Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 10, October, 2025

Using the Kalman Filter with Satellite Altimetry to Estimate the Water Level of Inland Water

Murtadha Aryan [1], Abd Wahid Bin Rasib [1*], Muhammad Imzan Hassan [1], Muhammad Hanif bin Hamden [1]

[1] *Geospatial Imaging and Information Research Group, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Skudai, Malaysia.*

Received 20 April 2025; Revised 18 September 2025; Accepted 23 September 2025; Published 01 October 2025

Abstract

The Euphrates River extends for approximately 2,700 km, making it the longest river in Southwest Asia. Reliable water level measurements are obtained through the integration of an advanced outlier rejection system with Kalman filter technology. This study employs water level data from the Database for Hydrological Time Series over Inland Waters (DAHITI) and validates them using in situ measurements collected from gauging stations along the Euphrates River. To improve the accuracy of water level time series across the study area (Lat: 31.9676, Lon: 44.9306 to Lat: 31.0955, Lon: 46.0942), the research incorporates multibeam altimetry data from Envisat, Jason-2, and Sentinel-3A/B/B. Validation of the altimetry techniques is carried out by comparing DAHITI water level records with in situ measurements and other satellite-based datasets. Both the Kalman filter and Hydroweb methods yield Unbiased Root Mean Square Difference (ubRMSD) values ranging between 0.2961–0.3922 cm and 0.536–0.577 cm, respectively. The Nash-Sutcliffe Efficiency coefficient for DAHITI-derived water levels varies between 0.5971 and 0.9831, while Hydroweb produces values from –0.871 to 0.567. Overall, DAHITI-based altimetry height estimates demonstrate superior accuracy compared to other altimeter datasets in most parts of the Euphrates River, with precision strongly influenced by river topography. The application of Kalman filtering further enhances water level monitoring, particularly in regions characterized by complex inland water structures.

Keywords: Altimetry; DAHITI; Sentinel; Kalman Filter; Euphrates River.

1. Introduction

Satellite radar altimetry has emerged as a powerful technique for monitoring rivers, lakes, and reservoirs, enabling highly accurate detection of river surface elevations [1, 2]. Over the past decade, its use in tracking terrestrial water bodies has grown considerably [3, 4], driving the launch of advanced satellite missions such as Jason-2, Jason-3, CryoSat-2, and Sentinel-3 [5, 6]. Among these, the Sentinel-3 (S3) mission stands out, as it is equipped with a synthetic aperture radar (SAR) altimeter and operates as a dual-satellite constellation with a 29-day repeat cycle, greatly enhancing the efficiency of surface water monitoring [7, 8]. This capability supports continuous observation of river water level fluctuations throughout the year [9, 10]. The Sentinel-3 altimeter provides a footprint of approximately 300 meters along the track, with a ground separation of about 7.5 km, enabling the detection of additional inland water bodies [11, 12]. Furthermore, its extended 369-day revisit period improves measurement accuracy. Nevertheless, the precise monitoring of inland waters remains challenging, as it requires effective capture of seasonal variations [13, 14]. With its enhanced temporal and spatial resolution, Sentinel-3 serves as a valuable tool for inland water monitoring and hydrological research [15, 16].

* Corresponding author: abdwahid@utm.my

http://dx.doi.org/10.28991/CEJ-2025-011-10-018

Detecting satellite signals over inland water bodies—particularly those with narrow widths and rugged surrounding terrain—remains a significant challenge [16-18]. To improve the accuracy of satellite data, several tracking techniques have been developed, including the Envisat Model-Free Tracker, the Jason-1 Split-Gate Tracker, the Jason-2 Diode/Median Tracker, and the Diode/DEM Tracker. In coastal regions, the Diode/DEM approach—also referred to as the Open-Loop Tracking Command (OLTC)—has demonstrated superior performance over the closed-loop mode in predicting sea level and wave heights. Initially tested on the Jason-2 and SARAL/AltiKa missions [19, 20], Sentinel-3 has been operating in open-loop mode since March 2019. Research on Chinese rivers has shown that OLTC substantially enhances water surface monitoring in hilly areas when compared with closed-loop tracking [16]. Nevertheless, certain cases have revealed that OLTC may lack adequate elevation adjustments when tracking water surfaces over newly constructed reservoirs [21]. Recent advancements in retracking and filtering techniques have further improved the accuracy of inland altimetry. For example, applying Pulse Peakiness and Misfit filters to Sentinel-3 waveforms at the Chashma Barrage reduced the RMSE to approximately 0.27 m ($R \approx 0.93$–0.95), compared to significantly larger errors without filtering [22]. Similarly, by optimizing retrackers and correcting DEM biases, innovative altimetry mapping approaches such as AltiMaP have enhanced the retrieval of water surface elevation at the watershed scale [23].

The utility of near-real-time (NRT) Sentinel-3 data for river monitoring has also been confirmed. A global three-year study reported a median RMSE of about 21–23 cm when compared to in-situ measurements, showing comparable performance to delayed products and supporting forecasting applications [24, 25]. Furthermore, high-resolution flood reanalysis in the Garonne basin has been achieved by integrating SWOT altimetry with Sentinel-1 flood extent data through ensemble Kalman filtering (EnKF), resulting in state-parameter updates that closely align with in-situ water level dynamics [26]. When combined with in-situ observations, the assimilation of SWOT altimetry into EnKF frameworks for hydrodynamic flood modelling has shown substantial improvements in riverine flood reanalysis, highlighting its strong potential for application in other basins [27]. Nevertheless, many watersheds still lack sufficient in-situ gauging stations, which limits validation capabilities and complicates the calibration of data assimilation and Kalman filtering methods.

