Response to reviewers comments

Anonymous Referee #1, 31 Jul 2022

The manuscript entitled "Ensemble streamflow prediction considering the influence of reservoirs in India" submitted to journal Hydrology and Earth System Sciences. The authors evaluated two weather forecast systems, namely the Extended Range Forecast System and Global Ensemble Forecast System, for streamflow prediction in India using the Narmada River Basin as a case study. The authors used a variant of VIC called VIC-Res to simulate rainfall-runoff and river flow. They concluded that the Global Ensemble Forecast System can provide reliable forecasts at a 1-5 day lead. Both the forecast products showed better skills for maximum and minimum temperatures than precipitation. It is also necessary to include reservoirs and their operations in simulating streamflow. Please see below my comments to the authors.

We appreciate the positive and constructive comments that have been addressed in the revised manuscript.

Major comments:

- It is likely the main novelty of this study is the combination of directly incorporating reservoirs in hydrologic modeling and weather forecast. While the topic of ensemble streamflow prediction has been studied worldwide, this topic has recently discussed in Nanditha et al. (2021) for the case of India. Here I have a question regarding to the information on the website https://www.iastoppers.com/articles/editorial-notes-flood-forecasting-in-india in which they mentioned "ensemble forecast" of flood forecasting systems. Does this mean ensemble forecast has been applied in India? Also, the authors should add more literature review about the importance of representing reservoirs in hydrologic models and how other similar studies have been conducted worldwide (e.g., methods, products, temporal/spatial scale).

  Thanks. We agree that Nanditha and Mishra (2021) discussed the need of an ensemble flood forecast system in the review paper. However, the current study differs from Nanditha and Mishra (2021) as they did not employ the ensemble forecast system. The aim of our study is to examine the forecast skills in the ensemble streamflow forecast based on the ERFS and GEFS. In addition, several previous studies ignored the influence of reservoirs in streamflow forecast. Thus, our work is novel and builds upon the challenges and opportunities identified in Nanditha and Mishra (2021). As per our understanding, most of the hydrological forecast systems in India currently do not use ensemble members of the meteorological forecast. Instead, those based on the ensemble mean (single realization), therefore, provide deterministic forecast only. We have included more details in the revised manuscript (lines 110-222).

- In my opinion, the use of one river basin can't represent for the whole India which is a large country and has different types of land scape and climate.

Thanks for the suggestion. We have changed the title of the study to - Ensemble streamflow prediction considering the influence of reservoirs in the Narmada River basin, India.

- How did the authors deal with the difference in resolutions between VIC model and Soil, Land Use – Land Cover, and SRTM data?

Thanks. Soil parameters were estimated at 0.25-degree spatial resolution. As the VIC model considers the sub-grid variability of vegetation and elevation, high-resolution datasets of these were used to estimate parameters for different tiles within a grid. We have mentioned this in the revised manuscript (Lines 129-133):

"Soil parameters at 0.25° were developed using the Harmonized World Soil Database (HWSD version 1.2) [Gao et al., 2009]. We used digital elevation model data from Shuttle Radar Topography Mission (SRTM) at 90 m spatial resolution (Jarvis, 2008). The hydrological model considers sub-grid variability of topography and vegetation (Gao et al. 2010). Therefore, the high-resolution vegetation and elevation datasets were used to extract values for different tiles within a grid."

- It is not clear to me how did the authors setup the optimization for model calibration. Do the authors use the multi-objective evolutionary algorithm for NSEs calculated at the four stations? Also, it would be useful to report parameters of the optimization exercise and VIC model parameters in the main text (not in the SI). Should the authors include a Pareto-front from the optimization or state how did you choose the solution (VIC parameters)?

