Supplement of

Assimilation of Transformed Water Surface Elevation to Improve River Discharge Estimation in a Continental-Scale River

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The supplementary materials include Text S1 to S4 and Figures S1 to S7.

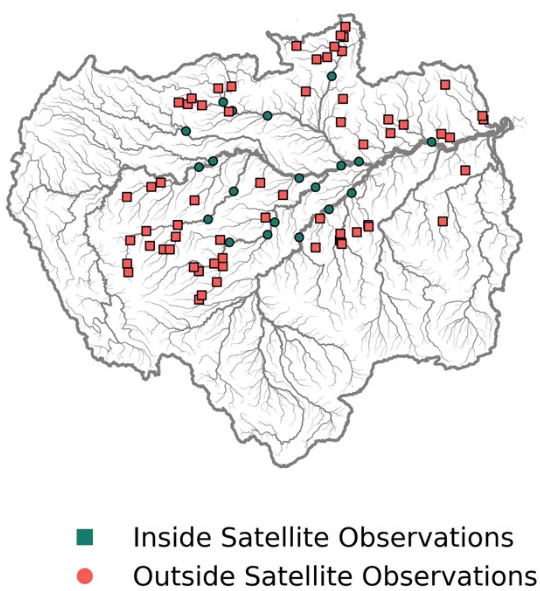

Figure S1: GRDC gauges within Satellite coverage of ENVISAT and Jason1/2 in green circles where others indicated by red squares.

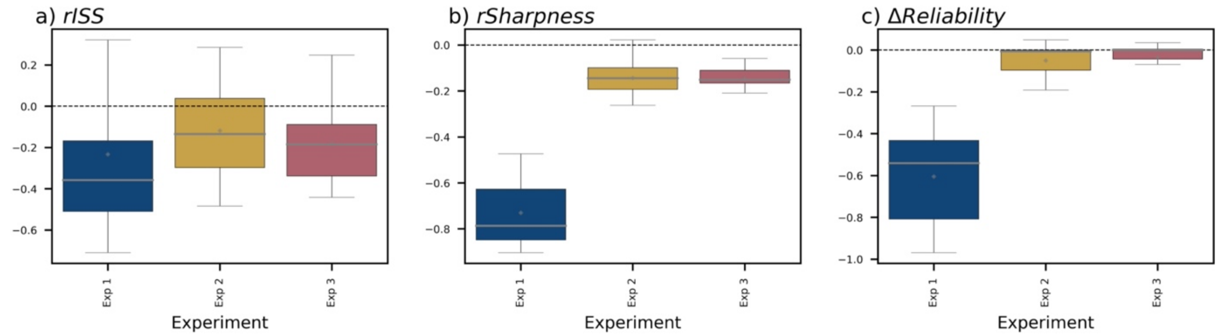

Figure S2: The boxplot of a) relative Interval Skill Score ($rISS$) , b) relative sharpness ($rsharpness$), and c) difference of reliability $\Delta Reliability$ for all the experiments. This figure indicates Exp 1 is better in reducing the confidence bound. But with the current limitations of hydrodynamic modelling reliability will become lower.

Text S1: Preparation of biased runoff

We introduced artificial bias into the runoff forcing data in the biased runoff experiment to determine the efficacy of DA methods when runoff is biased. We used a simple method to artificially corrupt the runoff ensemble rather than the ensemble generation method described in the main text. We generated the runoff ensemble by applying a –50% bias to the HTEESSEL (Balsamo et al., 2011) runoff product from E2O WRR2 (Dutra et al., 2017) and then perturbing it by 25% of the monthly mean runoff value. As a result of the introduction of this bias into the runoff forcing, river discharge and WSE were approximately 50% lower in the open-loop simulation results than in the observations. Figure S3 presents an example of river discharge estimation using biased runoff and GRDC observations.