Measuring river water levels using satellite altimetry, particularly over rivers such as the Euphrates, poses significant challenges due to their narrow widths, rough terrain, and variable surface reflectance. Although Open-Loop Tracking Commands (OLTC) improve measurement accuracy, they still encounter difficulties when applied to newly formed reservoirs or sudden elevation changes. Moreover, the absence of in situ gauges in many basins limits the validation of satellite-derived data. While near-real-time Sentinel-3 observations remain underutilized in arid regions, high-precision datasets such as SWOT often suffer from delays. Compared with large tropical rivers like the Amazon, Congo, and Ganges, which are generally more suitable for most filtering techniques, the Euphrates presents additional complexities. To address these challenges, this study applies data assimilation and OLTC-enhanced observations within a Kalman filter framework to smooth Sentinel-3 data, enabling near-real-time water level prediction in data-scarce regions.

The Euphrates River, extending approximately 2,700 km (1,678 miles), is the largest in Southwest Asia and flows through Turkey, Syria, and Iraq, playing a vital role in regional hydrology. This research provides a detailed examination of the Kalman filter approach alongside an extended outlier rejection methodology, which together support the water level estimations available through the DAHITI database.

The study addresses two central questions concerning DAHITI: (1) What is the accuracy of DAHITI-derived water level estimations for the Euphrates River basin? (2) How does the accuracy of DAHITI data compare with other satellite databases and missions? The research emphasizes the southwestern Iraq section of the Euphrates River and investigates the correlation between altimeter readings to improve the reliability of error estimation. Furthermore, it establishes clear guidelines for constructing water-level time series, incorporating a rigorous validation process that cross-compares results with datasets from other satellite missions and in situ gauging stations, such as Hydroweb.

The structure of the remaining sections of this article is as follows: Section 2 (Materials and Methods) introduces the study area, the utilized databases, and the relevant satellite missions, with particular emphasis on Sentinel-3 and the available in situ observations. Section 3 provides a detailed description of the adopted methodology and presents a comparative analysis between Gauging Station records and multi-mission Altimetry data obtained from Hydroweb and DAHITI. Section 4 examines the performance of the proposed approach along the Euphrates River, presenting and assessing the obtained results. Section 5 discusses the findings in terms of their practical implications and their significance within the broader research context. Finally, this section concludes the study and outlines recommendations for future investigations.

2. Material and Methods

2.1. Study Area

The primary source of validation data for water elevation time series derived from altimetry is in situ observations collected from gauging stations. The study area is restricted to inland water bodies, as only these provide the in-situ data necessary for accurate comparisons. This research focuses on the Euphrates River, which hosts several gauging stations. When selecting inland water bodies to evaluate the performance of the Kalman filter method, the availability of external time series generated from altimetry must be considered. It is also essential to compare the Kalman filter with alternative approaches. Fortunately, for nearly all the analysed inland water bodies, both in situ gauging stations and altimetry-derived time series are available.

This investigation concentrated on the southwestern region of the Euphrates River basin. The Euphrates extends from latitude 31.9676 and longitude 44.9306 to latitude 31.0955 and longitude 46.0942 (Figure 1). The Euphrates River basin spans approximately 1060 km. Based on Halicki & Niedzielski [24], the classification of inland water bodies depends on river width. Within the study area, the Euphrates is categorized as a narrow river, with widths ranging between 40 and 200 meters. The southwestern desert of Iraq is characterized by long, hot, and dry summers, where temperatures may rise to 55 °C in July and August. In contrast, during the winter months (December to February), temperatures can drop to –3 °C, with periods of intense cold and occasional rainfall.

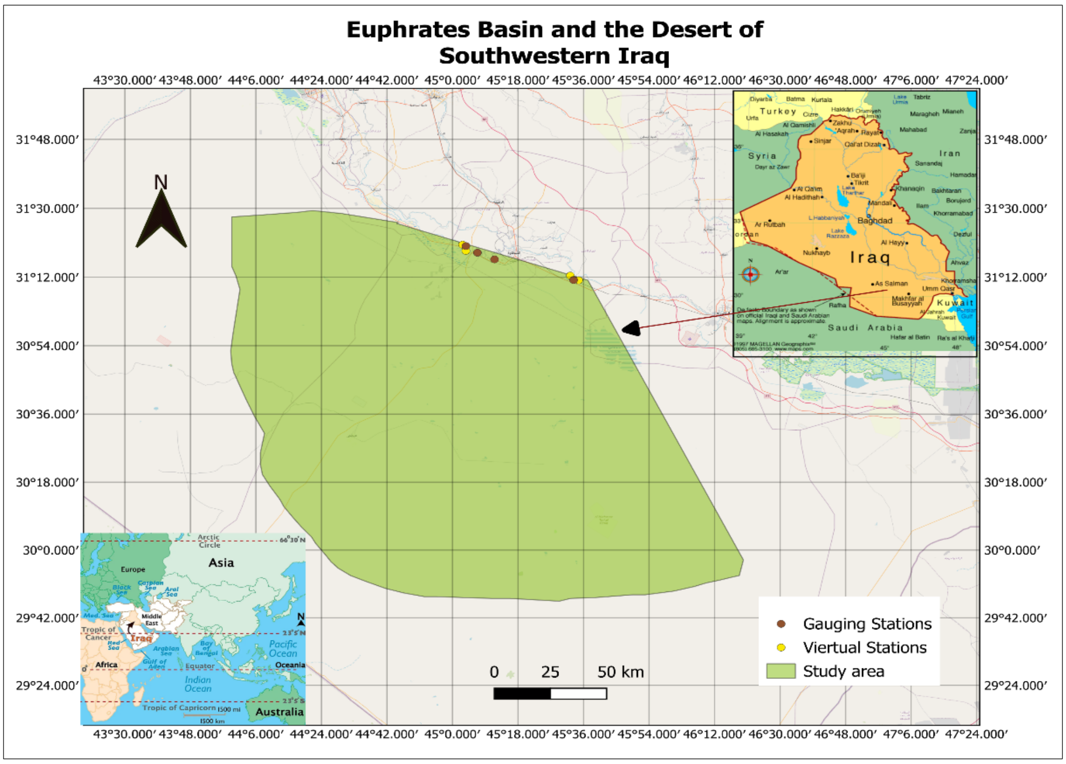


Figure 1. The Iraqi southwest desert and the Euphrates basin

On average, the study area (Figure 1) receives about 30 mm of rainfall per day in January. Rainfall also exceeds 20 mm in March, November, and December, while maximum daily precipitation varies significantly by location in other months. For example, Al-Nasriya reported only 0.2 mm of rainfall in September, whereas Baghdad recorded 89.1 mm in November. Overall, the study region is predominantly desert, featuring relatively flat terrain interspersed with dunes.