Thanks. We have provided more details in the revised manuscript (lines 185-200):

"An autocalibration module developed by (Dang et al., 2020) was used to calibrate soil parameters of the VIC-Res model for the Narmada River basin. The autocalibration module uses the ε-NSGAII multi-objective evolutionary algorithm (Reed et al., 2013) to adjust the values of sensitive soil parameters. The autocalibration module can be used to calibrate model parameters at the outlet of different sub-basins within a river basin. First, we used autocalibration to calibrate parameters of upstream basins, then the parameters for the downstream basins were calibrated for the grids that are not part of the upstream basins. We used five soil parameters (B_{inf}, D_s, D_{smax}, W_s, and depth of three soil layers) to calibrate daily streamflow at the selected gauge stations in the basin as described in Mishra et al. (2010). B_{inf} is the variable infiltration curve parameter. D_{smax} is the maximum velocity of baseflow. D_s is a fraction of D_{smax} where non-linear baseflow begins. W_s is a fraction of maximum soil moisture non-linear baseflow occurs (Liang et al., 1994). Further details of the calibration parameters can be obtained from Mishra et al. (2010). The autocalibration module optimizes the model's performance in simulating streamflow at selected stations considering reservoir dynamics. We set our objective to maximize Nash-Sutcliffe Efficiency (NSE) (Dawson et al., 2007; Nash and Sutcliffe, 1970). The model performance was evaluated for daily streamflow, the water level of reservoirs, and the live storage of reservoirs using NSE and coefficient of determination (R^2). Daily streamflow was calibrated and evaluated at Sandia, Handia, Mandleshwar, and Garudeshwar."

- Did the authors consider warm-up periods for hydrologic simulations?

  Thanks. We generated observed initial state using the long-term simulation (~ 20 years) using the observed meteorological forcing before each forecast date. Therefore, model-spin up for each forecast date was considered in observed initial state. We have mentioned this in lines 206-209 of the revised manuscript.

- Since the authors compared the streamflow forecast generated using ERFS and GEFS with simulated data for the period 2019 – 2020 (Lines 180-183), how uncertainty in model calibration will influence on this comparison?

  Thanks. The observed streamflow data is not available for 2019-2020 period. We calibrated the model considering the influence of reservoirs for sufficient long period to capture the climate variability. We have highlighted this limitation in the discussion section (lines 759-762).

- The discussion and conclusions section focused on the comparison between the two forecast products, and I did not see much discussion about "the influence of reservoirs" until the 2nd conclusion.

  Thanks. The main aim of the work is examining the forecast skills in GEFS and ERFS. Therefore, most of the discussion is around that. We have mentioned the role of reservoirs in the first paragraph of the discussion section (lines 391-394). In addition, we have added a separate paragraph in Introduction highlighting the need of inclusion of reservoirs in model simulations (lines 57-77):

  "Indian river basins are considerably affected by human interventions including presence of reservoirs, water withdrawal for irrigation, and inter/intra basin water transfer (Nanditha and Mishra, 2021; Madhusoodhanan et al., 2016; Gosain et al., 2006). India has more than 5000 large dams while about 450 are currently under construction (NRLD, 2017). Reservoirs and irrigation can considerably modulate terrestrial water and energy budgets in India (Shah et al., 2019). For instance, Shah et al., (2019) showed that evapotranspiration and latent heat flux are increased under the presence of irrigation and reservoirs in Indian river basins compared to their natural conditions. Dong et al. (2022) reported that reservoirs can significantly (~ 25%) contribute to the variation of terrestrial water storage in China. In addition, the presence of reservoirs can considerably affect streamflow variability in the downstream regions (Zajac et al., 2017; Yun et al., 2020; Chai et al., 2019). Reservoirs in India are multipurpose as they store water for the dry season, generate hydropower, and attenuate floods in the downstream regions (Tiwari and Mishra, 2022). Reservoirs store water during the summer monsoon season and release water during the dry season for irrigation. Similarly, based on the reservoir rule curve, a buffer storage is kept during the wet season to accommodate high inflow so that flood risk can be minimized in the downstream region. Therefore, there are several challenges associated with the streamflow forecast in the river basins that are affected by reservoirs. Most often hydrological model-based flood/streamflow forecast does not consider the influence of reservoirs that could lead to under or overestimation of flow depending on the season (Nanditha and Mishra, 2021). Incorporating reservoir influence in hydrologic models is essential as reservoirs significantly affect the magnitude and timing of streamflow (Zajac et al., 2017; Yassin et al., 2019; Dang et al., 2019). Several efforts have been made to incorporate the influence of reservoirs in the hydrologic models (Boulange Julien and Hanasaki Naota, 2013; Dang et al., 2019; Hanasaki et al., 2018). However, most of the previous studies on flood forecasts and early warnings in India did not consider the influence of reservoirs (Goswami et al., 2018; Sikder and Hossain, 2019)."