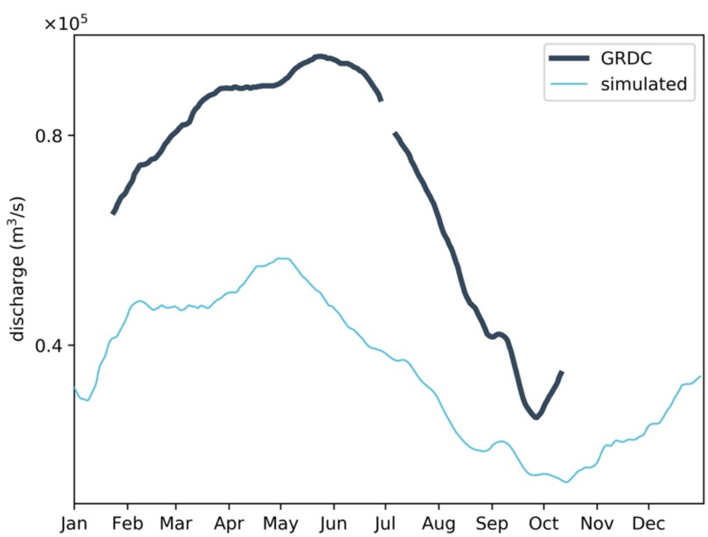

Figure S3: River discharge comparison between observation (GRDC) and discharge simulated by biased runoff of HETESSEL E2O WRR2.

Text S2: Preparation of corrupted bathymetry

We artificially corrupted river bathymetry by subtracting 25% of the river channel depth from the original bathymetry to investigate the efficacy of DA when river bathymetry is erroneous. Basically, this process deepened the river channel, lowering the river bathymetry. The original river channel depth was calculated with a power-law equation (Yamazaki *et al*., 2011; Zhou *et al*., 2022),

$$\boldsymbol{B = max\left(B_{min}, c_B Q_{avg}^{p_B}\right)} \tag{1}$$

where B is the channel depth (m) and Q_{avg} is the annual average discharge (m^3/s). Here the average climatological land surface runoff from the Minimal Advanced Treatment of Surface Interaction Runoff (MATSIRO; Takata *et al*., 2003), simulated by Kim *et al*. (2009), was used. Other parameters were estimated to be $B_{min} = 1.0, c_B = 0.1$, and $p_B = 0.5$. Figure S4 shows the difference in river channel depth between the corrupted and original values.

Text S3: Data assimilation into a calibrated hydrodynamic model

The hydraulic parameters were used to transfer the corrections to the next time step in DA. Therefore, we compared the river bottom–calibrated model with the conventional CaMa-Flood model to understand the impact of river bathymetry calibration on various DA techniques. We chose to calibrate the river channel bathymetry because uncertainty in river bathymetry is one of the largest sources of error in hydrodynamic modeling (Brêda *et al*., 2019). Inaccuracy in river bathymetry strongly affected the WSE and worsened the model's performance compared to satellite altimetry measurements. River bathymetry was calibrated with the rating curve method (i.e., the discharge–WSE relationship; Zhou *et al*., 2022). Calibration was

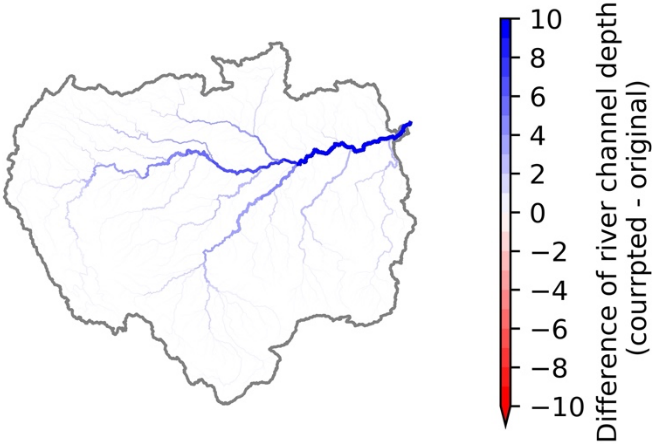

Figure S4: Difference of river channel depth between corrupted and original bathymetry.

performed with *in situ* river discharge observations and satellite altimetry. The calibrated model simulated WSE more precisely than uncalibrated methods relative to WSE observations, but river discharge was not drastically improved by this calibration method. More information about the methods used to calibrate river channel bathymetry can be found in Zhou *et al*. (2022). Hereafter, "calibrated model" refers to the CaMa-Flood model in which the river channel bathymetry was calibrated using the rating curve method. We denote the direct, anomaly, and normalized value DA experiments as Exp 1a, Exp 2b, and Exp 3c, respectively.

