Improving Large-Scale River Routing Models with ESA long-term CCI discharge data assimilation: Advancing Accuracy for Climate Studies.

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Abstract. Large-scale hydrological models like CTRIP and MGB are essential for simulating river dynamics and supporting large-scale climate studies. Their accuracy can be significantly improved through satellite data assimilation. This study leverages the stand-alone value of 20 years of ESA Climate Change Initiative (CCI) high-resolution discharge and water surface elevation (WSE) products (2000–2020) for improving large-scale hydrological simulations through data assimilation. To evaluate the added-value of these produtcs across contrasting modelling and hydrological contexts, we assimilate altimetry-derived discharge, multispectral-imagery-derived discharge, and WSE anomalies into two existing ensemble Kalman Filter frameworks: HyDAS in CTRIP, a global-scale physically based and uncalibrated river-routing model, and HYFAA in MGB, a calibrated semi-distributed regional hydrological model. The experiments are conducted over the Niger and Congo basins, which differ in hydrological variability, river-network structure, wetland influence, and CCI product availability.

Across the experiments, discharge assimilation generally outperformed WSE anomaly assimilation because discharge is directly represented in the routing models, providing a more direct and physically consistent correction, while WSE requires consistency between observed and simulated rating curves to be converted into effective discharge corrections. In the Niger basin, where the seasonal signal and station coverage better constrain the main river dynamics, assimilating altimetry-derived discharge led to the strongest improvement in MGB, increasing the median Nash-Sutcliffe Efficiency (NSE) to 0.83 and the correlation coefficient to 0.94. WSE anomaly assimilation was beneficial in specific cases, particularly when the baseline simulation was poor and when observed and simulated rating curves were well aligned. Temporal data density in discharge assimilation emerged as a key driver of performance gains. Assimilating high-frequency discharge data from multispectral imagery significantly reduced bias, from 1.2 to near 1 in MGB, and from 2.3 to 1.78 in CTRIP (median values), supporting hydrological assessments related to long-term variability. Furthermore, the higher temporal resolution allowed for better capture of flow variability, with Kling-Gupta Efficiency γ approaching 1.0 in MGB, which is relevant for both seasonal climate studies and short-term predictions, such as extreme hydrological events.

The comparison with the Congo basin highlights the limits of transferability across hydrological contexts and emphasizes the trade-offs between temporal resolution, spatial sampling, and product quality. Improvements within the Congo basin were more modest and more product-dependent because the available CCI stations provide a weaker spatial constraint on a basin where discharge integrates contributions from large tributaries, and because of lower discharge product quality at some stations. Overall, the results demonstrate that ESA CCI WSE and discharge products can improve large-scale hydrological simulations, but the magnitude and reliability of the improvements are not uniform and depend on the interaction between product type and quality, temporal and spatial sampling, model configuration, and basin-specific hydrological processes. Future work includes merging altimetry and multispectral discharge data, improving discharge retrieval algorithms using SWOT data, and refining data assimilation techniques to support climate studies and river system modeling in complex, climate-impacted basins.

1 Introduction

Accurately modeling river discharge and water storage is essential for understanding the water cycle at continental and global scales, particularly in regions where in situ hydrological data are sparse or unavailable. Large-scale hydrological models, such as ISBA-CTRIP (Decharme et al., 2019) and MGB (Collischonn et al., 2007; Pontes et al., 2017), are widely used tools to simulate river hydrodynamics, but they are limited by uncertainties in input parameters and by the simplifications required to represent complex local processes at larger scales (De Paiva et al., 2013). To address these challenges, Data assimilation (DA) of remote sensing observations has emerged as a powerful approach to reduce uncertainties and improve simulation performance (Wongchuig-Correa et al., 2020).

While many early studies focused on the added value of water surface elevation (WSE) data assimilation into hydrological models like ISBA-CTRIP and MGB (Pedinotti et al., 2012; De Paiva et al., 2013), the assimilation of discharge data has gained increasing interest. For example, Paiva et al. (2013) applied discharge data alongside precipitation estimates from TRMM into the MGB model to improve simulations of river dynamics in the Amazon Basin. Similarly, Wongchuig-Correa et al. (2020) showed that assimilating SWOT-simulated discharge enhanced peak flow predictions in data-sparse areas like the Solimões and Negro rivers. Emery et al. (2018) further explored the assimilation of altimetry-derived discharge estimates into ISBA-CTRIP, which improved both river storage and downstream discharge simulations. These studies underscore the growing potential of discharge assimilation, despite their inherent uncertainties, at large scales.

In parallel, data assimilation (DA) itself has become a crucial tool in hydrological modeling, aimed at reducing uncertainty in model states and improving forecast skill. By dynamically integrating observational data to update model states and parameters., DA frameworks are particularly effective in addressing uncertainties in model inputs and structural representations, especially in large-scale applications. Clark et al. (2008) demonstrated the value of in-situ discharge assimilation to refine streamflow forecasts. This was extended by Michailovsky et al. (2013) who used satellite-derived WSE to enhance discharge estimates in regions with limited in-situ data.

Subsequent studies has expanded both the types of assimilated variables and the technical complexity of DA methods. Paiva et al. (2013) demonstrated that assimilating both in-situ and satellite-derived discharge into the MGB model significantly improved river flow simulations and flood forecasts in the Amazon Basin. Building on this, Wongchuig-Correa et al. (2020) explored the assimilation of simulated Surface Water and Ocean Topography (SWOT) mission data, highlighting the potential of high-resolution satellite observations in refining hydrodynamic models. More recently, Revel et al. (2023) advanced DA techniques by incorporating transformed WSE assimilation, which led to notable improvements in discharge simulations. Extending these developments, Wongchuig et al. (2024) introduced the Multi-Observation Local Ensemble Kalman Filter (MoLEnKF), capable of simultaneously assimilating multiple satellite-derived hydrological variables, showing significant improvements in large-scale model performance. This progression reflects a growing shift toward using more complex and multi-sensor data in hydrological data assimilation.

Altogether, the progressive inclusion of both WSE and discharge data, whether in-situ or satellite-based, has reinforced the relevance of DA for improving hydrological model performance across a wide range of spatial and temporal scales. In large-scale hydrological models like ISBA-CTRIP and MGB, DA has been particularly valuable for mitigating biases related to parameter uncertainty and structural simplifications. While early efforts prioritized WSE assimilation (Pedinotti et al., 2012; Oubanas et al., 2018), the increasing focus on discharge assimilation reflects both the growing maturity of satellite-derived discharge products and recent advances in DA techniques capable of handling multiple uncertain inputs.

Recognizing the need for long-term, high-resolution data, the European Space Agency (ESA) initiated the Climate Change Initiative (CCI) Discharge Project to address the lack of consistent discharge records for climate applications. Although various satellite-derived hydrological data products exist, they are often limited in temporal resolution and do not cover long periods to support climate studies.

The ESA CCI products fill this gap by providing globally distributed, quasi-daily WSE and discharge products over a 20-year period (2000–2020). This rich dataset enables the characterization of seasonal and interannual variability, the detection of extreme hydrological events, and supports the development of long-term hydrological reanalyses in large river basins. They are thus particularly well-suited for supporting climate-relevant modeling applications, especially in large and complex river basins.

We build on this context by evaluating how these long-term satellite datasets perform when assimilated into two different large-scale hydrological models. While previous studies have explored the assimilation of long-term satellite-derived variables, such as terrestrial water storage from GRACE (Li et al., 2012; Getirana et al., 2020), few have investigated the assimilation of long-term WSE and discharge data, especially at quasi-daily resolution extended over two decades. This remains a significant gap, especially given the growing interest in using satellite-based observations to support hydrological reanalyses and long-term monitoring. Emery et al. (2018) demonstrated the benefits of assimilating altimetry-derived discharge time series for reducing bias in large-scale models. However, comprehensive assessments of long-term satellite-based discharge and WSE data assimilation over large river basins at climate-relevant timescales, remains largely missing from the literature.

Previous research has highlighted that the effectiveness of data assimilation depends not only on the accuracy of satellite products, but also on how well their spatial and temporal characteristics align with the scale and design of the target model (Oubanas et al., 2018). In this study, we evaluate long-term discharge and WSE products from the ESA Climate Change Initiative (CCI) in two existing large-scale hydrological models including their respective assimilation systems framework: CTRIP and MGB. CTRIP is a continental-scale, uncalibrated river routing model designed for use within Earth system modeling chains (Decharme et al., 2019). In contrast, MGB is a basin-scale, calibrated, distributed hydrological model commonly used for regional flood forecasting and water resource assessments (Collischonn et al., 2007; Pontes et al., 2017). Both models have been widely used in the past with distinct objectives. CTRIP is uncalibrated and uses forcings that are available at the global scale so that it can be applied over the whole globe and performances evaluated over gauged basins can be reasonably extrapolated to ungauged basins. On the other hand, MGB is usually applied for regional applications over some selected basins and calibration and local forcings ensure the best model performances for these applications, but prevent any extrapolation over other basins.

Rather than comparing model performance, we explore the robustness, limitations, and potential benefits of using these CCI-derived data products across two complete modeling/assimilation frameworks, each with its own assumptions, constraints, and intended applications. The study focuses on two major African basins, the Niger and the Congo, which provide contrasting hydrological and observational contexts. The Niger Basin is characterized by strong seasonal variability, the influence of the Inner Delta, and a comparatively denser in-situ network. In contrast, the Congo Basin has more stable large-scale flow variability, extensive wetlands and tributary storage effects, and a much sparser in-situ observation network. This dual-basin setup allows us to examine whether the assimilation impact of the CCI products remains consistent across different hydrological regimes and data-availability conditions.

To focus specifically on the stand-alone value of the ESA CCI satellite products, we deliberately exclude in-situ discharge assimilation and mixed-product assimilation experiments. This design enables a focused evaluation of CCI-derived WSE and discharge products as assimilation inputs, without confounding their impact with additional observation sources. The study is therefore framed as an application-oriented CCI product assessment, testing how assimilating these products improve model performance under operational constraints in two distinct hydrological frameworks.

In the context of data assimilation, both water surface elevation (WSE) and discharge ESA CCI products present distinct advantages and limitations. WSE is directly measurable from altimetry and typically less uncertain, but is often misaligned with the simplified river geometry used in hydrological models (which generally rather consider a conceptual river depth). In contrast, discharge estimates align closely with model outputs but are indirectly derived, either from altimetry or multispectral imagery, introducing additional uncertainties through empirical rating curves and processing chains (Gal et al., 2024; ESA CCI ATBD , 2023).

In this study, we focus specifically on the long-term satellite-derived ESA CCI WSE and discharge products, which are designed for climate applications and offer consistent, multi-decadal daily time series over a shared network of virtual stations. By comparing these products in data assimilation experiments over the Niger and Congo basins, we aim to examine their

respective potential and limitations in improving large-scale hydrological simulations through data assimilation. Within this defined framework, we seek to answer three research questions:

1. Does the assimilation of higher-uncertainty discharge data improve model performance more than the assimilation of lower-uncertainty WSE data?

2. How do trade-offs between spatial coverage, temporal resolution, and the quality of these long-term satellite-derived products impact the effectiveness of data assimilation for large-scale hydrological modeling?

3. How robust are these impacts across two contrasting hydrological modeling contexts and two basins with different hydrological regimes and observation availability?

This analysis aims to provide insights into the added-value of long-term, satellite-based data assimilation for improving model accuracy and variability representation, particularly in the context of developing reliable hydrological reanalyses for climate-related applications. While this study does not explicitly address climate attribution or trend detection, it contributes to climate-oriented hydrology by evaluating the reliability and value of these products for multi-decadal model improvement.

The paper is organized as follows: Section 2 presents the study area and the CCI satellite products used. Section 3 presents the modeling systems along with the data assimilation framework and explains the experimental setup. Section 4 presents the results of the assimilation experiments. Section 5 explores the trade-offs between different satellite data types, focusing on spatial and temporal resolution and their impact on DA performance. Finally, Section 6 summarizes the key findings and proposes future research directions in the context of using long-term satellite datasets in climate-relevant hydrological modeling.

2 Study domain and data used

2.1 Selected basins

This study focuses on two large and hydrologically significant African river basins: the Niger and the Congo. These basins were selected based on the availability of pre-existing model implementations and previous studies, access to satellite and in-situ observations, and their contrasting hydrological and climatic regimes (Figure 1). Their differences provide a valuable basis for assessing the robustness of data assimilation methods under diverse climatic and modeling conditions.

The Niger River, the third longest in Africa, spans over 4,200 kilometers and drains a basin of approximately 1.5 million km^2. It originates in the Guinean Highlands and flows through nine countries (Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Niger, and Nigeria) before reaching the Atlantic Ocean, discharging through a massive delta into the Gulf of Guinea (Figure 1). Its hydrology is characterized by strong seasonality and the presence of the Inner Delta, a vast floodplain the river traverses in Mali, averaging 73,000 km^2, which dissipates a significant proportion of its flow through absorption and evaporation (Andersen and Golitzen, 2005). Downstream of the Delta, the river continues its course till Niamey, receiving

water mainly from three intermittent right-bank tributaries responsible for a hardly predictable flood event known as the "red flood". On the left bank, most channels are not connected to the river system.

The Niger Basin traverses diverse climatic zones, from the humid tropical Guinean coast, where it generally rains every month of the year, to the arid Saharan region with very little precipitation. Its hydrological regime is highly dependent on monsoonal rainfall, and uncertainties in this seasonal forcing remain a primary source of streamflow modeling errors.The socio-economic situation of the basin countries depends heavily on river-related activities such as agriculture, freshwater fishing, and livestock farming, making water availability a critical development issue.

The Congo River Basin (CRB), the second-largest in the world, drains over 3.7 million km^2. Despite its major contribution to the global freshwater cycle, its hydrological behavior remains insufficiently understood. The Congo's mean annual flow is around 40,500 m^3/s (Laraque et al., 2020), with remarkably stable interannual variability, which makes it an interesting singularity among large tropical rivers. Despite its critical importance for local, regional, and global water and carbon cycles, the CRB has received less attention than others like the Amazon.

In the CRB, most people rely on local water resources, which are increasingly affected by climate change and water availability issues (Youssoufa Bele et al., 2013). The basin receives between 1,000 and 2,000 mm of rainfall annually, with average temperatures near 25°C and potential evapotranspiration around 1,000 mm/year that slightly varies across the basin. It is characterized by four major drainage systems (Ubangi (northeast), Sangha (northwest), Kasai (southwest), and Lualaba (southeast)) that converge to form the main Congo River (Figure 1), and includes numerous lakes and wetlands that influence its hydrology.

The selection of these two basins was guided by both scientific and operational considerations. They provide contrasting hydrological regimes and climate conditions, ranging from the monsoon-driven variability of Niger to the relatively stable flows of the equatorial Congo basin. They also have different hydrological characteristics: the Niger includes the Inner Delta with substantial evaporative losses, while the Congo includes an extensive tributary network, lakes and wetlands that buffer and redistribute flow. These physical and climatic contrasts provide both a scientific rationale and a valuable opportunity to evaluate the performance of data assimilation across basins with diverse hydrological challenges.

Their selection was further guided by operational factors, including model availability and data coverage, as discussed below.

In terms of in-situ observations, the Niger Basin benefits from relatively dense discharge gauge networks. In contrast, the Congo basin has experienced a significant decline in active hydrological stations since the 1960s (Tourian et al., 2023), making it an ideal testbed to evaluate the potential of satellite-only data assimilation approaches. Both rivers are among the largest in Africa and play a critical role in shaping regional water resources, ecosystems, and livelihoods.

Beyond their geographic and hydrological significance, the suitability of these basins is reinforced by the availability of well-established modeling frameworks. In particular, both large-scale hydrological models used in this study (CTRIP and MGB) have been previously implemented over these basins, providing a consistent and well-informed experimental setup. MGB, which has been applied in both basins, is also used for flood forecasting and enables us to assess the added value of data assimilation in flood-prone areas such as Niamey. CTRIP, as a global model, has previously been applied in the Congo Basin (Munier et al., 2022) and offers complementary insights into how data assimilation performs in an uncalibrated, coarse-

resolution setting. This dual-model setup offers a robust platform to test the effectiveness of data assimilation strategies under differing spatial scales and levels of calibration.