2.2. The Data and Principles of Altimetry

Space-borne radar altimeters are highly effective tools for monitoring inland water bodies, such as rivers and lakes, and for measuring water levels. These instruments transmit signals in the nadir direction, which reflect off the water surface and are subsequently received by the device. The shape of the returning signal, known as the waveform, provides critical information for estimating water levels. The time elapsed between signal transmission and reception corresponds to the distance between the satellite and the Earth's surface [25]. Water level is determined by subtracting the observed range (R) from the satellite's altitude (Halt), with necessary geophysical corrections applied to ensure accuracy [26] (Equation 1). Altimetry is a fundamental technique for determining water surface elevations from satellite data. Accurate measurements rely on two key parameters: the range (R) and the satellite's altitude (Halt). The range is calculated by measuring the round-trip travel time of the radar altimeter's electromagnetic pulses. The satellite's altitude is precisely determined by calculating its orbit relative to a reference ellipsoid. To improve measurement accuracy, corrections are applied to account for atmospheric effects, including ionospheric, dry tropospheric, and wet tropospheric influences, as well as geophysical factors such as solid Earth and polar tides [27]. The water surface height can then be determined using the following Equation:

$$\text{H-water level} = \text{Halt} - (\text{R} + \text{Corr-atmospheric} + \text{Corr-geophysical}) \tag{1}$$

When the altimeter range is denoted by R, the computed water level is represented by H, the atmospheric and geophysical corrections are represented by Corr atmospheric and Corr geophysical, and the Sentinel 3A altitude is represented by Halt.

2.2.1. DAHITI Approach

A precise and dependable method of combining altitude measurements from numerous tracks is essential. The irregularly spaced data from various locations must be combined into a single time series for each objective to obtain the most accurate outcomes from data with varying degrees of uncertainty. By estimating the water surface elevation using a Kalman filter and an enhanced outlier rejection, the DAHITI approach satisfies these criteria. As shown in Figure 2, the three stages of the DAHITI technique's processing approach for calculating the water surface levels for the inland waterways include pre-processing, Kalman filtering, and post-processing.

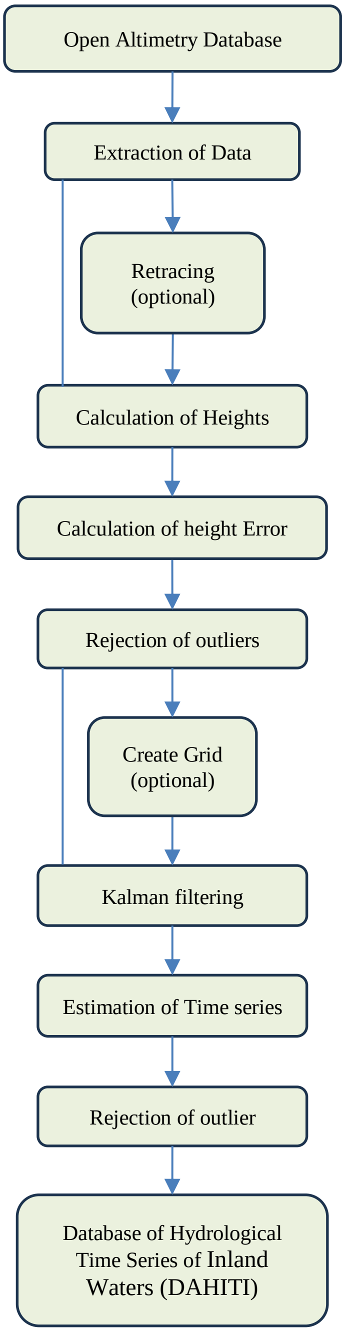


Figure 2. The three primary stages of the DAHITI processing approach

Pre-processing involves all essential operations required to refine altimeter height measurements before analysis. These steps include waveform re-tracking, outlier rejection, range corrections, and the computation of height errors. Water levels in lakes and rivers are estimated using the Kalman filtering method (see Table 1). This study applies the DAHITI technique, which utilizes Kalman filtering to derive a single estimated water level for each period at a specific location within the river. In the post-processing phase, all individual water level measurements obtained in the previous step are integrated into a continuous time series using a Kalman filter applied to a grid.

Table 1. List of geophysical adjustments and applicable models

Corrections	Sources/models	References
The wet troposphere	E.C.M.W.F. (2.5° * 2.0°) Vienna mapping functions. 1 (V.M.F1)	Böhm et al. (2006) [2]
Dry troposphere	E.C.M.W.F. (2.5° * 2.0°) for Functions. 1 for Vienna mapping (V.M.F1)	Böhm et al. (2006) [2]
The Ionosphere	N O A Ionosphere Climatology (2009) (NIC 09)	Scharroo & Smith (2010) [22]
Solid of the Earth's tide	I.E.R.S. Convention 2003	McCarthy & Petit (2004) [12]
The pole tide	I.E.R.S. Convention 2003	McCarthy & Petit (2004) [12]
Range bias	M.M.X.O.14	Bosch et al. (2014) [13]
Geoid	Eign- 6C3 stat	Förste et al. (2014) [18]

Kalman Filtering: The DAHITI methodology employs Kalman filtering to generate a time series of water elevation measurements. This approach continuously updates a model by incorporating observations with varying levels of precision, thereby improving the estimation of present conditions and forecasting future states [28]. The filter operates recursively, minimizing the number of input observations processed at each step, making real-time applications feasible. Various modified Kalman filter techniques have been developed for geodetic applications (e.g., [29-31]). Through sequential least-squares adjustment, the Kalman filter produces statistically optimal water elevation estimates by considering both deterministic and stochastic system behaviors.