Figure S5a illustrates the kernel density estimate of the probability density function for the Δr of river discharge. All experiments that used the calibrated model (i.e., Exp 1a, Exp 2a, and Exp 3a) showed an improvement in median Δr (> 0), which indicates improved simulation of the flow regimes with DA for 50% or more of all gauges. The Δr of river discharge in Exp 1a showed a left-skewed distribution, which suggests poor reconstruction of seasonality at some gauges (47.6%). At a few locations, the flow regimes improved greatly ($\Delta r > 0.2$) with calibration of the river bathymetry. More than 70% of gauges showed flow regime improvements in the anomaly and normalized value DA experiments. However, Exp 3a had positive median $NSEAI$ values, which indicates that at least 50% of gauges had improved NSE values with DA. Figure S5b shows a boxplot of $NSEAI$ for all experiments, indicating considerable improvement in the DA experiments with normalized value assimilation.

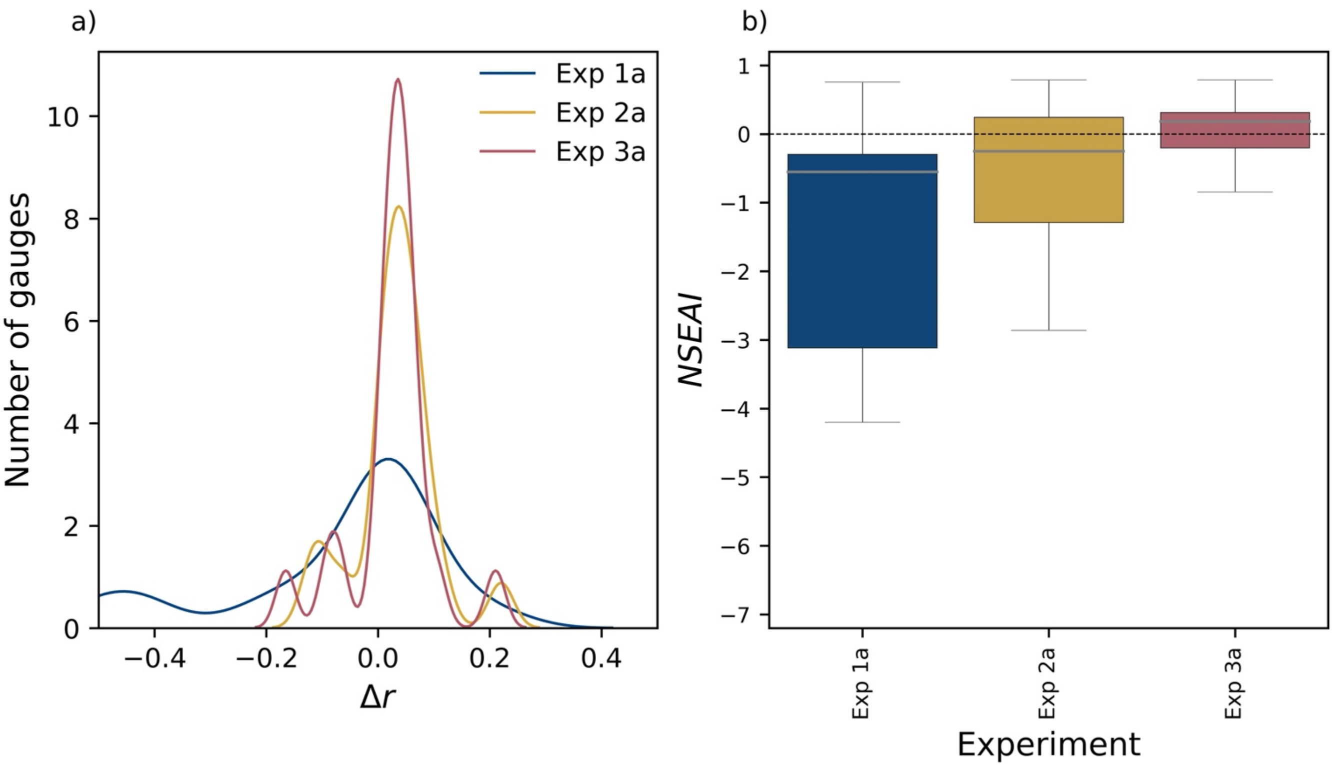

Figure S5: a) Cumulative distribution of the correlation coefficient (Δr) for each experiment, shown in blue, yellow, and red for direct (Exp 1a), anomaly (Exp 2a), and normalized value (Exp 3a) using calibrated model, respectively. b) Boxplots of the Nash-Sutcliffe based assimilation index ($NSEAI$) of assimilated compared to open-loop discharge for all the experiments. Boxes in blue, yellow, and red indicates direct (Exp 1a), anomaly (Exp 2a), and normalized value (Exp 3a) using calibrated model, respectively.