And lines (701-704):

The presence of reservoirs influence the water budget and streamflow (Shah et al., 2019 Zajac et al., 2017; Yun et al., 2020; Chai et al., 2019). Hydrological model parameters calibrated without considering the role of reservoirs can be erroneous and leading to errors and uncertainty in simulated hydrological processes (Dang et al., 2019). Therefore, we used the ensemble streamflow prediction approach to generate the daily streamflow simulations considering the influence of reservoirs in the Narmada river basin.

Minor comments:

Please revise the manuscript more carefully for writing issues; some are below:

- Although the case study can be scaled up for the whole India, the authors only conducted modeling and comparing the performance of the forecasting systems for the Narmada River Basin, the title sounds a bit misleading. I would call it "for a case study in India". The performance of these forecast products may be different in different river basins?

  Thanks. We have modified the title of the revised manuscript to address the suggestion.

- Line 28: the most common?

  Thanks. We have modified the sentence in the revised manuscript.

- Lines 29-30: the evidence (20% of the total flood-prone area gets affected every year) does not support the main sentence.

  Thanks. We have corrected this in the revised manuscript.

- Line 34: "mitigate economic loss and human lives"?

  Thanks. We have modified the sentence in the revised manuscript.

- Lines 34-36: financial loss can't be reduced with flood early warning systems?

  Thanks. We have modified the sentence in the revised manuscript.

- Line 41: how uncertainty quantification can reduce the risk of false alarms (according to Todini, 2007)?

  Thanks. We have modified the sentence in the revised manuscript.

- Line 50: if possible, please list some of the advantages of ensemble flood forecasts reported in the previous studies.

  Thank you. We have added the advantages in the revised manuscript (lines 53-55).

- The authors should add a table showing main parameters of the reservoirs simulated in this study.

  Thank you. We have added the table showing the key parameters of reservoirs in the main manuscript.

Table 1. Parameters of reservoirs that were considered in hydrologic simulations

Sr No	Name of dam	Year of completion	Type	Height above lower foundation (m)	Length of dam (m)	Gross storage capacity (BCM)	Effective storage capacity (BCM)
1	Bargi	1988	Other	69.8	5357	3.92	3.18
2	Tawa	1978	Earthfill Embankment	57.92	1944.92	2.312	1.94
3	Indira Sagar	2006	Other	91.4	654	12.22	9.75
4	Sardar Sarovar	2017	Other	163	1210	9.5	5.8

- Line 93: 25^{o} is ~ 27.5 km.

  Thanks. We have corrected this.

- Line 95: Pai et al. (2015) examined daily rainfall trends, long-term climatology, and variability over the central Indian region. What is the conclusion of this study?

  Thanks. We have discussed this in the revised manuscript (lines 118-119).

- Line 109: obtain/purchase

  Thanks. We have corrected this in the revised manuscript.

- The authors can add a table showing the list of data and sources of the data used in this study.

  Thank you. We have added the suggested table in the supplementary information (Table S1).

Table. S1 – List of data used with their resolution and sources

Sr. No.	Type of data	Resolution	Source
1	Precipitation	0.25° / Daily	Indian Meteorological Department (IMD) (Pai et al., 2014)
2	Temperature	1.0° / Daily	Indian Meteorological Department (IMD) (Srivastava et al., 2009)
3	Extended Range Forecast System (ERFS)	1.0° / Daily	Indian Institute of Tropical Meteorology (IITM)
4	Global Ensemble Forecast System (GEFS)	0.125° / 3-hr	Indian Institute of Tropical Meteorology (IITM)
5	Observed streamflow, reservoir water level and storage	Daily	India – Water Resource Information System (IWRIS)
6	Digital Elevation Model	30m	HydroSHEDS http://hydrosheds.cr.usgs.gov/

- The authors can discuss briefly about methods used to develop the forecast products (ERFS and GEFS).