Yet, despite the relevance of these basins, their potential in advancing satellite-based data assimilation remains underexplored. This study contributes to filling that gap by applying and evaluating the assimilation of long-term WSE and discharge products from the ESA CCI into large-scale hydrological models. In doing so, our objective is to advance satellite-based DA practices for long-term hydrological modeling in African river basins, where robust long-term simulations are essential for supporting water resource planning and adaptation strategies in the face of observational gaps, increasing climate variability, and growing water demand.

2.2 Observations - Assimilated satellite products

In this study, three satellite-based products are evaluated within data assimilation schemes: (i) water surface elevation (WSE) rom satellite altimetry, (ii) discharge estimates from altimetry-based WSE (Qalti), and (iii) discharge estimates based on multispectral remote sensing imagery (Qmultispec). These three products are part of the ESA Climate Change Initiative (CCI) River Discharge project (Gal et al., 2024).

The first product, WSE time series, is derived from the merging of data from multiple nadir altimetry satellite missions (Biancamaria et al., 2023), including ERS-1 and -2, Envisat, SARAL, Topex-Poseidon, Jason-1, -2 and -3, Sentinel-3A and –3B, Sentinel-6A and Cryosat-2. Time series are derived at reference virtual stations (VS), preferably located on the Jason-3 ground track since the Jason series is the longest continuous series of altimeter missions. To ensure consistency across missions, inter-mission biases are corrected by subtracting the mean difference between overlapping time series. In cases where missions do not overlap, intermission bias is corrected by computing the difference between the time average of time series of the two consecutive missions. Additionally, when VS from different missions are located within 10 km of each other, with no major tributary between them, their time series can be merged using fitted relationships with the reference VS (Biancamaria et al., 2024, 2017).

The second product corresponds to river discharge derived from altimeter-based WSE (Qalti). Different methodologies have been developed, but only the first one was used for data assimilated in this work. It relies on the existence of in-situ river discharge observations and the calibration of a rating curve between in-situ discharge and altimetry WSE. A comprehensive uncertainty analysis has been conducted to derive uncertainties associated with each discharge value. These uncertainties have been used in the assimilation experiment, in comparison with constant values to assess the importance of providing realistic uncertainties along with observations. For detailed methodologies and additional context regarding Qalti, refer to the Algorithm Theoretical Basis Document (ATBD) by Gal et al. (2024) and the relevant published studies (Kouraev et al., 2004; Paris et al., 2016; Zakharova et al., 2020, 2021; Tourian et al., 2013, 2017) which explore various approaches for deriving discharge from satellite altimetry.

The third product corresponds to river discharge based on multispectral images (Qmultispec) Gal et al. (2024). The multispectral images used comes from Landsat-5/7/8/9, TERRA and AQUA (MODIS sensors), Sentinel-2, and Sentinel-3 (OLCI) platforms. It assumes that the differences between the passice response of the reflectance signal from the soil and that from the water can

be used to identify a change in the land area near the river channel that is strongly correlated with river discharge. In this approach, different reflectance indices are computed for each considered VS where in-situ discharge is available. Then, the estimation of discharge from these indices is very similar to the rating curve approach applied for the water levels by altimetry. Here, the relationship is based on the evaluation of a non-linear regression relationship between the multi-mission time series and the observed river discharge values. It is important to note that no uncertainties were computed in this approach, and only constant theoretical error values were used in the assimilation experiment. Tarpanelli et al. (2013), Filippucci et al. (2022) provide more details on the generation of these products and the application of multispectral imagery data for estimating river discharge.

Table 1 summarizes the available stations and data periods for the different CCI products used in the experiments for both Niger and Congo basins.

Table 1. Data availability for WSE, Qalti, Qmultispectral products and in-situ discharge observations in Niger and Congo basins.

Basin	**Station**	**WSE (v1.1) / Qalti (v1.1)**	**Qmultispectral (v1.2)**	**Q in-situ**
Niger	Mandiana	-	-	[2010–2018]
	Banankoro	-	-	[2010–2017]
	Koulikoro	[1995–2023]	[2000–2022]	[2010–2018]
	Ke-Macina	-	-	[2010–2018]
	Nantaka	-	-	[2010–2018]
	Akka	-	-	[2010–2017]
	Dire	-	-	[2010–2018]
	Ansongo	[1995–2023]	[2002–2022]	[2010–2018]
	Alcongui	-	-	[2010–2017]
	Niamey	[2017–2023]	[2000–2022]	[2010–2022]
	Malanville	[1995–2023]	[2013–2022]	[2010–2017]
	Makurdi (Benue)	-	[2000–2022]	[2010–2016]
	Ibi (Benue)	[2002–2023]	-	-
	Lokoja	[2010–2016]	[2000–2022]	[2010–2018]
Congo	Chembe-Ferry	[2002–2023]	[2002–2022]	-
	Ouesso	-	-	[1947–2020]
	Bangui / Oubangui	[2002–2023]	[2000–2022]	[1911–2020]
	Kinshasa	[2002–2023]	[2000–2022]	[1947–2023]

The locations of the stations where data will be assimilated into both models are presented in the two maps shown in Figure1.

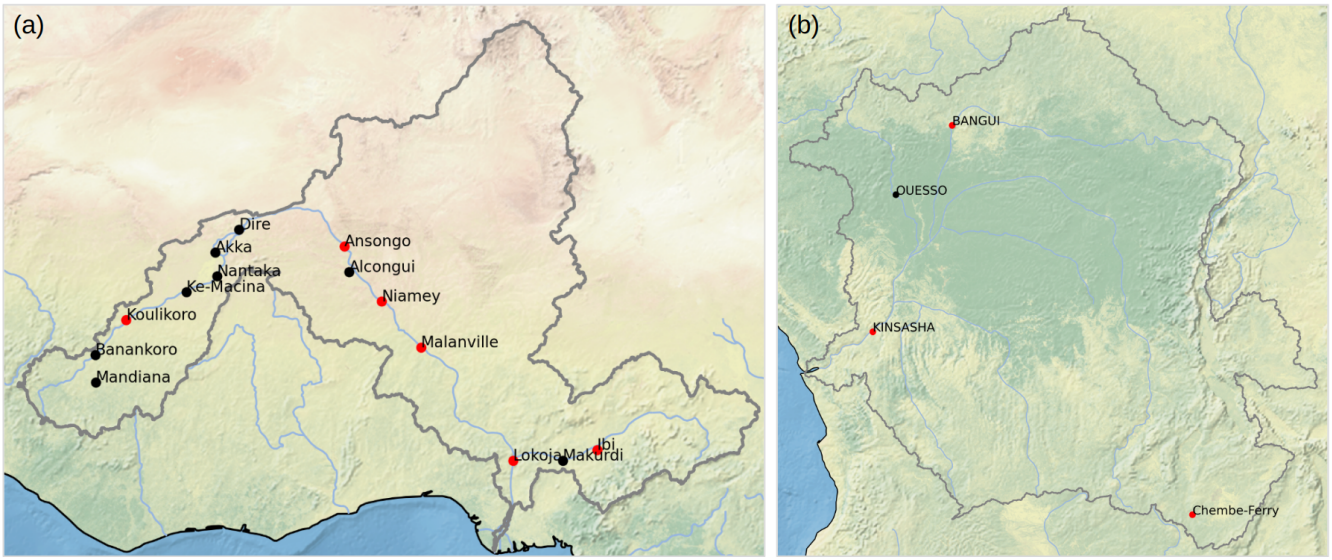

Figure 1. Maps showing the locations of stations in both the Niger and Congo basins. Red markers represent stations where data assimilation is conducted, and black markers indicate the remaining stations with in-situ data used for performance assessment of the assimilation experiments in both the MGB and CTRIP models.

To assess the reliability of the assimilated satellite discharge products, we compared both altimetry-based (Q_{alti}) and multispectral-based ($Q_{\text{multispec}}$) discharge estimates against the in-situ measurements in the Niger and Congo basins. In the Niger basin, Q_{alti} generally captures the seasonal cycle and high-flow dynamics well at upstream stations (e.g., Koulikoro, Ansongo), though it tends to overestimate peak flows. Further downstream (e.g., Lokoja), the accuracy decreases slightly, with growing underestimation of discharge. In contrast, $Q_{\text{multispec}}$ offers denser temporal coverage but shows greater noise and a temporal lag in capturing hydrological peaks, especially at Niamey and Lokoja, which can affect data assimilation performance by introducing corrections that are out of phase with the modelled hydrological cycle. In the Congo basin, results are available for Bangui and Kinshasa, where Q_{alti} performs well, closely tracking observed discharges with high correlations and low bias. While $Q_{\text{multispec}}$ shows acceptable performance at Kinshasa, it fails to reproduce the hydrological signal at Bangui, with low correlation and poor representation of seasonality. A full evaluation of the CCI discharge products against in-situ data, including KGE scores and hydrograph comparisons (Figures S1,S2), is presented in the Supplement.

3 Modeling framework and experimental setup

3.1 Large-scale hydrological models

This study relies on two large-scale hydrological models that differ significantly in structure, spatial resolution, and intended use: the ISBA-CTRIP global river routing model and the MGB regional hydrological model. Their combined use enables a

broader assessment of data assimilation (DA) strategies across diverse hydrological modeling contexts. The objective here is not to compare performances between the two hydrological models but rather to evaluate the potential of CCI discharge assimilation within those two conceptually different models.

3.1.1 CTRIP global river routing model

CTRIP is a physically based river routing model coupled to the ISBA land surface model (Figure 2). While ISBA represents the vertical exchanges of water and energy at the soil-atmosphere interface, CTRIP simulates river flows over an entire hydrographic network (Decharme et al., 2019). The ISBA and CTRIP models are used, in particular, in climate models such as the CNRM-CM6 that participated in the sixth phase of the Coupled Model Intercomparison Project (Eyring et al., 2016, CMIP6) as a contribution to the IPCC Sixth Assessment Report (AR6). CTRIP is based on a regular grid with a resolution of 1/12° (i.e. around 8 km at the Equator) obtained by the upscaling of the MERIT-Hydro global hydrographic network (Yamazaki et al., 2019), available at a resolution of 90 m and currently considered to be the most accurate on a global scale.

A number of hydro-geomorphological parameters, such as the lengths and slopes of river sections, are obtained from high-resolution data from MERIT-Hydro, while other parameters, such as widths, depths, and roughness, are obtained from empirical formulae (Munier & Decharme, 2022). It is assumed that each grid cell contains one and only one river reach, represented as a reservoir flowing into the downstream grid cell. The Manning equation is used to calculate the flow velocity as a function of the volume of water in the section, itself updated by the inflows from the upstream reaches and the runoff from the ISBA model.

The model also benefits from a two-dimensional representation of aquifer dynamics and groundwater-river exchanges (Vergnes and Decharme, 2012). Note that a 100-year spinup has been performed to reach a stabilized state of the aquifers. Finally, surface processes linked to vegetation (including real evapotranspiration) and snow cover (including sublimation and melting) are taken into account in the ISBA model.

It is also important to note that because the prior objective of CTRIP is to be integrated into climate models, it is based on quite simple approximations of rivers and aquifers dynamics. Consequently, unlike most hydrological models, the CTRIP model does not benefit from a parameter calibration stage. This choice ensures spatial consistency when the model is used in other regions of the world—or even globally—where few observations are available, particularly in climate projections. It follows a physically based parameterization strategy to ensure consistency across basins and scales.

3.1.2 MGB regional hydrological model

The MGB model ("Modelo de Grandes Bacias" or "Large Basins Model") is a semi-distributed hydrological model that uses physically and conceptually based equations to simulate rainfall-runoff processes and river hydraulics using a two-way coupling scheme between hydrological and hydrodynamic modules (Collischonn et al., 2007; Pontes et al., 2017). It has been extensively applied to large river basins such as the Amazon, and has shown good ability to represent complex processes, such as floodplain dynamics (De Paiva et al., 2013).

A key feature of MGB is its explicit simulation of wetlands and floodplain processes. It includes infiltration from flooded areas into unsaturated soil columns, which is crucial in regions where dry soils are inundated by exogenous floodwaters, such as the Niger Inner Delta. The model also dynamically simulates evapotranspiration and open water evaporation based on flood-driven land cover variation, capturing the differing effects of bare soil and vegetation across flooded zones. River routing includes flow propagation, backwater effects, and hydrodynamics in large floodplains (Figure 2). A full description is provided in Siqueira et al. (2018).

MGB is used for real-time and near real-time flood forecasting in various regions, including the Amazon basin, where it has been operational for flood forecasts and water resource management (De Paiva et al., 2013; Siqueira et al., 2018; Sorribas et al., 2020). Similar real-time forecasting applications have been implemented in the Paraná basin and other regions, showcasing the model's adaptability for hydrological forecasting at both local and large scales.

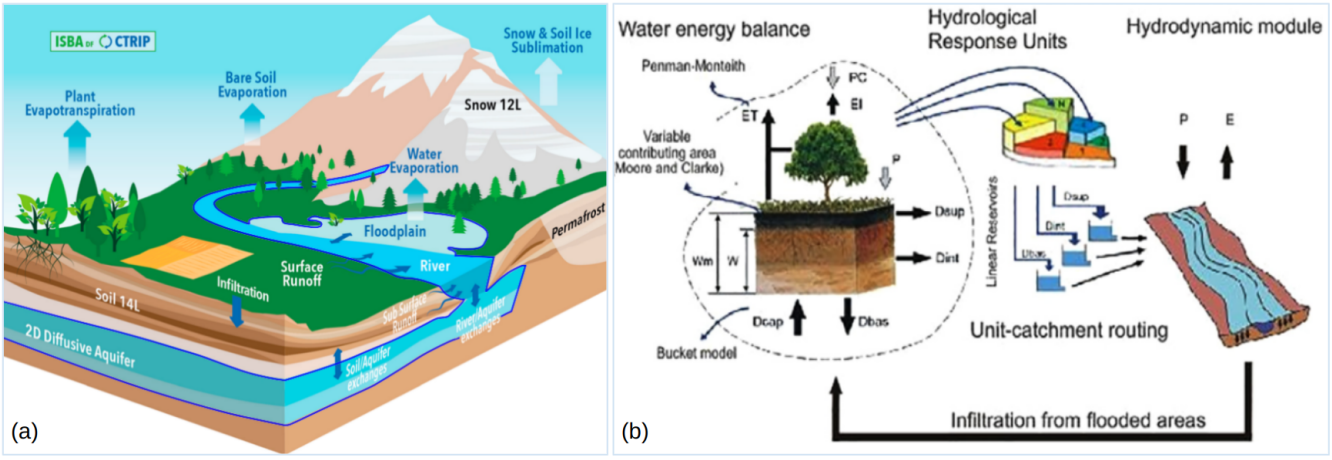

Figure 2. Schematic representation of the two large-scale hydrological models used in this study. Panel (a) illustrates the ISBA-CTRIP model (Decharme et al., 2019), a global river routing model coupled to the ISBA land surface model, which simulates river discharge at continental scale. Panel (b) presents the MGB model (Collischonn et al., 2007; Pontes et al., 2017), a semi-distributed hydrological model incorporating two-way coupling between hydrology and hydrodynamics, enabling the explicit simulation of floodplain processes such as evapotranspiration from inundated areas.

3.1.3 Models implementation over the Niger and Congo basins

Both ISBA-CTRIP and MGB hydrological models require meteorological forcings, including precipitation, surface temperature and air humidity, wind, and radiation forcings. The choice of forcing datasets differs based on each model's design and application.

ISBA-CTRIP is forced with ERA5 reanalysis data, which is chosen for its global coverage, temporal resolution and consistency, with its intended use for climate studies and water resource assessments (Dee et al., 2011; Hersbach et al., 2020). A bias-correction process of ERA5 precipitation was applied following Szczypta et al. (2012) to improve its accuracy in the hydrological

context. The configuration of ISBA and CTRIP models is the one used for global scale simulations, as described in Munier & Decharme (2022), except that the floodplain scheme was not activated. It is important to note that no observations were used to calibrate the model parameters.