Text S4: Annual peak and though estimation

We investigated further into the peak and low flow values of the normalized value assimilation experiments (Exp 3, Exp 3a and Exp 3b), since they are important parameters of a hydrograph that directly affects floods and drought occurrences. Normalized assimilation underestimated annual maximum discharges while accurately estimating annual low flows (Figure S7). Peak discharge underestimation is noticeable in larger river segments, such as the Amazon mainstem. Other limitations of global hydrodynamic modeling, such as the uncertainties of river width estimations, the assumption of rectangular river cross-sections and simplified floodplain physics, might contribute to these underestimations. Improving the parameters which are directly involved in the conversion of assimilated WSE values to prognostic variables in the model is important for a successful assimilation framework.

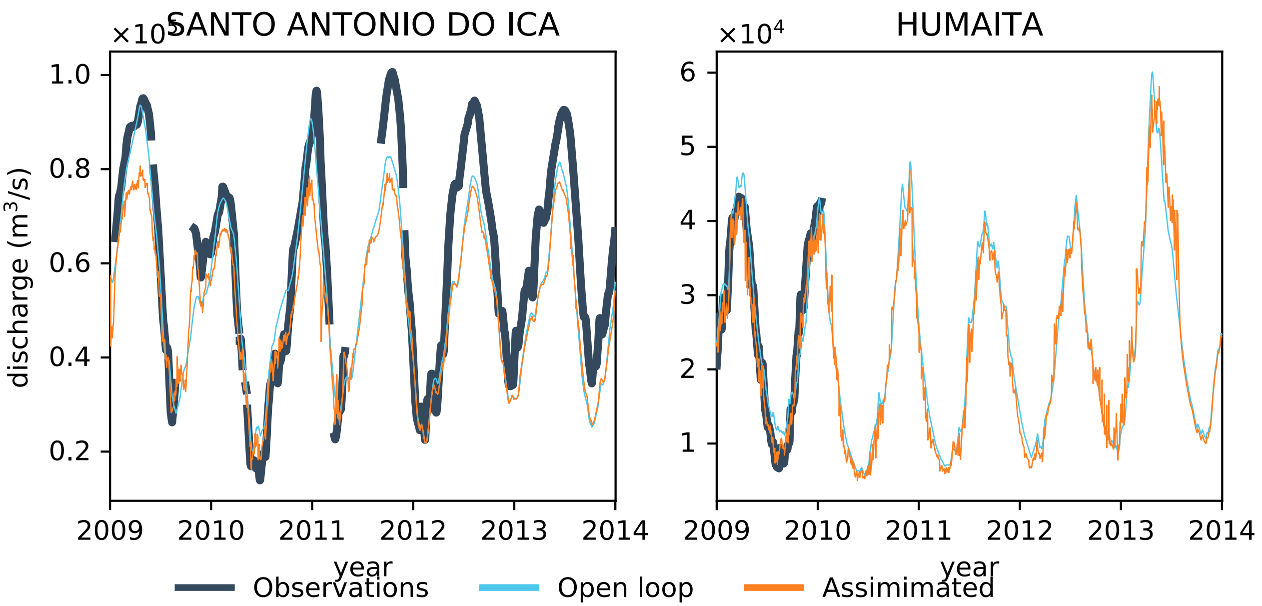

Figure S6: Hydrographs for Santo Antonio Do ICA, and Humaita in Amazon and Maderia rivers, respectively. Observations, open loop, and assimilated river discharge presented in black, blue, and orange. Santo Antonio Do ICA represents the ability of DA to characterise the unexpected secondary peak. Humaita hydrograph shows the DAs' ability to estimate low flows better.