  Thanks. The forecast products are described in the data and methods sections. We have added more information in the revised manuscript. However, the readers can refer to the cited articles for a detailed description.

- Line 137: "Therefore, … routing model" can be removed.

  Thanks. We have removed the sentence in the revised manuscript.

- Line 138: revise this sentence.

  Thanks. We have revised the sentence in the manuscript.

- Line 142: linearized Saint-Venant Equations

  We have revised the sentence in the manuscript.

- Line 143: fraction?

  Thanks. We have corrected this in the revised manuscript.

- Lines 153-154: this sentence can be removed.

Thanks. We have removed the sentence in the revised manuscript.

- Lines 347-348: it is not clear to me how limited efforts to establish an ensemble streamflow forecast system at river basin scale are since there are many efforts (e.g., see Alfieri et al., 2012 [cited in this study] and Troin et al., 2021)

  In the following sentence, we are referring to the efforts in Indian context. We have revised the sentence in the manuscript.

  Line 356: was GEFS only available for the period of 2019-2020?

  Yes. The GEFS ensemble members dataset was available only for the period 2019-2020.

- Figure 7: are there any reasons why simulated water level/live storage of Reservoir Bargi was significantly lower than observed water level in 2007-2008

  Thanks. We agree that the model performance is relatively weaker for Bargi reservoir that could be due to model parameterization.

- Figure 12: it is difficult to read this figure since the symbols and texts are too small.

  We have revised the figure.