In contrast, MGB is designed for basin-scale hydrology and operational forecasting. For the Niger Basin, MGB is based on the setup from Siqueira et al. (2018), with 11,595 unit catchments and river reaches of approximately 10 km. The model is forced using GSMAP precipitation (Ushio et al., 2006) and CRU 10′ long-term climatology data (monthly climate normals of wind speed, solar radiation, relative humidity, air pressure and air temperature) (New et al., 2002) to calculate the model evapotranspiration. For the Congo Basin, MGB is implemented with 9,220 units (20 km resolution) and forced by IMERG precipitation (Huffman et al., 2019). These datasets were chosen for their improved spatial and temporal representation of tropical precipitation (Kubota et al., 2020; Gosset et al., 2023; Peterson et al., 2015), which better aligns with the needs of short-term and flood forecasting.

The use of different precipitation forcings was deliberately retained to preserve the native configurations of the two modeling systems. CTRIP is used with bias-corrected ERA5, consistent with its global and climate-oriented configuration, while MGB is used with the precipitation products adopted in its calibrated basin-scale implementations. This choice is consistent with the scope of the study, which is to assess the ESA CCI products in realistic modelling/assimilation frameworks rather than to conduct a harmonized model-intercomparison experiment.

MGB was calibrated against in-situ discharge and evaluated using altimetry and flood extent data, while CTRIP follows an uncalibrated, physically based approach.

These differences in forcing, calibration strategy, spatial scale, and process representation are treated here as part of the native configuration of each modelling system. The dual-model setup is therefore used to examine whether the impact of long-term satellite-derived WSE and discharge assimilation is consistent across two contrasting hydrological modelling frameworks, rather than to compare absolute model performance or isolate the effect of individual model components.

Simulations are conducted over the period 2000–2020 for both basins and models, ensuring a common evaluation period for the DA experiments.

3.2 Data Assimilation schemes

Two distinct data assimilation (DA) frameworks are embedded within the CTRIP and MGB hydrological models: CTRIP-HyDAS and MGB-HYFAA. While both rely on ensemble-based Kalman filtering techniques, they differ in their implementation, model structure, and operational contexts. Their joint use allows us to explore the robustness and adaptability of DA across hydrological models with different configurations.

3.2.1 CTRIP-HyDAS and MGB-HYFAA

CTRIP-HyDAS (Hydrological Data Assimilation System) is a hydrological data assimilation system embedded within the CTRIP routing model. Developed since the early 2010s, it is primarily designed to assimilate observations from satellite altimetry missions. The system has been previously applied over the Amazon basin (Emery et al., 2018, 2020, b), where it was

used to assimilate either nadir altimetry or SWOT-like observations. With this system, it is possible to correct model states (mainly river storage) or parameters (such as roughness).

In past studies, the assimilation of SWOT-like data was implemented in twin-experiment Observing System Simulation Experiments (OSSEs) since real SWOT observations were not available yet. Some pseudo-OSSEs have also been conducted by using a different model (namely MGB) to simulate SWOT observations, thus providing more realism in the differences between the dynamics of CTRIP and reality. More recently, CTRIP-HyDAS has been extended to operate globally at 1/12° resolution in the context of the SWOT mission. In this study, only model states are updated, using either water surface elevation (WSE) anomalies or river discharge as observation input. Assimilated data are those derived in this CCI Discharge project.

HYFAA (Hydrological Monitoring and Forecasting Framework for Assimilation Applications) is a Python-based scheduler developed to support hydrological monitoring, forecasting, and assimilation tasks using MGB model. It manages the sequantial execution and communication between three components: the MGB hydrological model, an Ensemble Kalman Filter (EnKF), and an observations database.

In its forecasting mode, the HYFAA wokflow includes three main steps:

1. Pre-processing, which updates local forcing and assimilation databases from external sources, converts data to the required format, and keeps track of changes in data.

2. Processing, which launches hydrological simulations and, when observations are available, runs the EnKF to update the model state varaibles and/or parameters consistently with the observation and model uncertainties. The MGB model state variables and parameters are passed to the EnKF, which returns corrected values as new inputs to the MGB model. The processing module manages these exchanges of data.

3. Post-processing, which keeps track of the simulated or analyzed model states in an SQL database.

Beyond forecasting applications, HYFAA platform has also been used in various OSSE studies to assess the contribution of future satellite missions (SWOT, SMASH), as well as to evaluate the relevance of current observation systems, their spatial and temporal resolutions, and their uncertainties in estimating discharge over large river basins around the world.

Both CTRIP-HyDAS and MGB-HYFAA rely on Ensemble-based Kalman Filter (EnKF) approches to assimilate observations into their respective hydrological models. While based on the same core principles, the two systems employ slightly different variants:

1. CTRIP-HyDAS implements the Local Ensemble Transform Kalman Filter (LETKF), which updates the ensemble mean and perturbations separately to preserve the statistical structure of the ensemble (spread and statistical properties)

2. MGB-HYFAA uses the Local Ensemble Kalman Filter (LEnKF), which directly updates each ensemble member based on the observations and the model's error statistics

To better illustrate the methodological differences between the two data assimilation systems, Table 2 summarizes their main characteristics. It presents a comparative overview of model architecture, routing schemes, meteorological forcings, and assimilation strategies.

Table 2. Summary of the data assimilation frameworks used in this study

Feature	CTRIP-HyDAS	MGB-HYFAA
Hydrological model	ISBA-CTRIP (global river routing)	MGB (distributed hydrology-hydrodynamics)
Spatial resolution	1/12°	10–20 km unit catchments
Main application	Climate and Earth system modeling	Operational flood forecasting, hydrological monitoring
River routing scheme	Kinematic wave, single reach per cell	Muskingum-Cunge scheme, full 1D hydrodynamics with floodplain exchange
Land-surface coupling	Coupled with ISBA LSM (for vertical water and energy fluxes)	Includes land cover–dependent evapotranspiration
Calibration	None (physically based parameterization)	Calibrated using in-situ discharge, altimetry and flood extent
Precipitation forcing	ERA5 (bias-corrected, (Szczypta et al., 2012))	GSMaP (Niger) (Ushio et al., 2006), IMERG (Congo) (Huffman et al., 2019)
DA method	LETKF (Local Ensemble Transform Kalman Filter)	LEnKF (Local Ensemble Kalman Filter)
DA system architecture	Embedded module (Fortran-based) module	External Python scheduler managing MGB + EnKF
Assimilated variables	Water surface elevation (WSE) anomalies, discharge	
Localization approach	Hydrological local patch based on variogram range from 20-year model run (Revel et al., 2019)	
Ensemble generation	EOF-based perturbation (Munier et al., 2015)	Stochastic pixel-wise multiplicative perturbation using Gaussian noise

Evaluating data assimilation performance in both frameworks provides complementary insight into the potential and limitations of long-term satellite-derived discharge and WSE products under different model configurations, spatial scales, and data-availability conditions.

3.2.2 HYFAA: Local Ensemble Kalman Filter (LEnKF)

The Kalman filter (Kalman, 1960) is a foundational sequential data assimilation technique extensively used in hydrological sciences. At each assimilation step, it integrates observations with the forecasted state ensemble to produce an updated analysis state, effectively addressing both observational and model errors. Although originally developed for linear systems with Gaussian errors, the Kalman filter has been adapted for nonlinear models, with the Ensemble Kalman Filter (EnKF) being a notable extension (Evensen, 2009).

In the EnKF framework, an ensemble of model states is propagated forward in time, and at each assimilation step, observations are used to update the ensemble members. The general update equation for each ensemble member X_i is:

$$X_i^a = X_i^f + K(Y^o + \varepsilon_i - HX_i^f) \tag{1}$$

where X_i^f is the forecast state of the i-th ensemble member, X_i^a is the updated (analysis) state, Y^o is the observation vector (here, WSE or river discharge), ε_i is a perturbation sampled from the observation error distribution, H is the observation operator mapping model states to observation space, and K is the Kalman gain matrix, computed as:

$$K = P^f H^T (HP^f H^T + R)^{-1} \tag{2}$$

where P^f is the forecast error covariance matrix, and R is the observation error covariance matrix, determined from the uncertainty of the measurements.

HYFAA scheduler uses the Local Ensemble Kalman Filter (LEnKF) as DA approach, which directly updates each ensemble member based on the observations and the model's error statistics.

Finally, a localization strategy has been implemented into HYFAA, as described in Section 3.2.4.

3.2.3 HyDAS: Local Ensemble Transform Kalman Filter (LETKF)

The assimilation in CTRIP-HyDAS follows the Local Ensemble Transform Kalman Filter (LETKF). The LETKF updates the ensemble mean and perturbations separately, preserving the statistical structure of the ensemble. The analysis update in LETKF is given by (Revel et al., 2019):

$$X^a = X^f + E^f \left[VD^{-1}V^T (HE^f)^T \left(\frac{R}{w}\right)^{-1} (Y^o - HX^f) + \sqrt{(m-1)} VD^{-1/2}V^T \right] \tag{3}$$

where X^a is the posterior state estimator, X^f is the prior state estimator (or forecast), E^f is the prior state error covariance, which is obtained directly from the ensemble, w is the weighting term for the observation localization (described Section 3.2.4), and VDV^T is given by:

$$VDV^T = (m-1)I + (HE^f)^T R^{-1} HE^f \tag{4}$$

where I is the unit matrix with dimension m equal to the size of the ensemble. $VD^{-1}V^T$ and $VD^{-1/2}V^T$ can be calculated from the eigenvalue decomposition of VDV^T. It is important to highlight that R is consistently assumed to be diagonal, indicating independence among observation errors.

This approach allows for efficient assimilation of observations by transforming the ensemble in a way that accounts for both model and observation uncertainties.

3.2.4 Localisation Approach

Both CTRIP-HyDAS and MGB-HYFAA adopt the same localization strategy to constrain the spatial influence of observations, reducing the risk of spurious long-distance correlations and improving the numerical stability of the filter. The observations localization weight w, introduced in Equation 3, is computed using the method proposed by Revel et al. (2019), specifically adapted to the structure of river networks. Rather than solely relying on simple Euclidean distances or topological river-network distances, this approach defines spatial local patches based on the spatial correlation structure of hydrological variables.

For each pixel (or river reach) of the domain, a Gaussian semi-variogram is computed based on a long-term (20-year) reference simulation, used to estimate spatial correlations. The semi-variogram is fitted to time series of discharge or WSE anomalies, and its estimated range parameter determines the distance over which the variable is spatially correlated. This range is then used as a threshold to define the spatial extent of the local patch. For each observation, only the pixels within this hydrologically connected patch, both upstream and downstream, are updated during the assimilation process. This localization method is therefore more adapted to hydrology than classical methods as it accounts for the dynamic dependencies in river discharge and improves the physical consistency of the data assimilation procedure.

Figure 3 shows examples of the local patches for three pixels in the Congo basin, with the color bar representing the observation localization weight w.

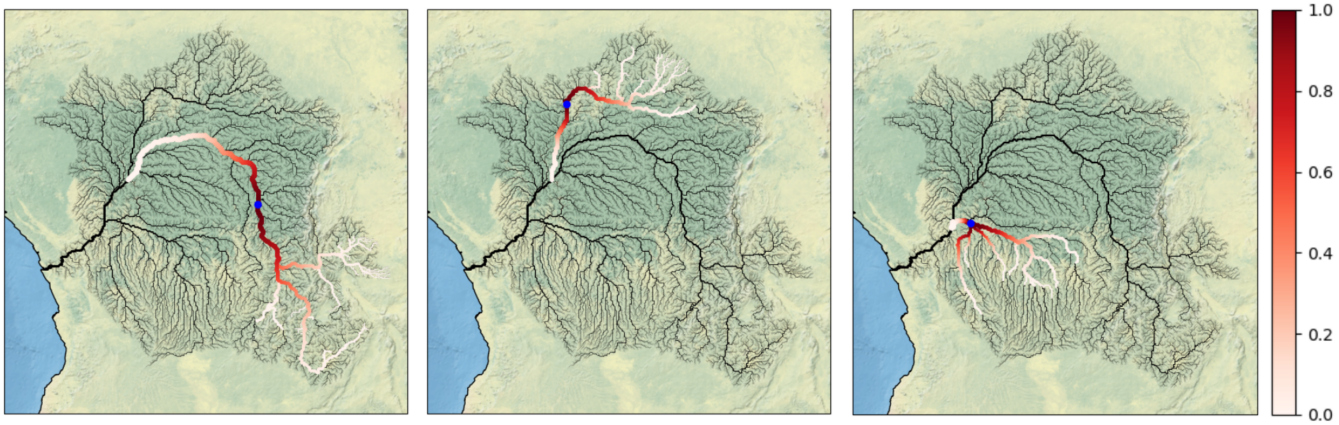

Figure 3. Examples of the localization for three pixels of the Congo basin. The color bar represents the observation localization weight w, which indicates the spatial influence of an observation on nearby hydrologically connected pixels during the assimilation process.

3.2.5 Ensemble Generation

The ensemble of model states, representing the best operating estimate, is systematically generated through the introduction of perturbed meteorological forcing. It is highlighted that only meteorological forcing is assumed to be subject to uncertainties, with the model structure and parameters assumed to be devoid of errors that could significantly impact the model outputs.

Perturbing the model parameters is also a possible way to create the model ensemble, and it is particularly useful when parameters are corrected during the analysis step.

Here, we used the method developed in Munier et al. (2015). The approach involves perturbing statistically significant modes obtained through the decomposition of the precipitation field into Empirical Orthogonal Functions (EOFs). Mathematically, for a variable X representing meteorological forcing (here precipitation), the decomposition can be expressed as:

$$X_{ijk} = X_{\text{mean},jk} + \sum_{\ell=1}^{\text{NEOFs}} U_{\ell,jk} V_{i,\ell} \tag{5}$$

Here, X_{ijk} represents the meteorological forcing variable at time step i, latitude j, and longitude k. $X_{\text{mean},jk}$ is the temporal mean of X at latitude j and longitude k. $U_{\ell,jk}$ denotes the spatial patterns, and $V_{i,\ell}$ represents the temporal coefficients of mode ℓobtained through the EOF analysis. The sum is taken over the retained EOFs, with NEOFs being the number of retained modes.

The leading modes, explaining 95% of the variance, are retained, with the perturbations applied as:

$$\tilde{X}_{ijk} = X_{\text{mean},jk} + \sum_{\ell=1}^{\text{NEOFs}} \epsilon_\ell U_{\ell,jk} V_{i,\ell} \tag{6}$$

Here, $\tilde{X}$ represents the perturbed variable, and ϵ_ℓ is the perturbation coefficient of the respective EOF mode, following a gaussian distribution centered in 1 and with a variance of 0.4 (a value obtained by trial and error to ensure a relevant discharge ensemble spread). This methodology ensures a realistic representation of meteorological forcing uncertainties, critical for generating the ensemble of model states for subsequent assimilation experiments.

3.3 Experimental Setup

To evaluate the impact of assimilating CCI discharge products Altimetry-based (Q_{alti}) and Multispectral-imagery based ($Q_{\text{multispec}}$) and water surface elevation anomaly (dH) into the CTRIP (with HyDAS scheme) and MGB (with HyFAA) models, a series of 8 experiments were conducted over the 2000–2020 period in both the Niger and Congo basins. A 1-year spinup is added at the beginning of all the simulations (1999) to ensure that the models reach a stable state before the assimilation starts.

Each model was first run in an Open-Loop (OL) configuration, without data assimilation, to establish a reference baseline. CTRIP was forced with ERA5 reanalysis data (Hersbach et al., 2020), while was driven by ERA5 atmospheric variables and GSMaP (Ushio et al., 2006) and IMERG (Huffman et al., 2019) precipitation products in the Niger and Congo basins, respectively (see Section 3.1.3). A 25-member ensemble was generated in each experiment using EOF-based perturbations of the precipitation field to account for meteorological forcing uncertainties (see Section 3.2.5).