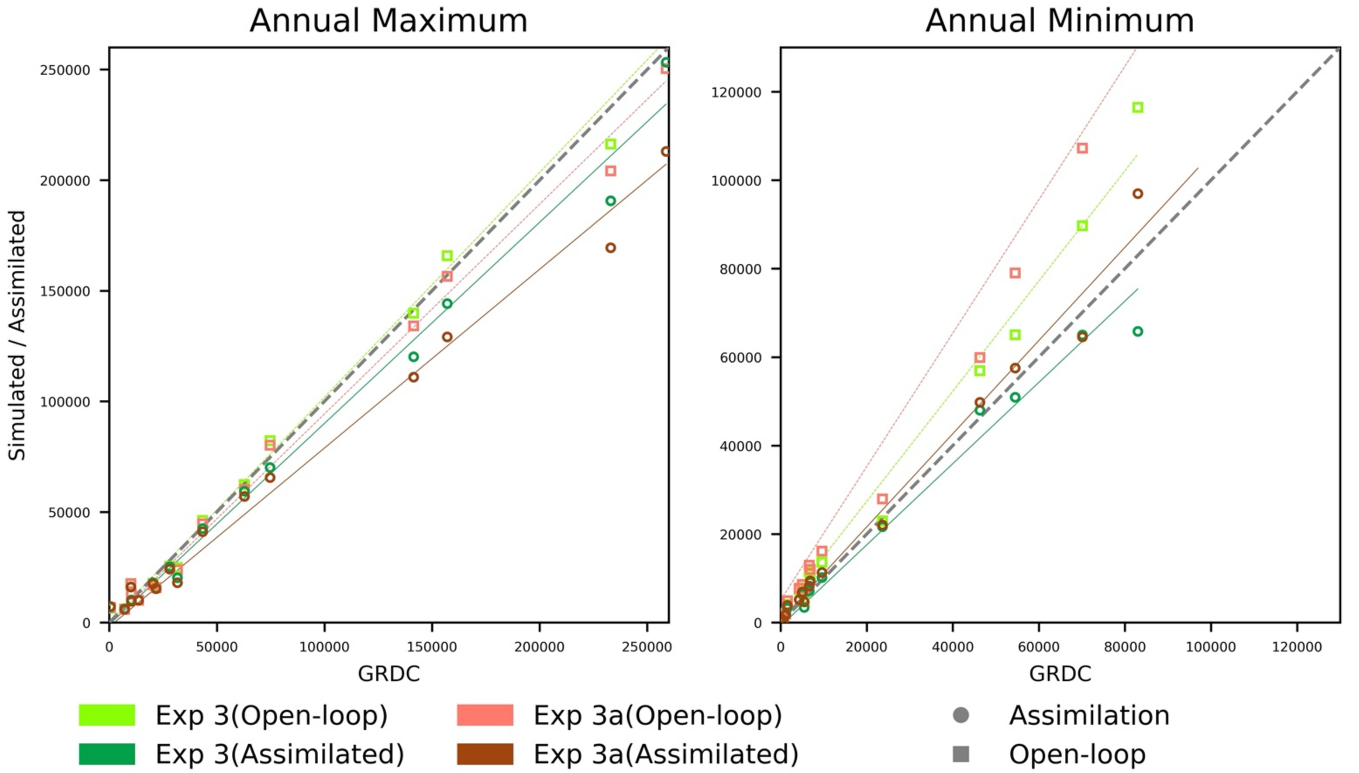

Figure S7: Scatter plot of the simulated annual maximum and minimum compared to observed maximum river discharge for Exp 3 and Exp 3a. Circles and squares represents assimilated and open-loop river discharge, respectively.

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