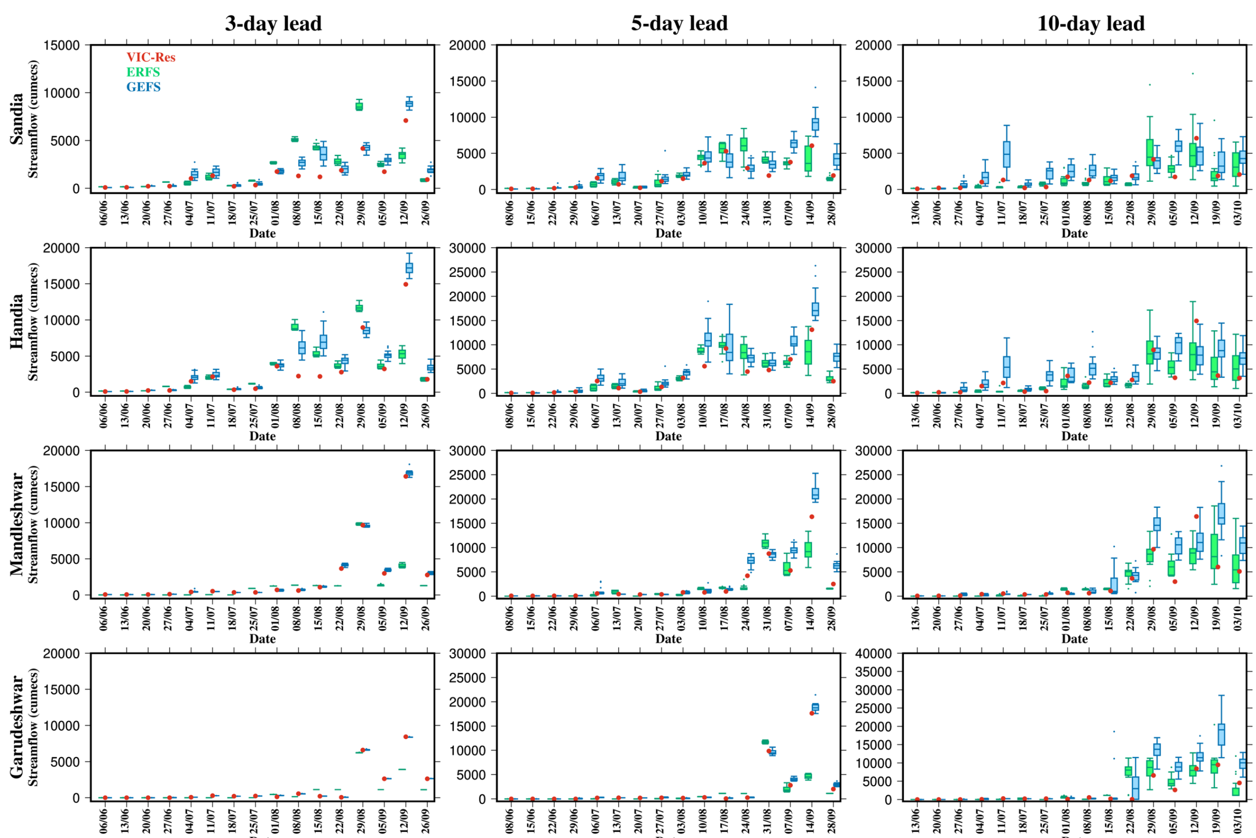

Figure 12. Comparison of ensemble streamflow simulated using the VIC-Res model with ERFS and GEFS forecast products during the summer monsoon of 2019. The forecast skill was evaluated considering the VIC-Res simulated streamflow with the observed forcing from IMD due to unavailability of observed flow.

- In References, all of the references missed name of the journals; there are two Dang et al. (2019a,b), Liang et al. (1994a,b), and Srivastave et al., (2009a,b) which are similar; some references have DOI, and some do not.

  Thanks. We have corrected the references in the revised manuscript.

References

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., & Pappenberger, F. (2013). GloFAS–global ensemble streamflow forecasting and flood early warning. Hydrology and Earth System Sciences, 17(3), 1161-1175.

Nanditha, J.S., Mishra, V. 2021. On the need of ensemble flood forecast in India. Water Security, 12, 100086.

Troin, M., Arsenault, R., Wood, A. W., Brissette, F., & Martel, J. L. (2021). Generating ensemble streamflow forecasts: A review of methods and approaches over the past 40 years.

Anonymous Referee #2, 11 Aug 2022

The paper Ensemble streamflow prediction considering the influence of reservoirs in India presents an original study aiming at setting up an ensemble hydrological prediction system at the scale of India. The authors propose a first regional approach on the Narmada river catchment. The authors rely on the VIC hydrological model that supports reservoir management. This approach is particularly interesting when it comes to improving flood forecasting in a context where reservoirs can be used to store water but also represent a danger if the reservoir management is not adapted in case of flood. The article focuses on 4 reservoirs of the same catchment area but it will be necessary to extend the study to other reservoirs of other regions for the implementation of a possible warning system at the scale of the whole country.

We thank the reviewer for the positive comments and suggestions. Extending the study to other river basins in India is beyond the scope as it would require a significant amount of additional work considering the challenges with the data availability. We have modified the title to reflect that the study is conducted in the Narmada River basin, which we feel can take care of the suggestion.

Major comments:

- It seems to me that the study should be extended to other catchments with more contrasting hydrometeorological conditions. The study focuses on a regional scale warning system.

  We thank the reviewer for the positive comments and suggestions. Extending the study to other river basins in India is beyond the scope as it would require a significant amount of additional work considering the challenges with the data availability. We have modified the title to reflect that the study is conducted in the Narmada River basin, which we feel can take care of the suggestion.

- In the description of the hydrological model, a table summarizing the parameters or a diagram could help the reader in the operation of the hydrological model. Additional information on the operation of the reservoir-specific module could be useful as this is one of the original features of this study. The characteristics of the reservoirs necessary for the operation of the hydrological model are also missing.

  Thanks. We have listed the calibrating model parameters with their ranges in the supplementary information (Table S2 and Table 1). In addition, we have listed the sub-basins upstream of the reservoirs and the calibrated parameters in Figure S5 (supplemental information)

