hydropower production and reservoir sedimentation are also systematically elaborated in ref below: Li, D., Lu, X., Walling, D.E. *et al.* High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nat. Geosci.* **15**, 520–530 (2022). https://doi.org/10.1038/s41561-022-00953-y
  Answer: *Thank you, we will include this.*
- Line 60: The recent review systematically elaborates on the sediment dynamics and hydrogeomorphic processes in cold regions and discusses their complexity: Zhang, T., Li, D., East, A.E. *et al.* Warming-driven erosion and sediment transport in cold regions. *Nat Rev Earth Environ* (2022). https://doi.org/10.1038/s43017-022-00362-0
  Answer: *Thank you, we will include this.*

- For introduction and discussion: some of the other quantitative evaluations of the climate change impacts on sediment transport in high-mountain rivers based on decadal observations are listed below for further reading.
  Zhang, T., Li, D., Kettner, A. J., Zhou, Y., & Lu, X. (2021). Constraining dynamic sediment-discharge relationships in cold environments: The sediment-availability-transport (SAT) model. Water Resources Research, 57, e2021WR030690. https://doi.org/10.1029/2021WR030690
  Li, D., Lu, X., Overeem, I., Walling, D. E., Syvitski, J., Kettner, A. J., ... & Zhang, T. (2021). Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. Science, 374(6567), 599-603.
  Answer: *Thank you, we will include them.*
- Line 175: "see map" is unclear. do you mean "Fig. 1" or the other map?
  Answer: Thank you, w*e will adjust this reference, it refers to fig.1.*

- Line 165: the section numbering is quite confusing here. Please check this issue throughout the paper.
  Answer: *Thank you, we will check that throughout the manuscript.*
- Figure 3: the meaning of the black dash line should be explained in the caption. Besides, the actual sSSY values for the four observed years should be highlighted in Figure 3b, for evaluating the model performance.
  Answer*: Thank you, we will add that (it is the 1:1 line) and highlight the points.*
- Line 240: the 5-fold cross-validation results are shown in any figures or tables or appendix. I would suggest the authors add at least one display item to show this result.
- Figure 2: Why there is no validation for Vent station? It seems that the extrapolation ability at this station can be tested by the cross-validation.
  Answer (to 10 and 11): *Thank you for these comments. We suggest to add a table to show cross-validation results at gauge Vent (see table 1 in attached pdf). For gauge VF, we suggest to extend the evaluation of validation B (training on 2019/20 and validation on 2000/01) to training on 2000/01 and validation on 2019/20, which is more descriptive and reasonable given the limited temporal extent of the data (see also answers to reviewer 1).*

- Figure 7c-d: the summer discharge trends are not shown, please add the summer discharge results and be consistent with the main text.
  Answer: *We will add July discharge to figures 7c-d, consistent with temperature, and the main text.*
- line 510: "satisfactory results" usually refer to the estimations with no significant overestimations and underestimations. Here, for accuracy, the authors should clarify that satisfactory results are found in annual sSSY estimations and there are underestimations for high Qsed events at the daily scale.
  Answer: *Thank you, we will clarify that.*
- Lines 580: an in-depth comparison with the world's cold regions would greatly enhance the discussion. For the sudden, tipping-point-like shifts of sediment transport in response to climatic changes have also been observed in the headwater of the Yangtze River on the Tibetan Plateau. The relative contributions of different factors can be also disentangled. Li, D., Li, Z., Zhou, Y., & Lu, X. (2020). Substantial increases in the water and sediment fluxes in the headwater region of the Tibetan Plateau in response to global warming. Geophysical Research Letters, 47, e2020GL087745. https://doi.org/10.1029/2020GL087745
  Answer: *Thank you, we will add that to the discussion.*

References

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Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations, Trans. ASABE, 50, 885–900, https://doi.org/10.13031/2013.23153, 2007.

Pilz, T., Delgado, J. M., Voss, S., Vormoor, K., Francke, T., Costa, A. C., Martins, E., and Bronstert, A.: Seasonal drought prediction for semiarid northeast Brazil: what is the added value of a process-based hydrological model?, Hydrol. Earth Syst. Sci., 23, 1951–1971, https://doi.org/10.5194/hess-23-1951-2019, 2019.

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Please also note the supplement to this comment:
https://egusphere.copernicus.org/preprints/2022/egusphere-2022-616/egusphere-2022-616-AC2-supplement.pdf