Radar altimetry is a remote sensing technique used to estimate water levels in rivers and lakes. In this study, several virtual stations along the Euphrates River were identified based on multi-mission altimetry tracks from Jason-2, Envisat, Sentinel-3A, and Sentinel-3B. These stations are situated within a latitude range of 31.967°N to 31.095°N and a longitude range of 44.930°E to 46.094°E. The analysis revealed that four virtual stations could be established using data from these altimetry tracks, each covering different time periods (see Table 2).

Table 2. Virtual stations for the multi-mission altimetry were identified based on altimetry passes.

Satellites	Pass	Data Availability	Nearest location (Gauging Stations)
Sentinel-3A	225	2016- Present	AL Hamza
Sentinel-3B	339	2018- Present	Al-Rumaila
Jason-2	209	2008- Present	Al-Khether
ENVISAT	270	2002-2012	Al- Rumaithah

In this study, the term "virtual stations" refers to the locations along the Euphrates River where altimeter measurements are taken. The altimeter data used in this research were obtained from DAHITI, an open-access archive available at *https://DAHITI.dgfi.tum.de/en/map/*. Both DAHITI and Hydroweb are multi-mission altimetry repositories. However, DAHITI applies a Kalman filter to remove measurement outliers, improving the accuracy of its altimeter data to within a few millimetres to centimetres. In comparison, Hydroweb operates virtual stations at a high frequency of 18–20 Hz, using datasets from Envisat, Jason-2, Sentinel-3A, and Sentinel-3B. These datasets are pre-processed to correct for factors such as polar motion, sea state, ionospheric effects, and orbital biases, thereby enhancing measurement reliability.

2.2.2. Data from Gauging Stations

This study collected water level time series data from four hydrological gauge stations along the Euphrates River: Al Hamza, Al-Rumaila, Al-Khether, and Al-Rumaithah. These data were obtained from the Iraqi Ministry of Water Resources, specifically the Irrigation and Land Reclamation Projects Operation Department. This dataset represents the only source of daily water level and discharge measurements that have undergone rigorous editing and quality control to ensure reliability.

3. Methodology

Although water surface elevation measurements from hydrological gauges exhibit high relative precision, several factors must be considered when utilizing in situ data. Uncertainties related to gauge positioning, reference height, and vertical datum complicate direct comparisons with satellite altimetry measurements. These discrepancies introduce height differences between gauge and altimetry-derived water level time series, which must be addressed during the validation process.

In particular, comparisons between altimetry-based and in situ water levels often reveal residual offsets. These discrepancies arise primarily due to the limited number of altimeter satellite tracks crossing rivers precisely at gauging station locations, combined with river slope variations that introduce additional offsets. To mitigate uncertainties associated with altimetry data from multiple missions, comparative analyses are conducted using water surface levels obtained exclusively from gauging stations.

3.1. Comparing the Gauging Stations with the Altimetry Data from DAHITI, and Multi-Missions' Altimetry Data from Hydroweb

This study utilized external inland altimeter databases, such as Hydroweb, to compare the derived water level time series with those obtained from altimeter satellites. These databases compile data from multiple altimeter missions, each employing different methodologies to calculate water levels. Consequently, the temporal resolutions of these time series vary between 10 and 35 days, covering a broad time frame. It is essential to consider these variations when comparing data from different sources.

In the first part of this analysis, the DAHITI technique was applied to estimate water surface elevations for four virtual stations along the Euphrates River using altimetry data from Sentinel-3A and Sentinel-3B [32-34]. The DAHITI database, accessed on June 5, 2023, provides water elevation data for these virtual stations. Each virtual station was assigned a corresponding nearby gauging station, with an average separation distance of 32.875 km. Despite station distances ranging from 0.750 km to 65 km, temporal discrepancies between measurements must be considered when comparing water level records.

The second part of this study involves a comparative analysis of altimetry data from various satellites hosted on different databases against gauging station data. Open-access altimeter data are widely recognized for their accuracy. To assess the reliability of multi-mission satellite altimetry data, this study compares them with DAHITI-derived altimetry measurements. This comparison is crucial for evaluating the effectiveness of the Kalman filter [32, 35], a core component of the DAHITI methodology, in enhancing data accuracy.

3.1.1. Statistical Matrices

Comparing water elevations presents challenges due to differences in vertical datums, such as the EGM 2008 geoid used for Sentinel-3A, Sentinel-3B, Jason-2, Envisat, and gauging station measurements. To mitigate this issue, Sulistioadi et al. [36] recommends using water elevation anomalies instead of absolute water elevation values. The anomalies for Envisat, Jason-2, and Sentinel-3A/B are computed by determining the height difference between observed and measured elevations from Hydroweb, facilitating the identification of irregularities in water level variations.

The observed data are derived from standard water surface elevations. To compute the water elevation anomaly for a specific virtual station, the variance between the recorded and measured elevations from Sentinel-3A and Sentinel-3B is calculated using DAHITI. This analysis was conducted for the period from February 2019 to January 2020. Additionally, the anomaly for the water level time series at a given hydrological gauge station is determined by calculating the difference between the observed data and their mean value over the same period.

3.1.1.1. Root Mean Square Deviation (RMSD)

The Root Mean Square Deviation (RMSD) is a widely used metric for assessing numerical data accuracy. It quantifies the average error magnitude and is particularly sensitive to large fluctuations, as it squares individual variances. The RMSD is computed to evaluate the extent to which satellite-based water elevation anomalies deviate from gauge-derived anomalies [37]. It is defined as:

$$RMSD = SQRT \sum_{\mathrm{i}}^{N} \frac{(H(gauge)\mathrm{i} - H(altimety)\mathrm{i})^2}{N} \tag{2}$$

where *H (altimetry)* is the Envisat, Sentinel-3A, B, Jason-2, and Jason-3 anomaly for the water elevation, *Hgauge* is the gauge data for the water elevation anomaly, and *N* is the size of the samples.