Table. S2 – The calibrating soil parameters of the VIC-Res model

Sr. No.	Parameter	Range
1	Ds	0 to 1
2	Ds_{max}	0 to 30
3	Ws	0 to 1

4	B_{inf}	0 to 0.5
5	Soil Depth (d1, d2 and d3)	0 to 1.5

Table 1. Parameters of reservoirs that were considered in hydrologic simulations

Sr No	Name of dam	Year of completion	Type	Height above lower foundation (m)	Length of dam (m)	Gross storage capacity (BCM)	Effective storage capacity (BCM)
1	Bargi	1988	Other	69.8	5357	3.92	3.18
2	Tawa	1978	Earthfill Embankment	57.92	1944.92	2.312	1.94
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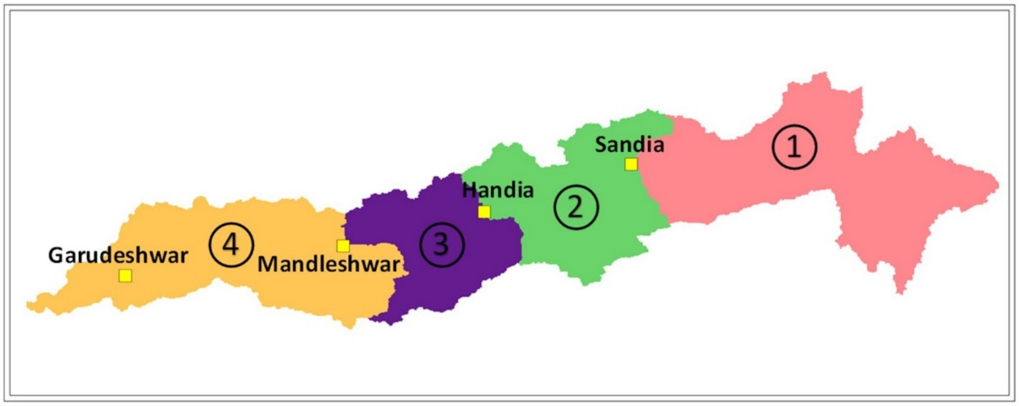
4	Sardar Sarovar	2017	Other	163	1210	9.5	5.8



Parameter	1	2	3	4
b_{inf}	0.18	0.26	0.15	0.89
D_s	0.91	0.94	0.34	0.29
D_{smax}	0.01	1.2	3.49	11.65
W_s	0.58	0.74	0.01	0.01
d1	0.05	0.24	0.12	0.05
d2	0.46	0.79	1.31	0.1
d3	0.14	0.1	0.11	0.1

Fig. S5 – VIC-Res calibration parameters in the respective upstream region of each station.

- Concerning the calibration and validation periods of the hydrological model on the 4 reservoirs, it is unfortunate that the periods are not identical for the Mandleshwar and Garudeshwar stations.

  Thanks. We agree that consistent observations for the same period would have been better for the comparison of the model's performance during calibration and evaluation. However, we could not keep the same period due to unavailability of the streamflow observations, which has been mentioned in the revised manuscript (lines 200-204).

- To evaluate the quality of the forecasts, the authors could also have used the NCRPS (Hersbach, 2020)

  Thanks. We have included the CRPS evaluation matrix in the revised manuscript (Figure S6). In addition, we included the details about CRPS in the methods and results sections.