Eight assimilation experiments were then carried out, with each CCI product tested at two to three uncertainty levels:

- WSE anomaly (dH): computed errors, 0.2 m, 0.4 m. Anomalies are computed by subtracting the mean WSE from a 20-year open-loop reference simulation [2000-2020] in both models.

- Altimetry-based discharge Q_{alti}: computed errors, 30%, 50% constant uncertainty.
- Multispectral-imagery based discharge $Q_{\text{multispec}}$: 30% and 50% constant uncertainty.

For each assimilated product, two levels of uncertainty have been chosen in addition to the uncertainty computed during the generation of the products. Theoretical uncertainty levels were selected on the basis of a combination of error distributions derived directly from the ESA CCI products and values commonly adopted in previous hydrological DA studies. For WSE anomalies (Figure S7 in the Supplement) , the computed uncertainties typically range between 0.01–0.85 m across Niger and Congo stations, with median values around 0.10 m in Niger and 0.24 m in Congo. We therefore retained two representative scenarios (0.2 m and 0.4 m) covering both typical and upper-bound conditions, consistent with uncertainty ranges adopted in previous WSE assimilation studies (0.1–0.5 m) (Andreadis et al., 2007; Paiva et al., 2013, 2015; Munier et al., 2015). For Qalti (Figure S8 in the Supplement) , the relative uncertainties showed a wide spread (4%–100%), with basin-wide medians around 62–79%. However, several well-instrumented stations (e.g., Bangui, Kinshasa, Niamey, Malanville) exhibit significantly lower values. To capture this variability while maintaining a balanced impact of the observations in the Kalman filter, we selected 30% (optimistic) and 50% (conservative) as representative levels, 30% being in line with values used in previous studies (Paiva et al., 2013, 2015). Since no station-based uncertainties are currently available for Qmultispec, the same levels as Qalti were adopted for consistency.

The performance of assimilation experiments was evaluated against independent in-situ discharge data. The validation datasets include 13 stations from the Niger Basin Authority (ABN, 2010–2017) and three stations from the So-HyBAM database in the Congo Basin (1950–2020).

An overview of the experimental setup, including the models, forcing datasets, and assimilated observations, is presented in Figure 4.

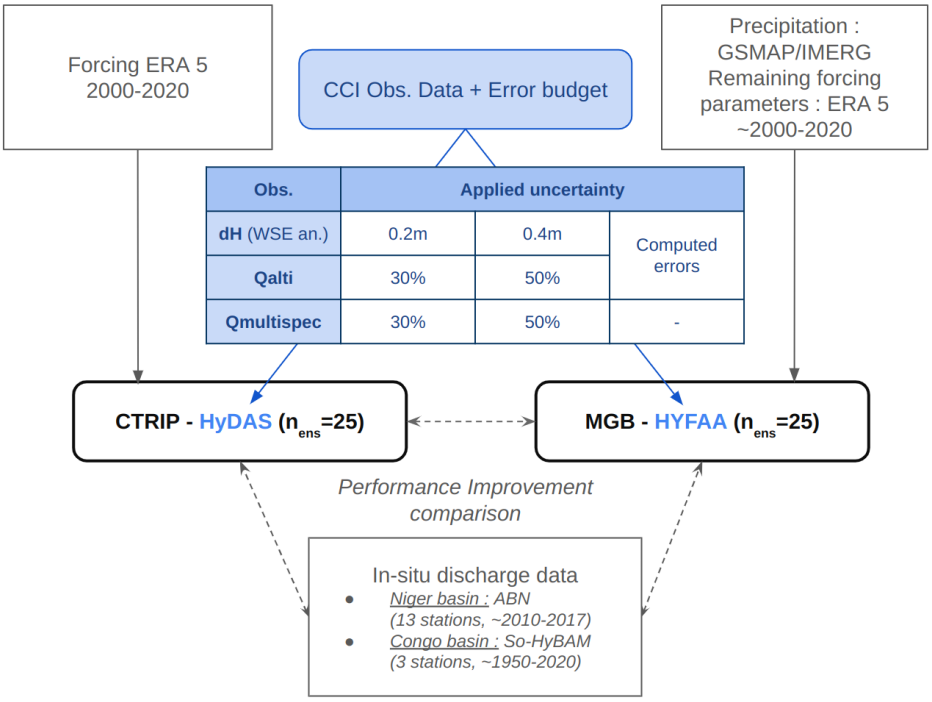

Figure 4. Overview of the experimental setup for the assimilation of ESA CCI discharge products into the CTRIP and MGB hydrological models. The models were forced with ERA5 reanalysis data (GSMaP/IMERG precipitation data for MGB in the Niger and Congo Basins respectively) and run in both Open-Loop mode and with data assimilation. The three assimilated observation types are: (1) water surface elevation anomalies (dH) derived from satellite altimetry, (2) altimetry-based discharge (Qalti), and (3) discharge estimated from multispectral imagery (Qmultispec). The EnKF framework (HyDAS for CTRIP and HYFAA for MGB) was used to update model states based on these observations

4 Results

To correctly understand the impact of the assimilation of satellite derived WSE or discharge, it is first important to analyze the performances of both models without assimilation (Open-Loop), which is described in the following section.

4.1 Open-loop Performance - Key issues in both models

A detailed evaluation of the Open-Loop (OL) simulations was conducted for both CTRIP and MGB models across the Niger and Congo basins to establish a baseline prior to data assimilation. The analysis, presented in the Supplement, compares model outputs with in situ discharge observations, and focuses on the models' ability to reproduce key hydrological features, including seasonal flow dynamics, the magnitude of high and low flows, and internal variability. These results provide a necessary benchmark for understanding how data assimilation may improve model performance.

The Open-Loop performance of the MGB and CTRIP models across the Niger and Congo basins reveals several key limitations. MGB generally performs well but tends to overestimate discharge during high-flow periods in both basins, particularly in the Inner Niger Delta and at Ouesso and Bangui in the Congo basin. It also slightly underestimates internal variability, leading to difficulties in reproducing short-term fluctuations, especially in the central Niger Basin. Additionally, at Kinshasa, the model underestimates discharge by 19%, indicating a bias in the overall flow magnitude.

In contrast, CTRIP faces significant challenges, with large overestimations during high flows—up to 2.3 times the observed values in the Niger Basin (mainly due to evaporation in the Inner Delta not represented in the model) and considerable underestimations, particularly during low flows, across both basins. In the Congo basin, CTRIP struggles with discharge underestimations of around 43% at Kinshasa, although it captures seasonal flow patterns relatively well in the tributaries. It has to be noted that improvements can be expected with the CTRIP model when coupled to the ISBA land surface model to account for evaporation, namely. Yet, as CTRIP is also used for large scale hydrological studies, we preferred to use this configuration in the present study.

These baseline limitations highlight opportunities for improvement, where data assimilation has the potential to reduce biases, improve discharge magnitudes, and refine flow timing in both models. The next section explores how different assimilation products can address these challenges and enhance model performance, taking into account the quality and temporal resolution of the assimilated products (Supplement, Figures S1,S2), and also the uncertainties set to the different data (Section 3.3).

4.2 Assimilation Impact

4.2.1 Overview

The impact of data assimilation for both models (MGB-HYFAA and CTRIP-HyDAS) across the Niger and Congo basins is first presented through a general overview of the performance changes observed across the different assimilation experiments.

To ensure clarity of the figures, only the ensemble means for each experiment are considered, given the number of assimilation experiments. It is worth noting that, for both CTRIP and MGB, the dispersion between ensemble members (standard deviation) has consistently decreased following data assimilation compared to the Open-Loop simulations.

The following initial comparison highlights the overall trends and improvements brought by the integration of observation products, which will then lead into a more detailed analysis in the following subsections. Two tables are provided in the Supplement with the detailed list of numerical performance scores shown in Figures 5 and 6 for all assimilation experiments in both basins.

In the Niger basin, when assessing the performance of MGB in assimilating discharge and WSE anomalies, Qalti shows the highest improvement in NSE (Figure 5, panel 1a), with a median value of 0.83 at 50% uncertainty, followed by WSE anomalies (NSE: 0.73-0.76). In terms of correlation, Qalti assimilation performs best, raising the median correlation to 0.94 (Panel 1b), while WSE anomalies maintain a similar value to the Open Loop (0.93). Although Qmultispec exhibits the lowest NSE (0.68-0.72) and correlation due to its higher data noisiness, it compensates by performing best in reducing bias and correcting internal variability (panels 1c,1d). Bias is best reduced by Qmultispec, improving the median from 1.2 to closer to 1 (Figure 5, panel

1c). In terms of internal variability, Qmultispec also outperforms, with KGE γ nearing 1.0 at 30-50% uncertainty, while Qalti and WSE anomalies range between 0.90-0.94 (Figure 5, panel 1d). Therefore, while Qalti leads in improving flow magnitude and correlation, Qmultispec proves superior in bias and internal variability correction. For completeness, the Supplement includes the discharge climatologies for all stations in the Niger basin (MGB-HYFAA), illustrating the general behavior of each assimilation experiment across the full domain (Figure S11).

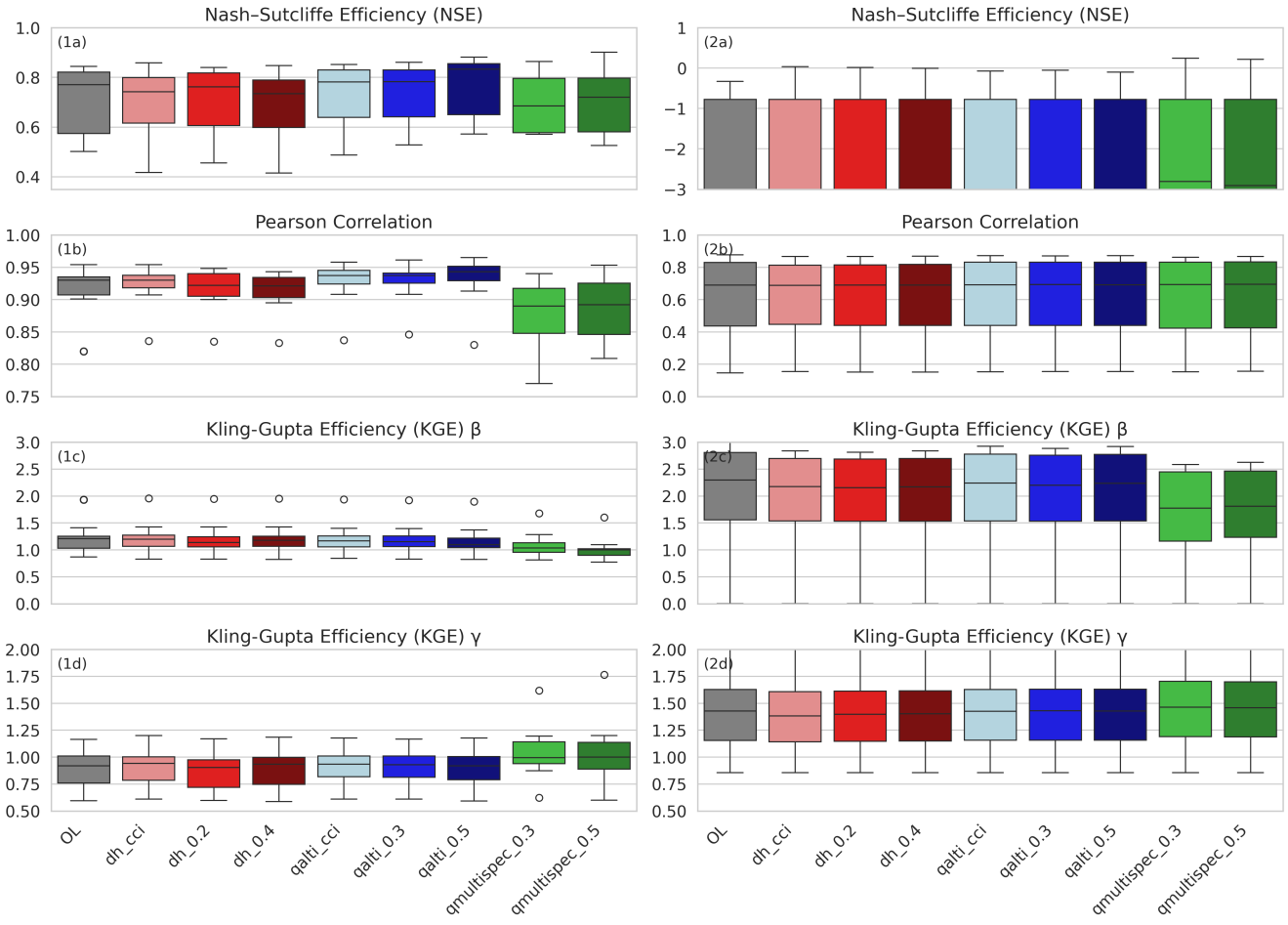

Figure 5. Distribution of NSE (a), correlation (b), bias (c), and internal variability (KGE γ, panel d) scores for MGB (1) and CTRIP (2) simulated discharge at 11 in-situ stations (Niger Basin, 2000-2020): comparison of open-loop (grey) and assimilation of water level anomalies (dH, red), altimetry-based discharge (Qalti, blue), and multispectral imagery discharge (Qmultispec, green) with different uncertainties. The lightest colours for dH and Qalti experiments represent uncertainties from computed errors, followed by the lowest values, while the darkest indicate the highest errors. For Qmultispec, the shades of green transition from light to dark based on increasing theoretical uncertainties.

In CTRIP-HyDAS, the Niger basin exhibits limited improvement due to the model's already poor performance in Open Loop. However, Qmultispec performs better than both Qalti and WSE anomalies in bias reduction and overall improvement of internal variability. The CTRIP model demonstrates improvements in NSE, where Qmultispec assimilation leads to a 15% increase in performance, whereas WSE and Qalti show more modest gains in both bias and correlation (panels 2a, 2b, 2c, 2d, Figure 5).

For the Congo basin, assimilation experiments reveal a more nuanced picture. The analysis is limited to only two of the four main tributaries and Kinshasa at the lower Congo, making the scope of conclusions more constrained. While MGB displays noticeable improvements with Qmultispec in the Niger basin, the product does not perform as well in the Congo basin, largely due to lower data quality and temporal density (Figure S2, Supplement). Here, Qalti delivers the best performance, notably improving NSE from 0 to 0.1 at Kinshasa. Correlation scores improve by about 5% at Kinshasa and other stations (Panels 1a, 1b, Figure 6). However, bias and internal variability are only slightly corrected (less than 5% overall improvement), as seen in panels 1c and 1d of Figure 6.

Meanwhile, in CTRIP, the assimilation of WSE anomalies leads to better performance over the Congo basin compared to discharge assimilation. This is due to a more coherent alignment between the model's rating curve and observed WSE data (as shown in the following section 4.2.2), along with the lower uncertainty attributed to WSE compared to discharge. Panels 2b and 2d of Figure 6 show improvements in correlation (+13%) and variability (-7%), particularly noted at Kinshasa, where Qmultispec underperforms. In contrast, Qmultispec data quality deteriorates performance in both MGB and CTRIP for the Congo basin, particularly at Bangui and Kinshasa, where it fails to accurately represent the hydrological cycle.

When comparing the influence of the observations characteristics (spatial density, temporal frequency, and data accuracy) with uncertainty values, the distribution of performance indices across experiments shows that the characteristics of observed data play a more decisive role in both models and basins. Data assimilation is primarily driven by the spatial density of virtual stations, followed by temporal resolution and data accuracy, with uncertainty having a lesser impact. However, uncertainties become important in the presence of outliers, as higher uncertainty values reduce the likelihood of outlier assimilation, minimizing hashed effects in the analysis. This is evident in the assimilation of Qmultispec products in the Congo basin, where poor data quality degrades model performance. Nevertheless, higher uncertainty (50%) limits degradation compared to 30% uncertainty (Figure 6).

From these results, two key findings are highlighted to explore more specifically the contributions of the different CCI discharge products. In one hand, the comparison between discharge assimilation and WSE anomaly assimilation in large-scale hydrological models is examined. In the other hand, the added value of Qmultispec data is analyzed, particularly in the Niger Basin, where it outperforms Qalti in correcting bias and internal variability.