3.1.1.2. Unbiased Root Mean Square Error (Ub RMSE)

Compared to the Random RMSE, which accounts for random errors, the unbiased RMSE (Ub RMSE) eliminates bias between datasets, providing a more accurate assessment of discrepancies [37-39]. By minimizing the bias introduced by the spatial distance (less than 50 km) between observations on the same water body, the Ub RMSE [39] offers a reliable estimate of inaccuracies between in-situ measurements and satellite-derived water level datasets. The Ub RMSE is computed using Equations 3 and 4.

$$Ub\ RMSE = sqrt\ (rmsd^2 - md^2) \tag{3}$$

$$MD = \sum_{\mathrm{i}}^{N} \frac{(H(gauge)\mathrm{i} - H(altimety)\mathrm{i})}{N} \tag{4}$$

The Nash-Sutcliffe efficiency (NSE) is often used to compare anomalies [39-41]. It is one of the few recognized indicators for assessing the effectiveness of hydrologic models. The following formula defines the NSE statistics:

$$NSE = 1\text{-}\sum_{i}^{N} \frac{(H(gauge)i - H(altimety)i)^2}{(H(gauge)i - H(gauge)mean)^2} \tag{5}$$

where N represents the sample size, B represents the anomaly for the surface water elevation, H represents the gauge water level anomaly, and Hgauge represents the average of the elevation anomalies in the gauge station dataset. H (altimetry) is the Envisat, Jason-2, Jason-3, and Sentinel-3A. As an indicator of estimating skills, the Nash-Sutcliffe efficiency statistics characterize the degree of agreement between observations and estimates rather than directly reflecting errors. As a result, it makes it possible to evaluate a method's efficacy across many rivers. The range of the NSE values is -∞ to 1.

3.1.2. Topographic Factors

If altimetry-derived water levels and in situ measurements align in terms of mean, phase, and amplitude, the Nash-Sutcliffe Efficiency (NSE) approaches 1. When NSE is near zero, satellite-derived water elevations are comparable to the average of gauge measurements. However, negative NSE values indicate that averaging gauge data provides a more accurate estimate of water levels than reconstruction using Sentinel-3A and 3 B.

This study also aimed to evaluate the land cover (LC) near the river using the 2018 Corine Land Cover (CLC) dataset. To achieve this, we analysed the geographic context surrounding each virtual station (VS) along the satellite ground track, precisely mapping land features within a one-km radius of each VS. Furthermore, river morphology was assessed using Sentinel-1 imagery, taking into account factors such as the presence of sandbars, the orientation of the river channel relative to the satellite ground tracks, and the frequency of river crossings along these tracks. This methodology allows for distinguishing VS locations and passes lines for all missions based on the presence or absence of these features.

4. Results and Discussion

This chapter examines altimetry data derived using the Kalman filtering technique, focusing on the Euphrates River. The accuracy of water level measurements from four virtual stations on the DAHITI platform was validated by comparing them with data from gauging stations, Hydroweb, and altimetry satellites provided by other sources. To enhance the reliability of results, multiple altimetry missions were utilized. The study specifically analysed a section of the Euphrates River in southern Iraq to align DAHITI data with measurements from gauging stations and multi-mission satellites.

4.1. The Precision of Surface Water Heights Derived using DAHITI Altimetry

For the virtual stations and their nearest gauging stations, the derived ubRMSD, RMSE, and NSE values are reported in Table 3 with a mean of 0.35, 0.35, and 0.78m, respectively.

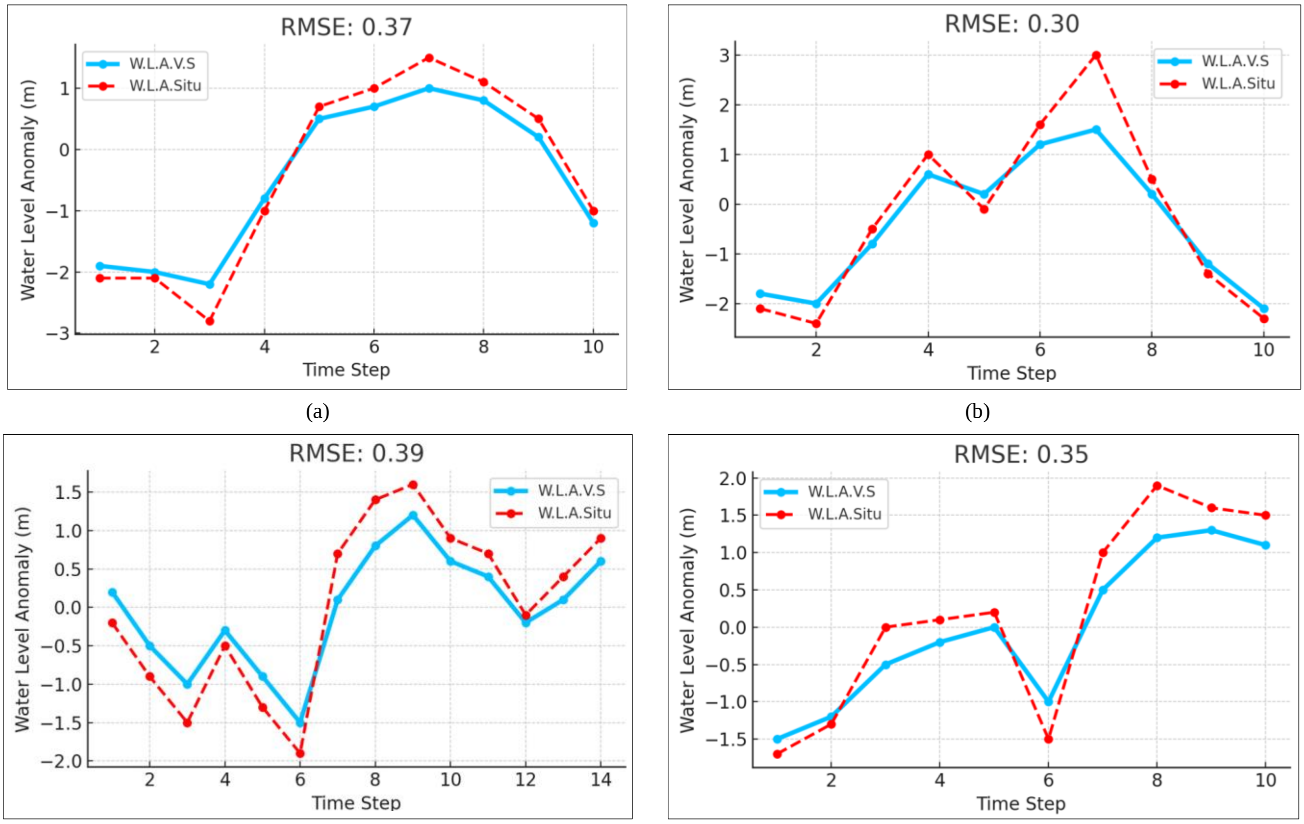
Table 3. The altimetry method for neighbouring gauge levels is the basis for the altimetry data for the Sentinel-3B and the water surface level