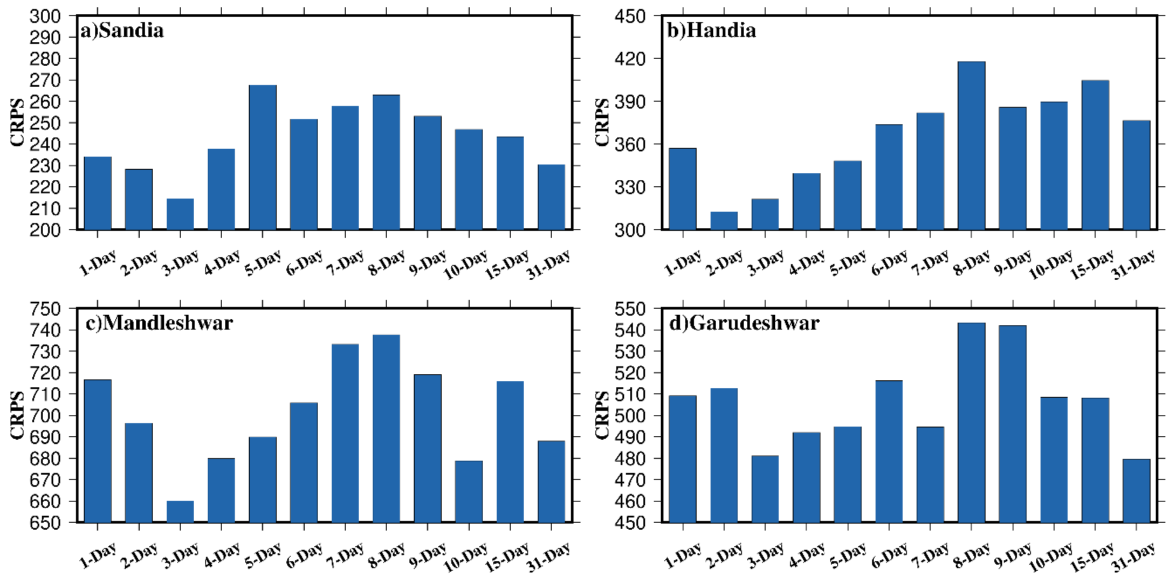


Fig. S6 – CRPS of streamflow forecast for years 2003-2018 at different leads (1-10 day, 15 day, 31 day).

- When evaluating the VIC hydrological model, it can be seen in Figure 8 that the model underestimates the volume of water in the reservoir compared to the observed level, isn't this a problem when looking at flood events? Finally, one may think that the volume of the flood can be stored in the reservoir when it is not the case. I wonder if for a future publication, we should not look at the propagation of uncertainties along the modeling chain.

  Thanks, the model underestimates reservoir storage at Bargi. We acknowledge that this weaker performance of the model can affect streamflow forecast. However, we have not examined the propagation of errors in the current manuscript. We have mentioned this in the revised manuscript (lines 604-605).

- For the comparison of the two forecast products, do we have enough hindsight on the GEFS product? Indeed, if we look at Figure 13, the dispersion of the ensemble for the year 2019 is much larger than for the year 2020.

  Thanks. We agree that longer hindcast can provide us more confidence in forecast skill of GEFS. However, the GEFS hindcast is available only for two years. As this is operational product, we hope that more data will be available for near future. However, the conclusion of improved forecast skills of the GEFS for short-term lead is robust and unlikely to change. We have mentioned this limitation in the revised manuscript (lines 762-765):

A multi-model approach, where more than one hydrologic model is used, can generalize the uncertainty introduced by the hydrologic model. Various studies have reported improved forecast skills using the multi-model approach (Muhammad et al., 2018; Velázquez et al., 2011; Zarzar et al., 2018). Also, our analysis is based on just for the 2019-2020 as the GEFS hindcast is available only for this period. Availability of longer hindcast from the GEFS can help to understand the forecast skills for hydrologic extremes (drought and floods). Moreover, we did not examine the forecast skill of reservoir storage, which can provide a better understanding of the impacts of storage during the floods.

- As an additional comment, I think it might have been interesting to show a hydrometric station not influenced by reservoirs to evaluate the forecast products before adding complexity to the study with the introduction of reservoirs. This would have allowed us to see if the same biases were observed.

  Thanks. Even without considering the role of reservoirs the VIC model can be calibrated with a reasonable performance. However, as shown by Dang et al. (2019) the parameter estimates are erroneous as the observed flow is affected by the presence of reservoirs. We have mentioned this in the revised manuscript (lines 391-394):

  The presence of reservoirs influence the water budget and streamflow (Shah et al., 2019 Zajac et al., 2017; Yun et al., 2020; Chai et al., 2019). Hydrological model parameters calibrated without considering the role of reservoirs can be erroneous and leading to errors and uncertainty in simulated hydrological processes (Dang et al., 2019).

- A comparative analysis of the four reservoirs is missing. Are the observed biases due to the hydrometeorological context of the reservoir, or are they due to the characteristics of the reservoir?

  Thanks. We appreciate the valuable suggestion that we will consider in the future work as the aim of the present work was not to examine the forecast skills of reservoir storage rather, we examined only streamflow forecast skills. This has been mentioned in the introduction of the revised manuscript. Please see lines 764-765 in the discussion section.