4.2.2 Assimilation of Discharge Compared to WSE Anomalies in Large-Scale Hydrological Models given same temporal and spatial resolution - Qalti vs dH

The comparative performance of dH and Qalti assimilation is influenced by several factors, including product uncertainty, model open-loop baseline simulation, and how well observations integrate with model dynamics. Among these, the mismatch

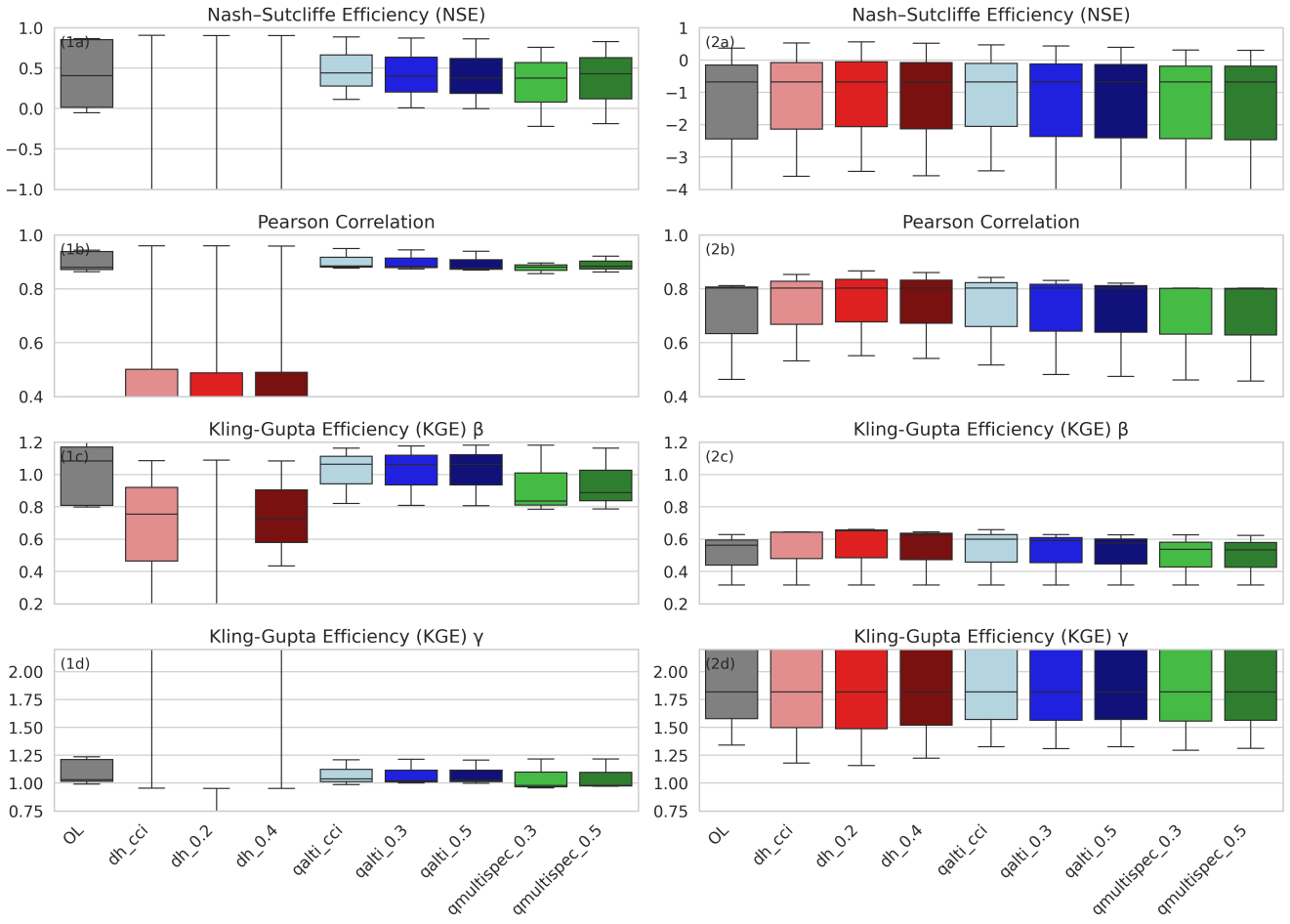

Figure 6. Distribution of NSE (a), correlation (b), bias (c), and internal variability (KGE γ, panel d) scores for MGB (1) and CTRIP (2) simulated discharge at the 3 in-situ stations (Congo Basin, 2000-2020): comparison of open-loop (grey) and assimilation of water level anomalies (dH, red), altimetry-based discharge (Qalti, blue), and multispectral imagery discharge (Qmultispec, green) with different uncertainties.

in rating curves between models and observations emerge as a key recurring limitation for dH assimilation and is highlighted at relevant points throughout this section.

In the Niger Basin, MGB shows a clear advantage for discharge assimilation (Qalti) over water surface elevation anomalies (dH). Qalti improves Nash-Sutcliffe Efficiency (NSE) to 0.83 (+14%) and raises correlation to 0.94 (+18.5%), ensuring smoother flow predictions across stations.

As shown in Figure 7, in Ansongo and Malanville, discharge assimilation produces smoother results, while WSE assimilation introduces noise, with visible jumps in the simulated discharge after each update. These hashed effects arise when corrections

555 are applied intermittently, and the model gradually returns to its prior state between updates. They are especially pronounced when observations are temporally sparse and when there are large discrepancies between observed and simulated values.

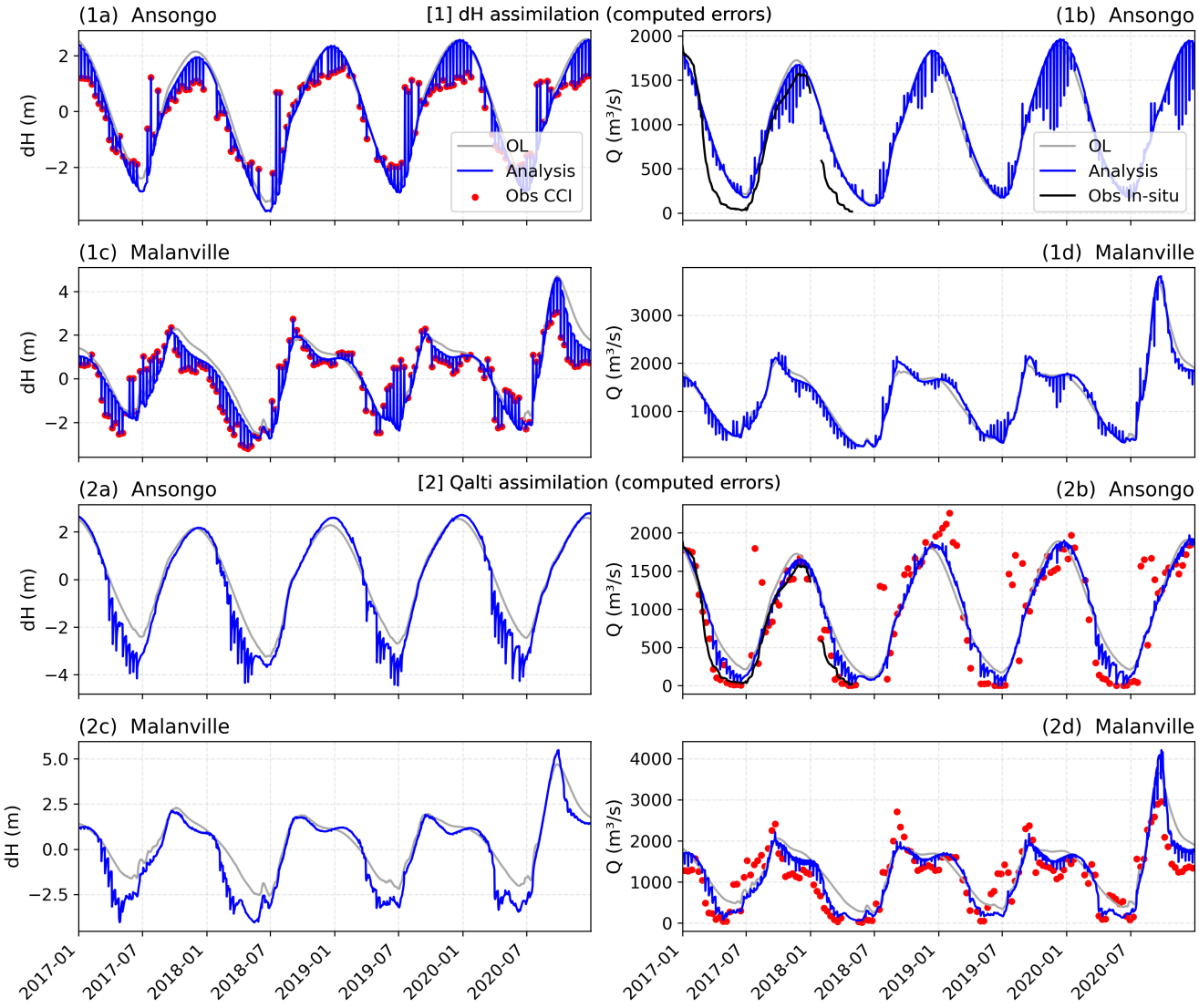

Figure 7. Comparison of water surface elevation (dH) and altimetry-based discharge (Qalti) assimilation with computed errors for Ansongo and Malanville stations (2017-2020), within MGB-HYFAA. Panel (1a-d): dH assimilation (computed errors) showing time series of dH (1a, 1c) and discharge (Q) (1b, 1d) for Ansongo and Malanville. Panel (2a-d): Qalti assimilation (computed errors) showing time series of dH (2a, 2c) and discharge (Q) (2b, 2d) for the same stations. *Obs CCI* represents water surface elevation (WSE) from satellite altimetry in panels (1a,1c) and altimetry-derived discharge in panels (2b,2d).

The hashed effect is further amplified when assimilating WSE at stations with a strong mismatch between observed and simulated rating curves. At Ansongo, for example, this mismatch (Figure 8) leads to conversion errors when using WSE anomalies to update discharge, amplifying the hashed effect. In contrast, these are much less pronounced at stations like Malanville (Figure 7), Ibi, and Lokoja, where the model and observation rating curves from the model and observation are more consistent (Figure 8, panel b ; Figure S10 in the Supplement). These stations also benefit from overlapping local patches that include observations from nearby stations (e.g., Malanville includes Niamey; Lokoja includes Malanville and Ibi), which helps sustain corrections between assimilation steps. However, the overall effectiveness of the local patch remains constrained by the limited spatial and temporal coverage of the CCI products. To provide further context, the Supplementary Material includes an illustration of the local patches for the six stations in the Niger basin (Figure S9 in the Supplement), along with rating curve comparisons between MGB (Open-Loop) and CCI observations (dH, Qalti) at Ibi and Lokoja. Finally, because Qalti is a directly modeled variable, it integrates more consistently into the hydrological model equations. This contributes to the smoother corrections observed across all stations during its assimilation, as illustrated for example at Ansongo and Malanville (panels (2b) and (2d), Figure 7), and similarly seen the rest of the stations.

In addition to these structural mismatches, such as those seen in Ansongo, the behavior of the assimilation filter is also shaped by how observation uncertainties are handled in the EnKF. At Ansongo, the MGB model results for two experiments (dH 0.4m and Qalti 30%) from 2010-2020 reveal additional differences in assimilation, as shown in Figure 9. Panels (1b) and (2b) represent the time series of increments, defined as the difference between the model analysis and the background (i.e., the forecast prior to assimilation). These increments quantify how much the model state was updated by the assimilation process. Panels (1c) and (2c) show the residuals, defined as the difference between the analysis and the assimilated observations: a low residual indicates the model is closely following the observations, while a large residual suggests a partial rejection of the observation. Finally, the innovation (not explicitly shown here) would be the difference between the observation and the background (forecast), and shows the initial discrepancy before assimilation.

With dH assimilation, the model almost entirely follows the observations, as indicated by the near-zero residuals. The same pattern is observed for CTRIP. Due to their lower uncertainty compared to the other products, dH observations, even at 0.4m uncertainty value, are still assimilated even when they diverge from the model's theoretical WSE values. This introduces erroneous information into the model, which can disrupt the simulated discharge and amplify the hashed effect after assimilation.

Qalti, in contrast, despite its 30% uncertainty, results in larger residuals, especially during high flow periods. This is mainly because the error given to the discharge products is proportional, so the higher the discharge value, the higher the absolute uncertainty given to that value and the lower is the weight given to observation within the EnKF scheme compared to model background. These residuals help maintain more reliable results by preventing the full assimilation of outliers (Figure 9). This selective assimilation behavior of Qalti, driven by proportional uncertainty, is particularly useful for reducing the influence of extreme outliers during flood peaks. However, during low-flow periods, Qalti's uncertainty becomes very small in absolute terms, potentially leading the filter to overfit isolated or erroneous low-flow observations. This limitation should be considered when evaluating Qalti assimilation performance across all flow regimes. dH is less sensitive to this effect due to its fixed absolute uncertainty.

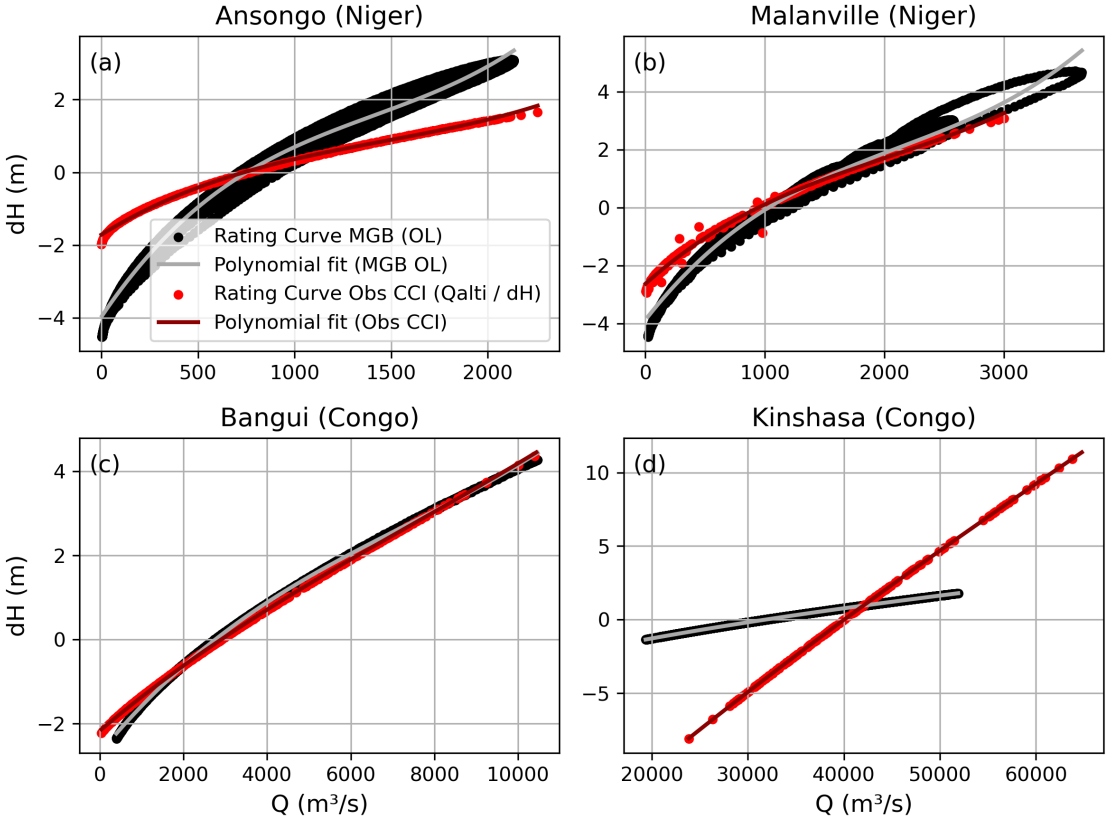

Figure 8. Rating curves from MGB (Open-Loop) vs. Obs CCI (dH, Qalti) at (a) Ansongo and (b) Malanville stations in the Niger basin, and at (c) Bangui and (d) Kinshasa stations in the Congo basin.