Basin	River	ID	Latitude	Longitude	River Width	Gauging Station	Distance to VS (km)	Ub RMSE	RMSE	NSE
Euphrates	Euphrates River	41508	31.3520	45.0311	65	Al- Hamza	64.7	0.3702	0.3705	0.5971
		41509	31.3147	45.0586	105	Al- Rumaithah	0.750	0.2961	0.2985	0.8631
		24448	31.2885	45.5161	50	Al-Khether	65	0.3922	0.3963	0.7233
		41512	31.2878	45.5188	45	Al-Rumaila	58.3	0.3334	0.3516	0.9831

The in-situ and altimetry datasets yielded statistically significant results, with the unbiased Root Mean Square Error (ubRMSE) ranging between 0.29 cm and 0.33 cm. As presented in Table 3, the Nash-Sutcliffe Efficiency (NSE) coefficients range from 0.59 to 0.98, with an average of 0.78, indicating the high quality of the Sentinel-3A (S3A) and Sentinel-3B (S3B) datasets. The maximum NSE value of 0.98 was observed for water surface elevation estimates at the virtual station (VS) when compared to the nearby Al-Rumaila gauging station (Table 3). This excellent performance is attributed to the sandy riverbanks with minimal vegetation, promoting desert regeneration, which contributed to the highest NSE values.

Table 3 also provides a comparison between the reported river widths (40–200 m), derived from Sentinel-1 data, and the distances between the VSs and nearby gauge stations. In the study area, virtual station locations, averaging approximately 50 m in width, are situated at a mean distance of 32.875 km from adjacent gauge stations, with distances ranging from 0.75 km to 65 km.

Figure 3 illustrates the convergence of water level anomalies for the VSs relative to the adjacent in-situ measurements. The consistency between the anomalies is evident, with the Al-Rumaithah station showing a low RMSE of 0.29 m and a high NSE of 0.86. The lower performance at the Al-Hamza station (NSE 0.59, RMSD 0.37) may be due to the high reflectivity of sandbars within the river channel. Nevertheless, the altimetry data presented in Figure 4 demonstrates excellent agreement with the in-situ time series, showing minimal errors.



(a) (b) (c) (d)

Figure 3. Comparing the water elevation variations between the nearest gauge stations on the Euphrates River and four simulated Sentinel-3A and B satellite sites

In other words, there is a strong agreement between in situ measurements and the analysis of DAHITI altimetry data from four gauging stations along the Euphrates River. The model demonstrates reliable performance, with RMSE values ranging from 0.2985 m to 0.3963 m and Nash-Sutcliffe Efficiency (NSE) scores exceeding 0.59 at all locations (Table 3). Despite the river's relatively narrow width (45 m), the Al-Rumaila station achieves the highest NSE (0.9831), reflecting nearly perfect monitoring of observed water levels. Even at a close distance (0.75 km) to the virtual station, the lower RMSE at Al-Rumaithah (0.2985 m) indicates highly accurate satellite retrievals. These results highlight the effectiveness of DAHITI for hydrological monitoring in semi-arid basins with sparse observational data

4.2. Water Level Time Series for the Multi-Missions from the Hydroweb

Table 4 presents the calculated Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) values for the water elevation time series along the pass line, derived from HydroWeb's in-situ measurements and multi-mission altimetry data (Envisat, Jason-2, and Sentinel-3A/B). The average RMSE and NSE values were 0.618 m and 0.458, respectively. These metrics were computed to evaluate the reliability of the data from the different satellite missions. The results from HydroWeb's dataset showed discrepancies when compared to the DAHITI database, with elevated RMSE values indicating relatively poor performance of the missions, despite the generally flat topography of the study area. One major source of uncertainty in predicting inland water surface levels is the limited temporal resolution of satellite altimetry. To mitigate this issue, the study employed data from multiple altimeter missions to compare the estimated water surface elevations with those recorded at gauging stations.

Table 4. Working metrics for the multi-mission water levels depend on the altimetry for nearby gauge station elevations

Basin	River	Gauging Station	The number of passes for the multi-Mission satellites				Distance to Pass-line. (km)	Ub RMSE	RMSE	NSE
			Envisat	Jason-2	Sentinel-3A	Sentinel-3B				
Euphrates	Euphrates River	AL Hamza	-	-	225	-	77.1	0.662	0.628	0.225
		Al- Rumaithah	270	-	-	-	50.8	0.639	0.537	0.567
		Al-Khether	-	209	-	-	80.1	0.936	0.485	0.170
		Al-Rumaila	-	-	-	339	22.5	0.577	0.823	0.871

Figure 4 illustrates the water levels of the Euphrates River obtained from Envisat, Jason-2, Sentinel-3A, and Sentinel-3B via HydroWeb, alongside the measurements from the gauging stations. Time series from all satellite altimetry data were used to calculate the anomalies in the water levels. The width of the Euphrates River ranges approximately from 40 to 200 meters.