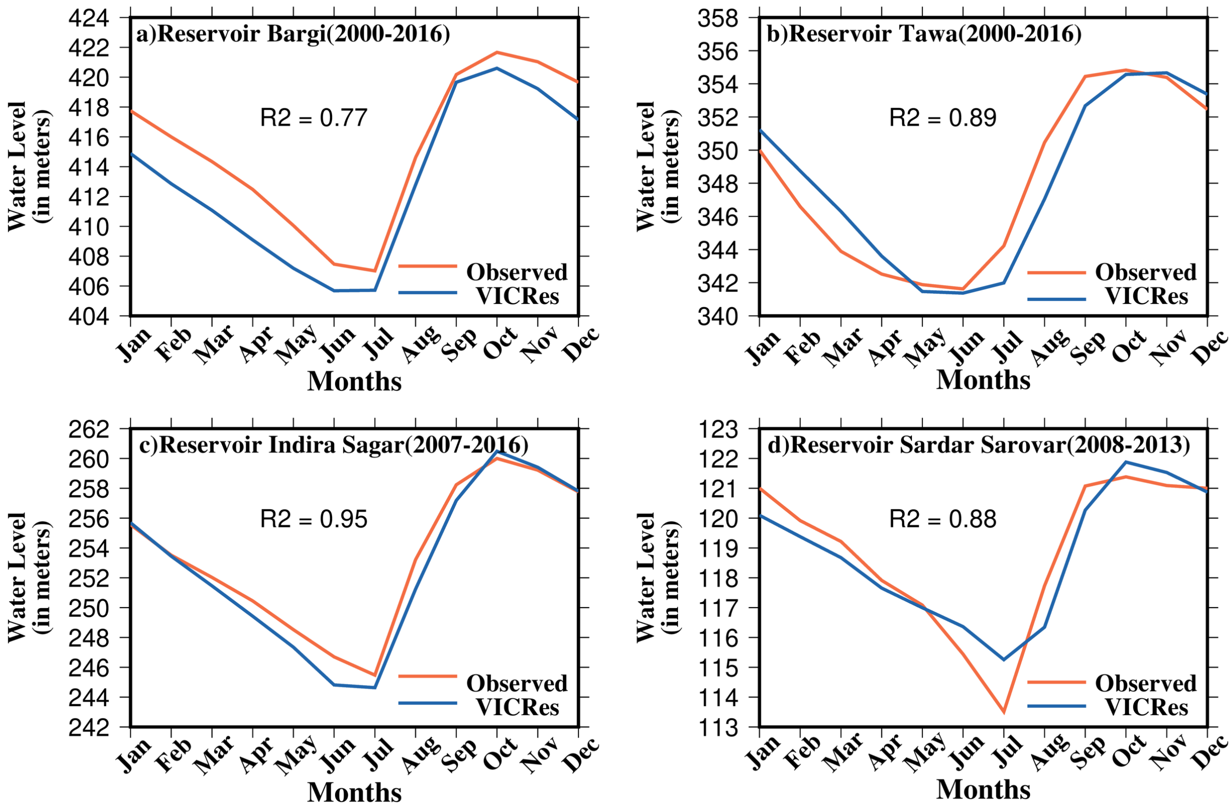
Minor comments:

- In Figure 7, do the authors have any idea of the difference between observation and simulation for the year 2007 for Bargi Reservoir. The minimum and maximum reservoir levels are missing. Were there any spills in the management operations simulations?

  We carefully checked the simulations, and this could have been caused because of: 1) errors in observed reservoir storage, or 2) substantially low inflow from the upstream grids of the Bargi reservoir. Only a small area (~8-10 grids) of the catchment contribute inflow to the reservoir. We have mentioned this in the revised manuscript (lines 604-605).

- In the legend of Figure 8, perhaps the dates of the periods should be indicated. Comparing the seasonal cycle of the reservoirs is a little difficult because the average cycle was not calculated over the same periods.

  Thanks. We have modified the figure in the revised manuscript.



- The boxplots in Figure 12 are difficult to read for the fourth reservoir.

  We have revised the figure.

Reference:

Hersbach, Hans. "Decomposition of the Continuous Ranked Probability Score for Ensemble Prediction Systems", Weather and Forecasting 15, 5 (2000): 559-570, https://doi.org/10.1175/1520-0434(2000)015<0559:DOTCRP>2.0.CO;2

Citation: https://doi.org/10.5194/hess-2022-218-RC2