Another key advantage of Qalti lies in its temporal continuity, since discharge is a mass-conserving quantity that evolves continuously over time steps, supporting more physically consistent updates throughout the river network. In contrast, dH values are tied to local rating curves and may produce temporally inconsistent discharge increments between time steps and across stations. A 0.4 m WSE anomaly may lead to a discharge correction that varies widely across the river network, depending on the local shape of the rating curve. In reaches with steep slopes or narrow channels, this may correspond to small discharge changes. In contrast, in flat floodplain areas or during low-flow periods, this can induce disproportionately large discharge corrections, potentially destabilizing the model.

In the Congo Basin, the mismatch between the MGB model's rating curve and the observed altimetry data is even more pronounced, especially at Kinshasa. At this location, Qalti outperforms dH, as dH assimilation fails to capture the large observed WSE variations due to the model's flat rating curve (Figure 8). At Kinshasa, the MGB model has a flatter slope, meaning that for similar discharges, the model produces much smaller changes in water surface elevation. In contrast, the observed rating curve from altimetry (dH and Qalti) shows a much steeper slope, indicating a larger variation in water surface

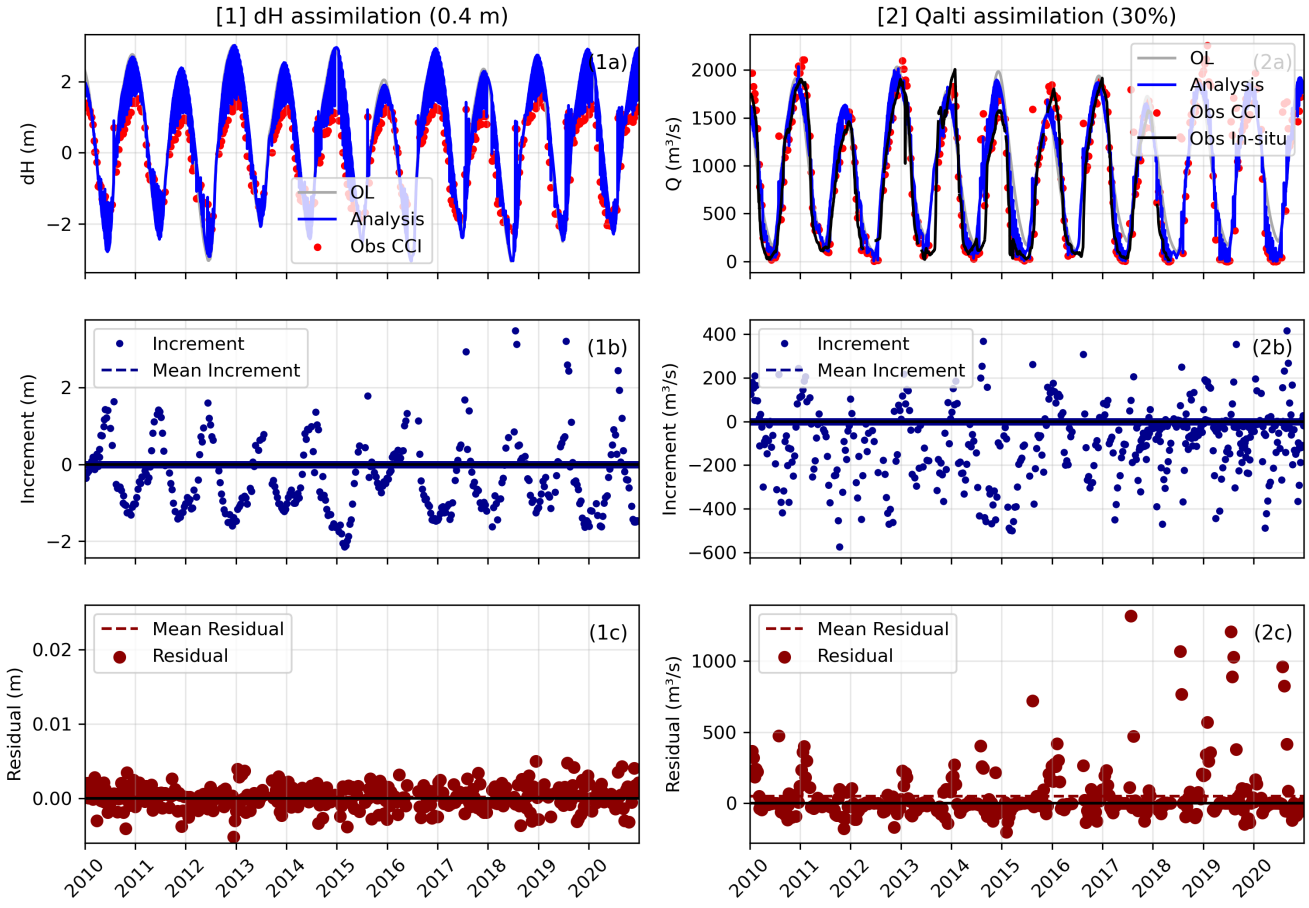

Figure 9. Comparison of dH and Q assimilation at Ansongo, Niger, over the 2010-2020 period, within MGB-HYFAA: Top panels show time series of (a) dH assimilation with 0.4m uncertainty and (b) Qalti assimilation with 30% uncertainty, with open-loop, analysis, and observed data. The middle and lower panels show the corresponding innovation and residuals, with the mean innovation and residuals represented by dashed lines, illustrating the model's performance and adjustments after assimilation.

elevation for the same discharge fluctuations. Altimetry observations show dH variations reaching up to ± 7 meters, while the MGB model's maintains nearly constant WSE values. This mismatch between modeled and observed rating curves, also noted in the Niger Basin (Ansongo, Figure 8), illustrates a broader structural limitation of dH assimilation in MGB : when rating curves slopes differ significantly, converting WSE anomalies to discharge can introduce significant errors.

This mismatch leads to EnKF filter divergence, resulting in outliers and highly negative NSE values, which makes dH assimilation unreliable at stations such as Kinshasa and Ouesso (Figure 10). Ouesso, correlated with Kinshasa through the localization matrix, is also impacted by the discrepancies observed at Kinshasa. These inconsistencies propagate backward to Ouesso, resulting in unstable discharge estimates with extreme fluctuations, including both excessively high and negative

values. These issues lead to poor performance scores at Ouesso as well. It is worth noting that, in this version of MGB-HYFAA, the EnKF does not impose numerical constraints on discharge, which allows for negative values when unrealistic corrections deviate from physical plausibility, as seen in Figure 10.

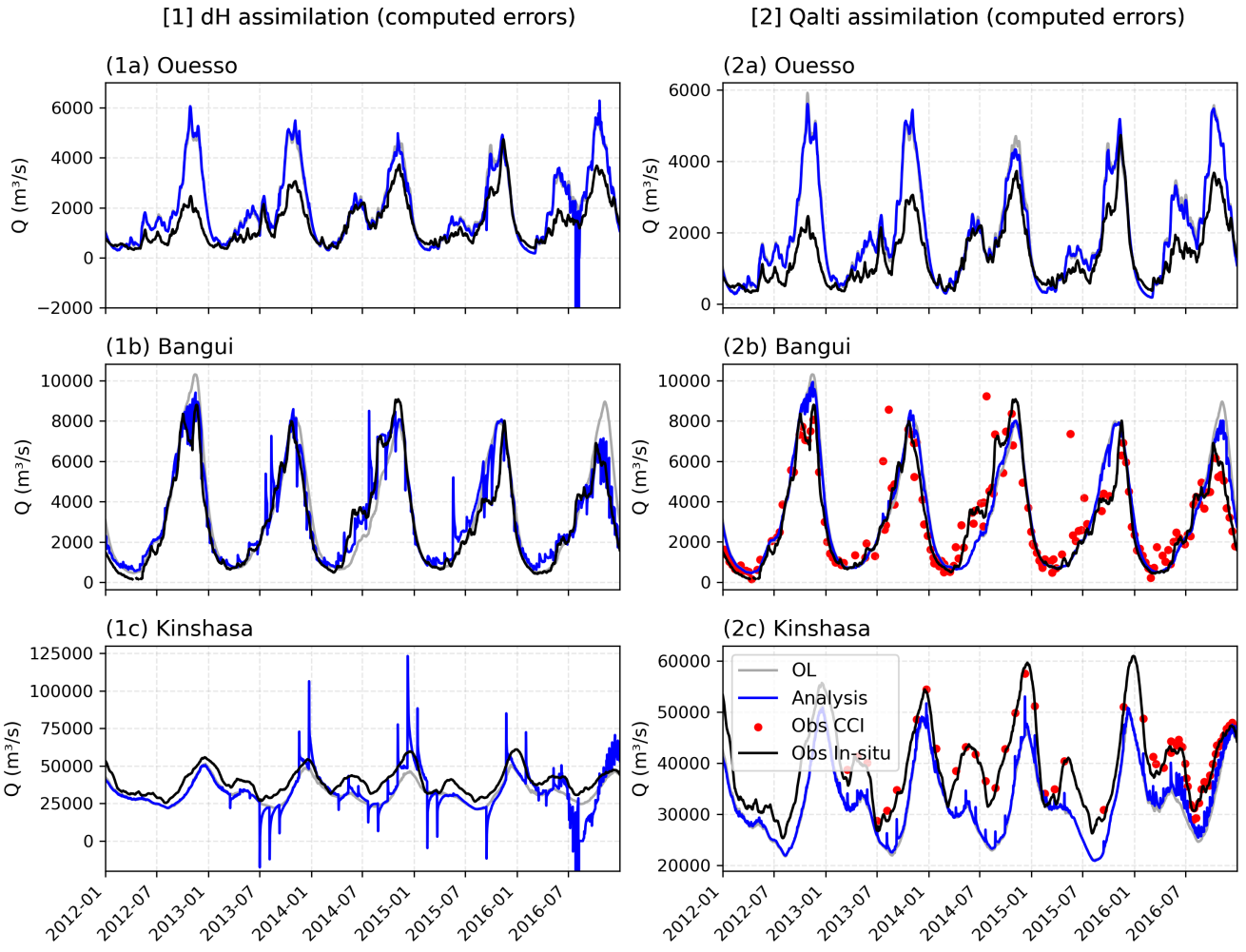

Figure 10. Comparison of dH (1) and Qalti (2) assimilation in Ouesso, Bangui, and Kinshasa, within MGB-HYFAA : OL Simulation in black, Assimilation Results in blue and Observed CCI Data in red.

While MGB benefits more from Qalti due to its compatibility with discharge as the primary modeled variable, CTRIP shows a different behavior. The assimilation of dH consistently outperforms Qalti across the stations in both basins. This difference is most notable in the Niger Basin, where the Open-Loop (OL) simulation performs poorly. In such cases, the EnKF favors the observation with the lowest uncertainty, typically dH, even when Qalti would be more consistent with the model's output. Since Qalti is indirectly derived from altimetry and involves transformation through rating curves, it carries higher uncertainty

and is thus assigned lower weight in the analysis. This may lead to over-reliance on dH, even if the structural limitations (e.g., flat rating curves) make it less appropriate.

dH assimilation is most effective in CTRIP when large model biases are present and when model rating curves align well with observations. In fact, CTRIP's rating curves closely match altimetry-based ones at most stations, including Niamey, as shown in Panel (c), Figure 11. Panel (a) shows that dH assimilation shows consistently higher KGE scores. Given equal temporal resolution, the lower uncertainty of dH (0.2–0.4 m) gives the observation more relative weight in the analysis, compared to Qalti (30–50%).

However, this comes at the cost of physical consistency and temporal continuity. Q is a mass-conserving variable that evolves continuously over time steps, supporting more physically consistent updates throughout the river network and therefore offering more stable integration with hydrological model dynamics. WSE anomalies, by contrast, do not conserve volume and require geometric assumptions through rating curves, which can reduce consistency between time steps.

In CTRIP, where structural errors, like missing evaporation downstream the Inner Delta in the Niger, lead to biased flow, dH assimilation leads to better improvements, but only when the model's rating curve matches observations (Figure 11).

In contrast, MGB includes explicit evaporation and provides a better OL simulation. In this case, Qalti proves more effective: it updates discharge directly and avoids transformation errors, and better reflects seasonal flow signals. Even at stations with good rating curve alignment (e.g., Malanville), Qalti outperforms dH assimilation (Figure 7). This is supported by comparisons with in-situ data (Supplement), which show CCI discharge capturing seasonal dynamics reliably.

These results indicate that discharge assimilation tends to be more effective when the model provides a reliable physical representation of the river system and the open-loop is not structurally too poor.

The preferred assimilation variable thus depends on a combination of the model's open-loop performance, the uncertainty of the observation, and rating curve alignment. In CTRIP, structural limitations and accurate alignment with observed rating curves favor WSE assimilation. In contrast, Qalti assimilation in MGB is supported by stronger internal discharge simulation and more realistic physical representation. The issues with rating curve mismatches in MGB (Kinshasa, Figure 8) and the close performance results between dH and Qalti in CTRIP (Figure 11) highlight the sensitivity of each variable's performance to model context.

The choice between dH and Qalti should consider not only uncertainty but also how well each variable aligns with the model's structure and dynamics. For large-scale hydrological models, whose primary objective is to accurately simulate discharge rather than water surface elevation (WSE), it is more robust to assimilate a variable directly related to the flows they simulate. Adjusting rating curves across model cells to accommodate dH is more complex and introduces errors, especially when the model's simplified river geometry does not match real-world conditions. Discharge assimilation avoids these conversions and ensures consistency across both model cells and time steps, making it the more reliable choice overall. Thus, when the model is not too structurally biased, Qalti assimilation tends to outperform dH and is better suited for large-scale hydrological applications.

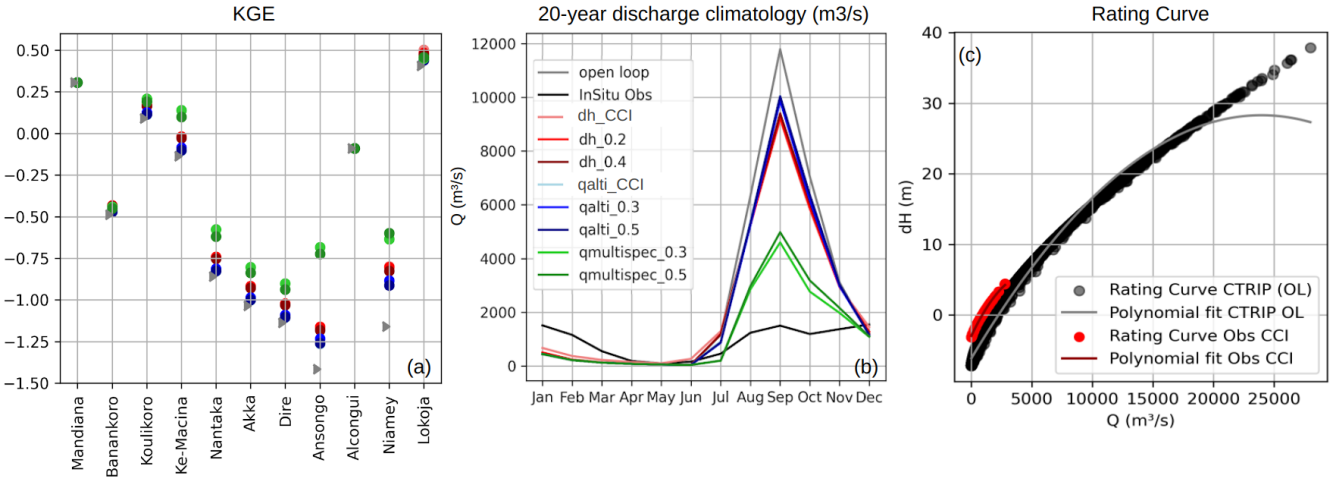

Figure 11. Panel (a) presents the Kling-Gupta Efficiency (KGE) performance results from CTRIP for each assimilation experiment (colored markers) at 11 stations in the Niger Basin, with Open-Loop (OL) performance shown as grey triangles for reference. Panel (b) displays the corresponding discharge climatology at Niamey, comparing observed discharge (black) with Open-Loop simulations from CTRIP (grey) and different assimilation experiments (colored), illustrating seasonal variations in modeled and observed discharge. Panel (c) shows the rating curve at Niamey from CTRIP Open-Loop (black), compared to Obs CCI (dH, Qalti) (red)

4.2.3 Bias and internal variability correction : Outperformance of Qmultispec assimilation over Qalti

In the Niger Basin, despite its lower performance in other metrics, Qmultispec outperforms in bias correction by significantly reducing flow overestimation in both models. This improvement is particularly notable in the upper Niger and Inner Delta within MGB, where the Open-Loop (OL) simulation consistently overestimates discharge. Koulikoro serves as a key example, where the bias is reduced by 17-20% (depending on the uncertainty levels), bringing the bias from 1.2 in the Open-Loop down to approximately 1. In fact, Qmultispec's higher temporal density enables better alignment with the observed rising and falling limbs of the hydrograph, providing more consistent results over the annual cycle.