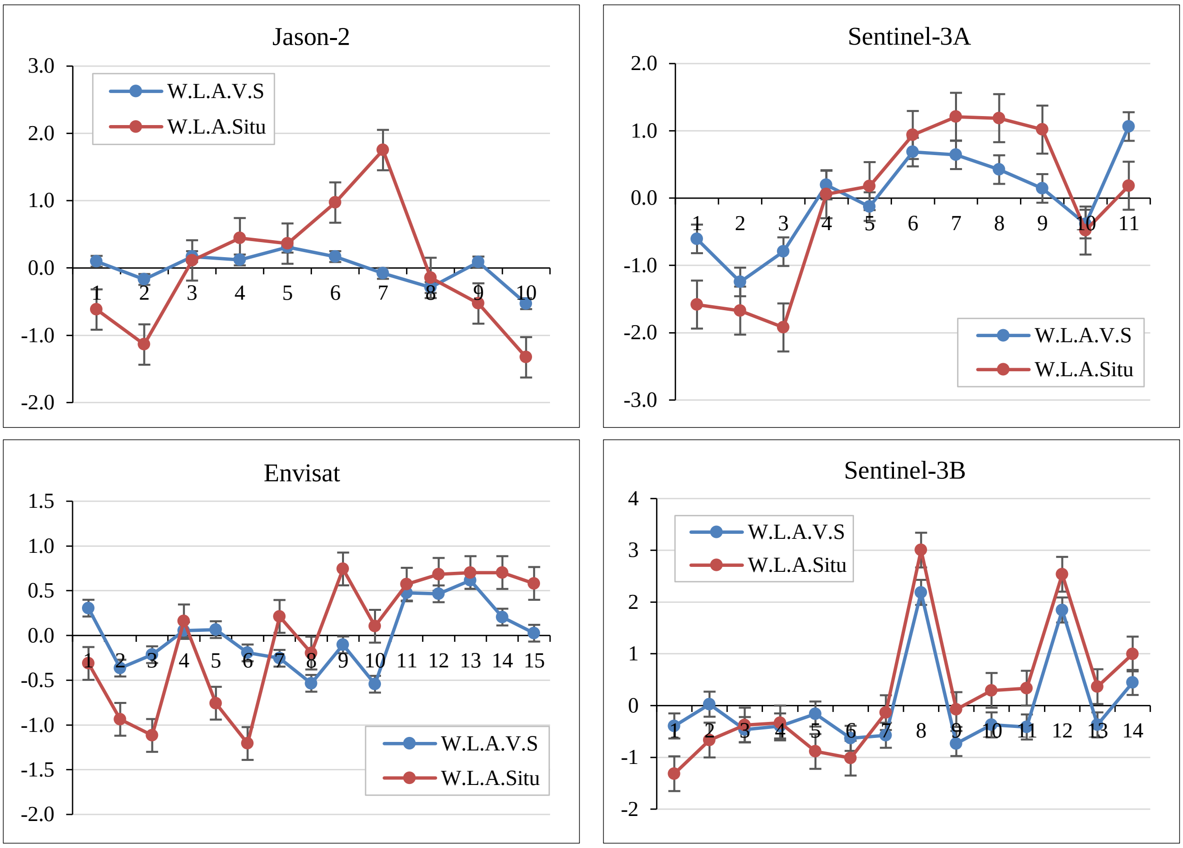


Figure 4. The water levels time series and the water surface elevation for the gauging stations for the multi-missions from Hydroweb

It is significant to highlight that river morphological characteristics like river width and azimuth, as well as surrounding bright objects, such as tiny sand bars, islands, and water bodies, can have an impact on river level monitoring using altimetry [24]. Furthermore, the surrounding terrain has an indirect impact on the echo signals from radar. These elements will be thoroughly examined in this section.

The superior precision and consistency of DAHITI products are evident when comparing DAHITI altimetry data with multi-mission satellite observations from four gauging stations along the Euphrates River. Although Table 3 shows high NSE values (up to 0.9831) and DAHITI RMSE values ranging from 0.2985 to 0.3963 meters, Table 4 highlights greater variability and generally lower performance across conventional satellite missions. The best-performing multi-mission dataset (Sentinel-3B) produced an RMSE of 0.823 m and an NSE of 0.871 despite the relatively close distance (22.5 km), whereas DAHITI at Al-Rumaila achieved an RMSE of 0.3516 m and an NSE of 0.9831. Similarly, DAHITI outperformed Jason-2 at Al-Khether, achieving a substantially higher NSE (0.7233 vs. 0.170) and a lower RMSE (0.3963 m vs. 0.485 m) (Tables 3 and 4). These comparisons demonstrate DAHITI's ability to provide more accurate water level estimates, even in cases where satellite tracks are sparse or not well aligned with river morphology, and highlight its robustness in narrow or complex terrain.

4.3. The Virtual Station's Water Elevation Compared to Adjacent Gauges

Water level predictions made at virtual stations using altimetry can differ from in-situ measurements due to various factors. To ensure accurate validation, it is crucial to select gauge stations located near the virtual station. According to Kittel et al. [15], gauges should be within 20 kilometres of the virtual station to ensure a reliable comparison. However, Bogning et al. [41] used data from a virtual station situated more than 100 kilometres away from the gauge. Furthermore, the comparison may be influenced by tributaries between the two locations, as noted by Kittel et al. [15] and Biancamaria et al. [42], who excluded pairs with significant tributaries. Additionally, the presence of hydraulic structures such as dams or weirs can degrade the agreement between altimetry and gauge data. For example, Biancamaria et al. [42] reported that dams on the Garonne River between the local gauge and virtual station led to significant RMSE in water surface height calculations.

Figure 1 illustrates the geographical distribution of the virtual stations (VS) and gauge stations. Despite the gauges being located up to 65 kilometres away from the virtual stations, the distance did not significantly affect the results. Our investigation found that the water elevations at a virtual station located approximately 0.750 kilometres from the Al-Hamza gauge yielded an NSE of 0.59, one of the lowest values among the closest measurements (see Table 3 for details). Moreover, Table 3 shows that the virtual station's NSE value of 0.72, located farther from the Al-Khether gauge, suggests a higher agreement. Figure 5 presents the statistical values for each monitoring station along the Euphrates River included in this study.