Figure 12 shows time series at Koulikoro (2010–2020, MGB) for two experiments at 30% uncertainty: Qalti (1a) and Qmultispec (2a). Panels (1b, 2b) show the time series of increments (analysis minus background). With frequent updates, bias corrections occur steadily throughout the hydrological year, correcting both high- and low-flow biases.

Panel b of Figure 13 confirms that Qmultispec produces smaller mean increments during the high-flow period (June–November) compared to dH or Qalti assimilation. At Koulikoro, Qalti actually overestimates discharge by 35% compared to in-situ data, while the MGB Open-Loop overestimates by 25%, and Qmultispec by 20%. Although the Qmultispec data is noisier, particularly during the recession phase, its frequent updates prevent the model from reverting to its biased pre-assimilation state.

In the CTRIP model, the trend is similar: Qmultispec provides the greatest reduction in bias, followed by dH and Qalti. This difference comes from the lower uncertainty levels of the WSE anomalies (0.2m-0.4m) compared to Qalti (30%-50%). In the

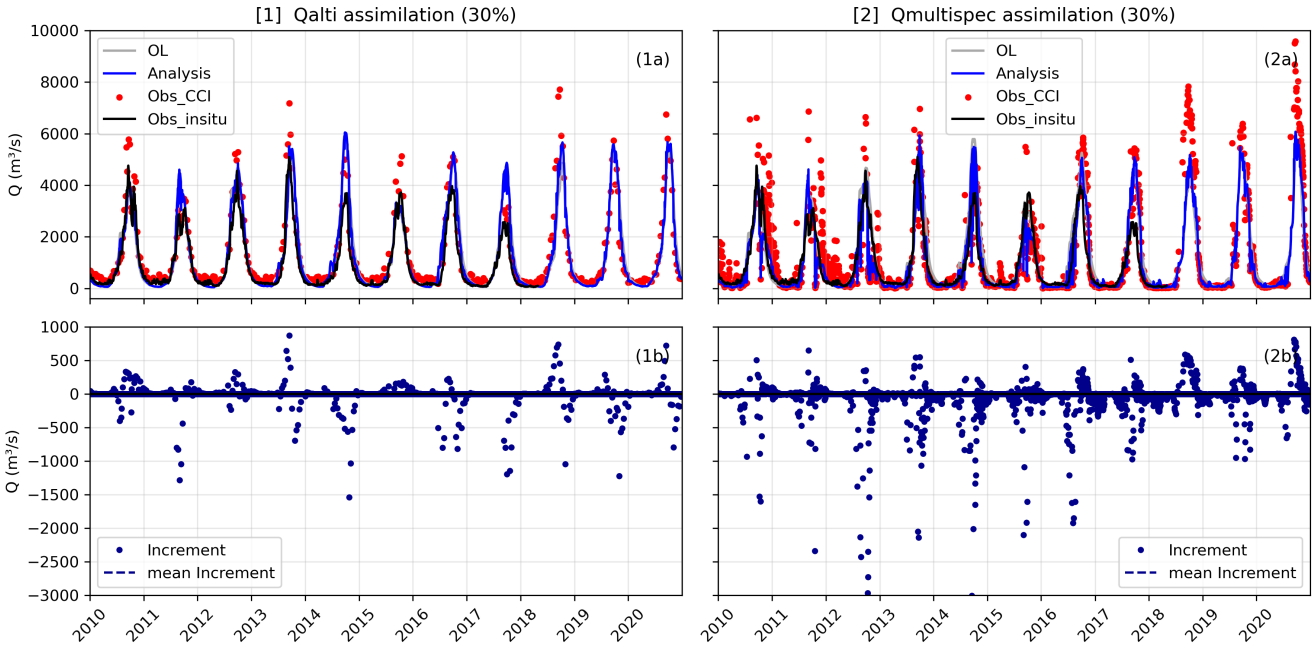

Figure 12. MGB model results at Koulikoro over 2010-2020 for two experiments: (1) Qalti with 30% uncertainty and (2) Qmultispec with 30% uncertainty. Time series for open-loop (black), Analysis (blue), and Observations to be assimilated (red) are shown in panels (1a) and (2a) for Qalti and Qmultispec, respectively. The increment (Analysis - Background) is shown in (b), and the residual (Obs CCI - Analysis) in (c). Dashed lines in (b) and (c) represent the mean innovation and residual over 20 years

Niger Basin, CTRIP's Open-Loop simulation overestimates discharge significantly, so all satellite products help reduce this positive bias. The frequent assimilation from Qmultispec helps constraining the model and reduces the tendency to revert to biased states (Open-Loop). This is particularly visible in the monthly climatologies, as shown at Niamey in Figure 11.

Beyond bias correction, Qmultispec also improves internal variability, particularly in MGB. With dense temporaly data coverage, it enables dynamic corrections that reduce simulation divergence caused by model internal errors or the omission of complex physical processes. This is evident in both the MGB and CTRIP models, as seen in Figure 13. It is worth noting that within the Niger basin, the internal variability is less effectively corrected by any of the products in CTRIP, largely due to the model's poor Open-Loop performance, which limits its ability to capture short-term fluctuations.

Qmultispec's improved capture of short-term fluctuations makes it particularly valuable for climate studies focusing on flow variability and its evolution over time. Capturing this internal short-term variability is essential for modeling extreme events such as floods and droughts, which makes this product doubly relevant for MGB, as it is designed for forecasting applications.

Overall, in both models, Qmultispec outperforms Qalti and dH in reducing bias and correcting internal variability. Despite some data noisiness, Qmultispec delivers more consistent and reliable performance compared to Qalti and WSE anomalies.

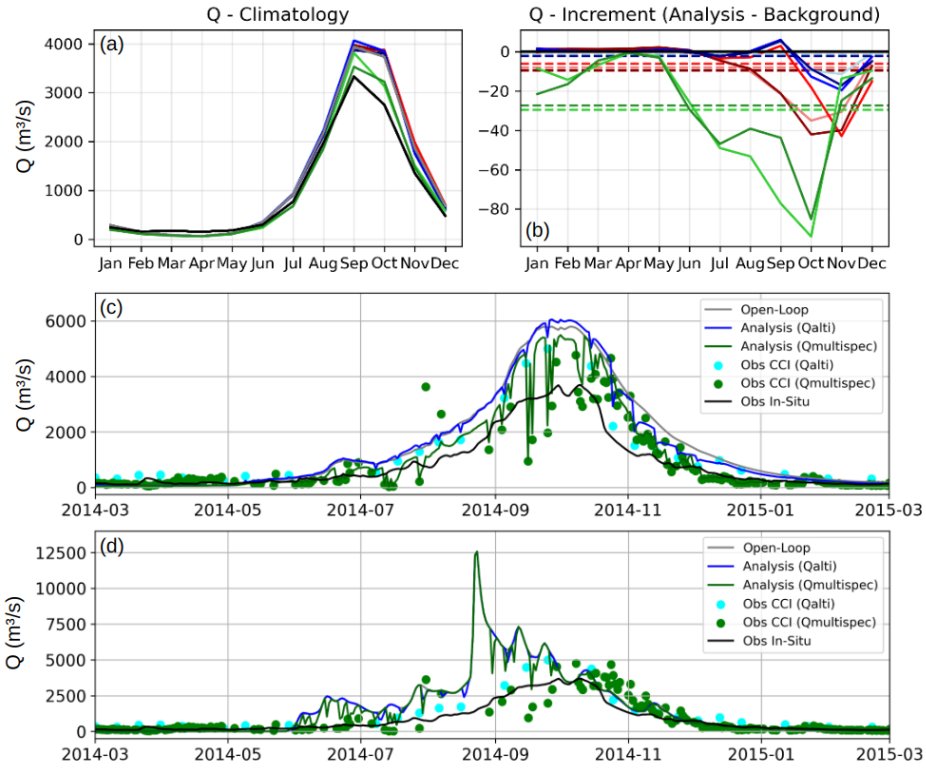

Figure 13. (a, b) MGB model results at Koulikoro for different experiments (dH in shades of red, Qalti in shades of blue, Qmultispec in shades of green); (a) Discharge climatologies, with in-situ observations in black. (b) Increment (Analysis minus Background) shows differences after assimilation, with mean increments indicated by dashed lines. (c, d) Example of assimilation results over a year (2014) for Qalti (blue) vs Qmultispec (green) at Koulikoro within MGB (c) and CTRIP (d), both CCI products assimilated at 30% uncertainty.

This makes it particularly valuable for long-term studies on the evolution of discharge and water resources, such as those related to climate change, as well as for forecasting extreme events.

5 Discussion

5.1 Role of ESA CCI assimilated variable and product characteristics

This study demonstrates that discharge data assimilation (Q) provides robust and physically consistent results in large-scale hydrological models. However, the effectiveness of WSE anomaly (dH) assimilation depends strongly on the model's structural realism and rating curve alignment with observations. For instance, in Kinshasa, the discrepancy between the modeled and observed WSE values resulted in poor model performance when assimilating dH in MGB, whereas Q assimilation provided more reliable discharge corrections. In CTRIP, dH assimilation produced better statistical scores than Qalti, but this was

primarily due to the model's poor open-loop performance caused by missing evaporation processes. In such contexts, the EnKF filter tends to give more weight to the observation with the lowest uncertainty—dH—especially when the model's rating curve aligns well with altimetry data. This favorable alignment enables more efficient conversion of dH to Q, improving assimilation outcomes despite dH being less physically consistent than discharge. This underlines the need for careful consideration when integrating dH data into discharge-driven models, especially in cases where the river bathymetry and geometry are not well represented.

Temporal data density plays a critical role in hydrological modeling, particularly for climate studies where capturing internal variability and correcting biases are essential. High-frequency data, like Qmultispec, provides continuous updates that helps correcting seasonal and interannual flow patterns, which are important for modeling extreme events such as floods and droughts. In the Niger Basin, Qmultispec assimilation significantly improved the model's representation of seasonal flows and reduced systematic biases. However, a trade-off exists between data quality and temporal density. High-frequency datasets, such as Qmultispec, tend to be noisier compared to lower-frequency, but more accurate datasets like Qalti. In regions such as Bangui in the Congo Basin, where Qmultispec data was noisier, the assimilation led to poor model performance due to the excessive noise, despite its high temporal resolution. This highlights the importance of balancing the density of observations with their quality to avoid degrading the model with inaccurate data. Figure 14 illustrates this trade-off, with high-frequency data improving flow timing but introducing noise into the analysis.

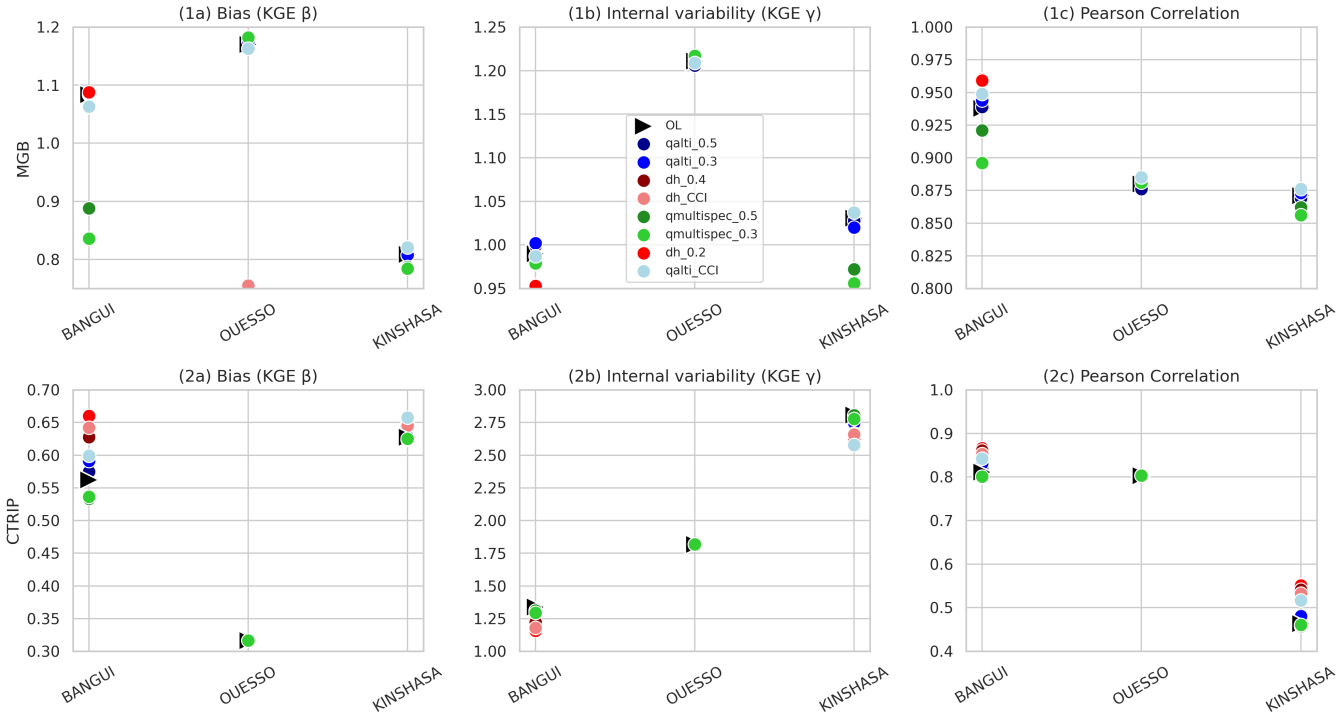

Figure 14. Comparison of bias (KGE β), internal variability (KGE γ), and Pearson correlation for different assimilation experiments in MGB (first line) and CTRIP (second line) models: daily scores at Ouesso, Bangui, and Kinshasa stations.

The trade-off between temporal density and data quality is especially evident in the Congo Basin, where Qmultispec performs poorly compared to its performance in the Niger Basin. In the Congo, the lower data quality and poorer temporal density reduce the effectiveness of Qmultispec, particularly in stations like Bangui and Kinshasa. While CTRIP is more influenced by WSE and discharge assimilation, the mismatches between the modeled and observed rating curves in MGB create additional challenges, leading to errors when assimilating dH. Furthermore, at stations like Ouesso, the high-water periods in Qmultispec are out of phase with the modeled output, diminishing the assimilation performance. This trade-off is critical for discharge assimilation, as the percentage-based uncertainty of discharge observations leads to seasonally variable correction weights. During high-flow periods, the larger absolute uncertainty reduces the influence of discharge data within the EnKF, limiting overcorrections, whereas in low-flow periods, the lower absolute uncertainty increases their relative weight, which may lead to overfitting of local or spurious fluctuations. These seasonal differences in correction weights should be taken into consideration when interpreting assimilation results.

Spatial data density is another critical factor in complex river basins like the Congo. The Congo's major tributaries contribute significantly to the overall discharge, necessitating adequate observation points for proper basin-wide hydrological representation. For example, insufficient coverage in the upper tributaries of the Congo, such as the Chembe-ferry station, limits the overall influence of data assimilation across the basin. Figure 15 presents the normalized root mean square difference (NRMSD) between the Open-Loop and Qalti (0.20m) assimilation experiments over both basins. As shown in this figure, the impact of spatial coverage on data assimilation effectiveness is significant, especially when comparing the spatial coverage in the Niger Basin to the Congo Basin.

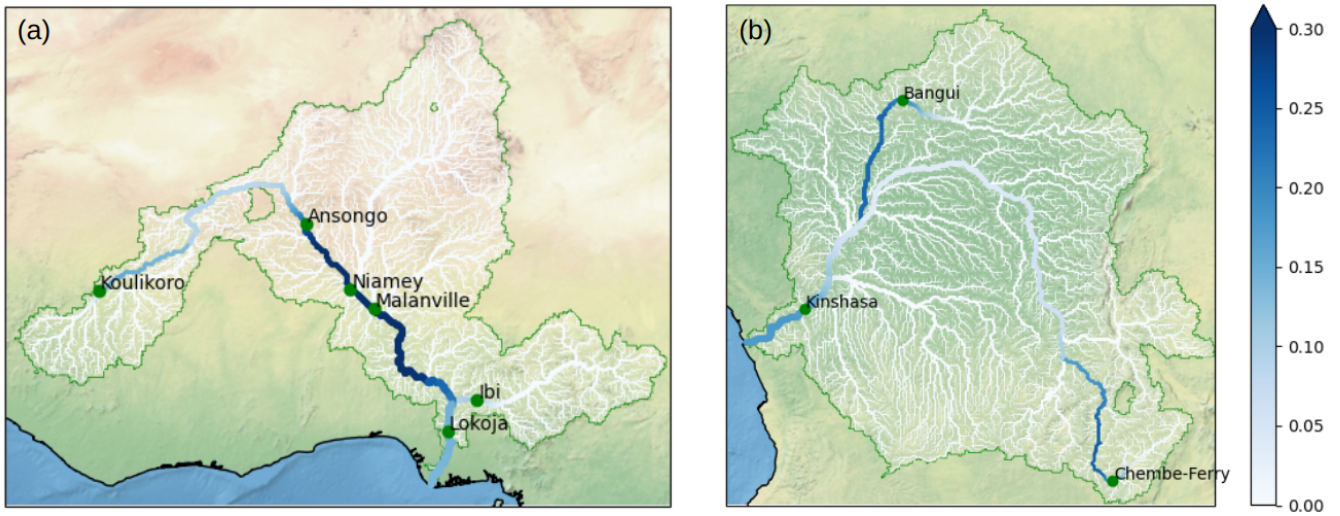

Figure 15. NRSMD comparison between Niger and Congo basins, illustrating the impact of spatial coverage on DA influence.

It is important to recall that this study was designed to isolate and evaluate the specific contribution of the long-term CCI discharge and WSE products. While combining them with other satellite datasets could enhance spatial coverage and improve

assimilation performance—especially in data-scarce regions like the Congo Basin—this would make it difficult to isolate the specific effect of the CCI products. This proof-of-concept study focuses solely on the CCI products to analyse their added value for long-term, large-scale hydrological modeling. In future work (CCI Discharge Phase 2), we plan to explore how these products can be integrated with additional satellite observations, particularly higher-density WSE datasets from different altimetry missions, to further improve model performance.

5.2 Robustness across modelling frameworks and basin contexts

The comparison between CTRIP-HyDAS and MGB-HYFAA, and between the Niger and Congo basins, helps distinguish product-related effects from framework- and basin-dependent responses. A first product-related result is that discharge assimilation is generally more directly representative than WSE anomaly assimilation, because discharge is directly represented in the routing models, while WSE anomalies depend on the consistency between observed and simulated rating curves. However, this result is not absolute: WSE anomalies can still provide substantial corrections when the open-loop simulation is poor when the modelled and observed rating curves are sufficiently aligned, as observed for CTRIP in some cases, because the lower WSE uncertainty gives these observations a stronger weight in the EnKF update. A second robust result concerns the role of temporal density. In the Niger Basin, the high temporal sampling of Qmultispec helps reduce bias and improve internal variability, particularly in MGB-HYFAA and, to a lesser extent, in CTRIP-HyDAS. However, this benefit is conditional on product quality. The Congo experiments show that high temporal density alone is not sufficient: when Qmultispec is noisy or out of phase with the hydrological cycle, as observed at Bangui, assimilation can degrade model performance. Dense observations are therefore beneficial only when their retrieval quality is adequate.

The model-DA-framework comparison further shows that DA acts differently depending on the baseline model behaviour. In MGB-HYFAA, where the model is calibrated and includes a more detailed representation of floodplain and wetland processes, data assimilation mainly refines discharge magnitude, timing, bias, and variability. In CTRIP-HyDAS, which is used here in its uncalibrated global-scale configuration, assimilation can reduce some open-loop errors, with the strongest gains often related to bias reduction, but it cannot fully compensate for missing or simplified physical processes, such as floodplain storage and evaporation in the Inner Niger Delta, or for forcing-related water deficits such as those contributing to discharge underestimation in the Congo Basin.

The basin comparison finally shows that the assimilation impact is easier to detect in the Niger Basin than in the Congo Basin. In the Niger, the strong seasonal hydrological signal, the availability of several assimilated stations along the main river, and the denser validation network allow the DA impact to be more clearly diagnosed. In the Congo, the hydrological regime is more stableed, and the outlet discharge integrates contributions from several large tributaries, while the available assimilated and validation stations provide a more limited spatial representation of the basin. Consequently, improvements are more modest and more dependent on product quality and spatial coverage.

These results suggest that ESA CCI products could support long-term hydrological modelling across different large-scale frameworks. However, their impact should be considered alongside the realism of the models in relation to basin-specific hydrological processes, as well as the products' quality and observation density.

Table 3. Synthesis of generalized, basin-specific, and framework-specific findings of the study.

Dimension	Main take-away	Specific interpretation
Product type	Q assimilation is generally more robust than dH assimilation.	Q is directly represented in routing models; dH depends on rating-curve consistency. However, dH can still perform better in poor open-loop configurations when rating curves are aligned, as observed in some CTRIP cases.
Temporal density / quality	Dense observations help reduce bias and improve internal variability only if product quality is sufficient.	Qmultispec improves bias and variability, as seen in the Niger Basin, but can degrade results when noisy or phase-shifted, as seen in the Congo Basin.
Basin signal / spatial sampling	DA impact is clearer when the dominant hydrological signal is well sampled by hydrologically connected assimilated stations.	The Niger Basin has a strong seasonal signal and several assimilated stations along the main river, favouring coherent upstream/downstream corrections. In the Congo Basin, the discharge signal is distributed across large tributaries, and sparse assimilated stations only weakly constrain basin-wide dynamics.
Validation network and independence	Gauge density affects confidence in evaluation. Validation is more independent in the Niger than in the Congo.	The Niger Basin has a denser independent ABN network. The Congo Basin has few validation stations, limiting basin-wide diagnostic confidence, and Bangui/Kinshasa partly rely on SO-HYBAM data also involved in CCI rating-curve calibration/validation.
Model framework	DA response depends on the open-loop error type.	MGB calibrated simulations are mainly refined by adjusting magnitude, timing, and variability; in CTRIP, DA can reduce larger open-loop biases but remains limited by missing physical processes and forcing-related errors.

Table 3 summarizes the main factors controlling the DA impact across the two basins and modelling frameworks. It distinguishes product-related findings from basin-specific effects related to hydrological variability, spatial sampling, and validation data, and from framework-specific effects relating to model behaviour.

A further limitation concerns the independence of the in-situ validation data, which differs between the two basins. In the Niger Basin, the CCI discharge products were generated using rating curves calibrated and validated against GRDC discharge data, while model evaluation was performed using independent ABN observations. The Niger validation metrics can therefore be considered independent from the in-situ data used in the CCI discharge product generation. In the Congo Basin, the validation at Bangui and Kinshasa is less independent, because SO-HYBAM observations are the only available long-term in-situ discharge records and were used both for CCI discharge product generation and for model evaluation. The Congo validation scores should therefore be interpreted with more caution than the Niger scores. Nevertheless, they remain useful for

analysing the behaviour of the DA experiments, since the metrics are computed from the model discharge simulations after assimilation and not directly from the assimilated observations themselves. Supplementary Figure S3 summarizes the temporal availability of the assimilated CCI products, the in-situ observations used for model evaluation, and the in-situ data involved in the CCI discharge rating-curve calibration.

In summary, the effectiveness of data assimilation in large-scale hydrological models depends on the interaction between the assimilated variable, product quality, observation sampling, model behaviour, and basin characteristics. Discharge assimilation is generally more directly consistent with routing models than WSE anomaly assimilation, although dH can still provide useful corrections when the modelled and observed rating curves are aligned and the observation uncertainty is low. The results also show that high temporal density is beneficial only when the assimilated product is sufficiently reliable: Qmultispec helps reduce bias and improve internal variability in the Niger Basin, but can degrade the analysis in the Congo Basin when observations are noisy or phase-shifted. Finally, the comparison between the two basins highlights the importance of spatial sampling and hydrological connectivity. The stronger seasonal signal and better station coverage in the Niger Basin make DA impacts easier to diagnose, whereas the sparse sampling of the Congo tributary system limits basin-wide correction and makes the results more dependent on product quality and validation constraints.

6 Conclusions and Perspectives

Hydrological models such as CTRIP and MGB are essential tools for climate studies and forecasting at large scales, including continental regions and large river basins. Their accuracy can be greatly enhanced through satellite data assimilation, which improves model performance by addressing key factors such as the model's initial open-loop performance (errors in the forcings data, missing physical processes, modeling approximations), the temporal and spatial density of observations, and the quality of the assimilated data. Assimilating discharge data has proven more reliable than water surface elevation anomalies (dH) assimilation, particularly in models focused on discharge simulations. This is because direct discharge assimilation avoids the uncertainties involved in converting dH into discharge, especially in models with simplified river geometry. In contrast, dH assimilation often introduces errors in regions where discrepancies exist between observed and modeled water surface elevations. However, in poorly performing models with low open-loop skill and well-aligned rating curves, WSE anomalies can become more effective than Q, as their lower observation uncertainty leads to more impactful corrections. This was the case for CTRIP in the Niger basin, where structural limitations led to large discharge biases. This underlines the importance of considering both the model structure and observation characteristics when selecting assimilation variables.

Temporal data density is also critical for improving model performance. High-frequency updates, such as those provided by Qmultispec, enable more continuous corrections, reducing bias and better capturing flow variability over time. However, noisy data can reduce model performance if not balanced with data quality, as seen in the Congo Basin at Bangui, where Qmultispec's higher temporal resolution introduced noise into the model. High-quality data like Qalti, which has lower uncertainty, consistently reduces bias and improves model accuracy, though its limited availability restricts the frequency of model updates. Spatial data density is equally important, particularly in complex river basins like the Congo, where major

tributaries play a crucial role in the overall discharge. Insufficient spatial coverage can result in errors in basin-wide simulations, whereas better station coverage in regions like the Niger Basin has led to more consistent improvements.

The comparison across CTRIP-HyDAS and MGB-HYFAA and across both basins shows that the main conclusions are not controlled by a single factor. Discharge products are generally more directly assimilated into routing models than WSE anomalies, and temporal density is a key factor for correcting bias and internal variability when product quality is sufficient. However, the magnitude and stability of the improvements depend strongly on the modelling framework and basin characteristics. In calibrated regional configurations such as MGB-HYFAA, DA mainly refines already constrained simulations. In uncalibrated global-scale configurations such as CTRIP-HyDAS, DA helps reduce bias and can partly compensate for larger open-loop errors, but remains limited when relevant basin processes are missing. The Niger Basin illustrates the benefit of denser observations along a strongly seasonal main river system, while the Congo Basin highlights the need for improved spatial coverage across large tributary systems and greater sensitivity to assimilated product quality.

Looking ahead, Phase 2 of the CCI Discharge project presents an opportunity to build on this proof-of-concept by expanding both the scope and methodological depth of data assimilation experiments. In particular, this next phase will investigate how the integration of CCI products with other available satellite observations can enhance hydrological modeling by improving spatial coverage and reducing uncertainty. By relying solely on CCI products in this study, we were able to isolate the specific contributions of long-term (20 years), high-temporal resolution discharge and WSE data. Future work will assess how these products interact with other data sources in a multi-sensor assimilation framework. In future research, we also plan to incorporate additional spatially distributed observations, especially in regions lacking in-situ stations, to enhance the localization process and improve model performance. The assimilation of combined WSE and discharge products will also be explored more systematically, especially in regions where spatial coverage is limited. By leveraging the spatial availability of dH and the physical consistency of Q, this combined approach is expected to densify the network of assimilated data, thereby enhancing the performance of models such as CTRIP and MGB. This phase will also incorporate outlier detection and combined data assimilation methods for both discharge and dH in order to densify the spatial coverage. By leveraging the high spatial coverage of dH and the direct relevance of Q, these combined approaches are expected to enhance models accuracy like CTRIP, especially in regions with low observation density. For MGB, challenges may arise with dH assimilation when simulated and observed rating curves diverge significantly; however, in areas where these align well, combining Q and dH assimilation could offer complementary benefits. Additional experiments will be conducted using newly developed datasets for large scale hydrological models, CTRIP and MGB, assessing the impact of combined assimilation on hydrological simulation.

To further explore the interaction between model structure and assimilated variables, future work will examine the behavior of routing reservoirs in MGB and relevant routing parameters in CTRIP. A seasonal analysis of assimilation performance could also help clarify the respective benefits of the different CCI products under different hydrological regimes.

Furthermore, the integration of SWOT (Surface Water and Ocean Topography) satellite data offers distinct advantages for enhancing models accuracy through its detailed measurements of water surface slope.The inclusion of remote sensing data such as river width and slope could enable joint state-parameter estimation, offering a more complete assimilation framework. These advantages, combined with the previously discussed improvements in space-time sampling and refined uncertainty

quantification, will enable models to better represent critical parameters such as slope. This synergy is expected to significantly reduce uncertainties in discharge predictions and improve the overall performance of the models in simulating river discharge and water storage dynamics.

On the data assimilation side, future research should also evaluate the role of ensemble inflation and outlier handling strategies. While in this study, high-flow outliers were naturally down-weighted by the EnKF due to large observational errors, the impact of low-flow outliers remains less understood and deserves further investigation. A dedicated sensitivity analysis would help assess how the EnKF processes extreme values across different flow regimes and whether adjusted inflation settings could improve filter robustness.

Future improvements in data assimilation schemes will be crucial for further enhancing model performance, with one promising approach being the implementation of dynamic localization distances in models like CTRIP. This innovation will enable models to adapt to both natural variability and anthropogenic influences, such as the effects of dams and irrigation on river systems. By incorporating these dynamic localization techniques, models will be better equipped to account for changes in hydrological processes, thereby improving the reliability of hydrological forecasts.

As models continue to evolve, namely in improving parameterization or in integrating new processes (like evaporation over the Niger Inner Delta for the CTRIP model), the focus will be on refining data assimilation schemes to maximize the benefits of satellite data. The introduction of smoother methods, especially in Kalman filter-based systems, could mitigate the hashed effects observed in dH assimilation, ensuring more accurate corrections. Such methods could help refining corrections where dH assimilation currently leads to noisy or unstable updates, particularly during discharge assimilation where residual hashed effects remain. These advancements, combined with SWOT data integration, will address current gaps in data coverage and enhance the simulation of climate-impacted and human-modified river systems.

. The CCI-Discharge datasets are available at the following link: https://climate.esa.int/en/projects/river-discharge/ ("Data" section). The Product User Guides for each product are available in the "Key Document" section.

. MS, GN, VP, and SM conceived the research design and experimental setup. MS and GN processed the data, ran the experiments, processed the results, and analyzed the findings. VP, SM, and KV assisted with data assimilation tools setup (SM and KV developed/improved HyDAS for CTRIP, and VP developed HYFAA in MGB) and contributed to the discussions. MS merged the findings of both models and wrote the initial draft, with input from GN, SM, and VP. CA, SB, and AA reviewed the paper and provided valuable insights. All authors contributed to the final version of the paper.

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