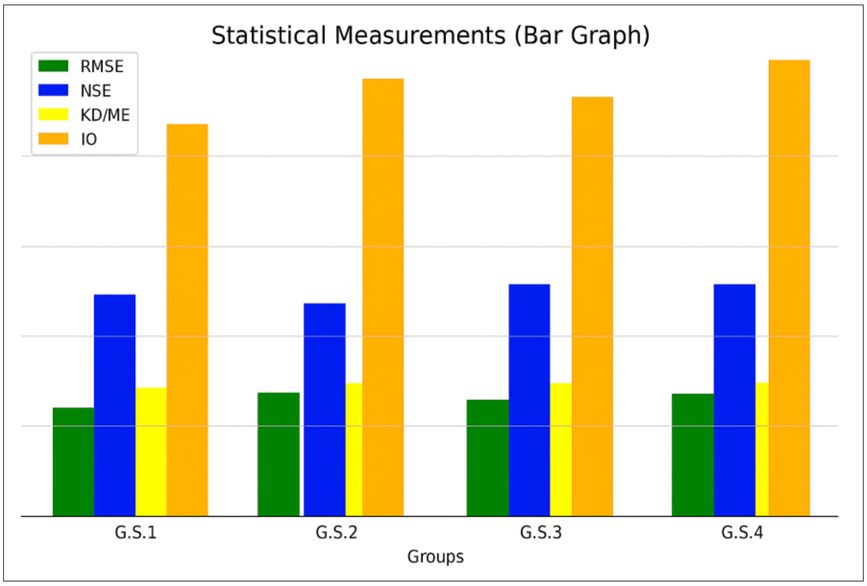


Figure 5. Statistics from measurement sites dispersed along the Euphrates River in the study area

Land contamination in waveform signals poses a significant challenge in determining the width of the Euphrates River, which is classified as narrow. This issue affects nearly all altimeter readings, as nadir measurements over the river are scarce. Even when such measurements are available, they may originate from river branches, potentially distorting the water level time series for the target area.

Validation of the DAHITI water level time series for the Euphrates River, through comparison with Hydroweb data, showed noticeable improvements. This comparison provides a valuable assessment of the impact of outlier rejection and Kalman filtering on the refinement of DAHITI data. Differences in RMSE across four inland water levels indicate a slight decrease, suggesting that the combined approach yields only a moderate improvement in overall accuracy.

4.3.1. Factors Influencing Altimetric Mensuration

Radar altimetry poses inherent challenges for measuring river heights (see Introduction). An analysis of the virtual station (VS) on the Euphrates River—a relatively narrow water body—shows no significant correlation between the acquired altimetric data and river width. If any relationship exists, it is strongly inverse with respect to (1) unbiased root-mean-square difference (ubRMSE), (2) Nash–Sutcliffe efficiency (NSE), and (3) root-mean-square error (RMSE). The strongest absolute correlations between river width and either RMSE or NSE are observed in narrow rivers, reaching values of 0.29 and 0.98, respectively, when comparing VS data with corresponding gauge measurements.

Analyses using DAHITI data indicate that variations in the Euphrates River's width—from 40 to 200 m—do not have a noticeable effect on altimetric accuracy. Previous studies, including Maillard et al. [43], provide detailed insights into how ambient factors influence altimetric measurements. This study further demonstrates that land cover (L.C.)

within 1 km of each VS does not significantly correlate with Sentinel-3A and 3B data quality. Nevertheless, vegetation appears to slightly affect measurement precision, as evidenced by the lower NSE value (0.59) recorded at the Al-Hamza station (Table 3). The predominance of agricultural land along the Euphrates River, characterized by low surface roughness, is generally suboptimal for altimetric measurements. Furthermore, a river morphology analysis identified features such as river crossings, parallel channels along the satellite's ground track, and sandbanks near the Al-Hamza station that may influence altimetric performance.

4.3.2. Factors Affecting River Morphology

While altimetry is known to perform better over large water bodies, data from Tables 3 and 4 indicate no significant relationship between river width and altimetry satellite performance. The RMSE for the four virtual stations (VS 1, VS 2, VS 3, and VS 4), with widths ranging from 50 to 200 m, remains suboptimal. Previous studies [15, 16, 24, 41, 44] have explored the relationship between river width and the performance of Sentinel-3A and 3B, helping to resolve inconsistencies observed within a single study area. Notably, most RMSE values are below 1 m; therefore, this study focuses only on cases where RMSE is less than 1 m.

If a relationship existed between river width and Sentinel-3A performance, the data would exhibit a negative correlation, regardless of the evaluation method applied. However, the findings suggest either no correlation or an inconsequential one. Sentinel-3A measurements are effective for both small- to medium-sized and large rivers. While river widths exceeding 50 m may not impact measurement accuracy, they could limit data availability and the feasibility of using altimetry for river monitoring.

5. Discussion

The DAHITI time series outperforms previous methods and shows strong agreement with in situ data. However, challenges persist, particularly for narrower rivers. Comparisons of four DAHITI stations reveal RMSE differences ranging from 29 to 39 cm (Table 3). Notably, Al-Hamza and Al-Khether stations exhibit reduced altimetry consistency. A primary issue affecting altimeter readings along the Euphrates River is land contamination, which distorts waveforms and reduces measurement accuracy.

Validation of DAHITI water level data against in situ measurements, as well as a comparison with Hydroweb data, demonstrates clear improvements. However, Nash-Sutcliffe efficiency (NSE) values for the Euphrates River using HydroWeb's water level time series range from -0.871 to 0.567 (Table 4), indicating that the estimated error variance of the modelled time series exceeds that of the observations. Consequently, a negative NSE suggests that the observational mean is a more reliable predictor than the model when NSE < 0.

The impact of outlier rejection and Kalman filtering on DAHITI data improvements is evident (Table 3). RMSE differences for four inland water elevation datasets show a slight decrease, suggesting only moderate accuracy gains from this combined approach. The most significant improvements stem from data re-tracking and robust outlier detection, while Kalman filter enhancements through dynamic modelling enhance real-time applicability.

Numerous studies have shown that altimetry accuracy over inland water bodies can be influenced by land cover and land use. For instance, a study on virtual stations (VSs) along rivers in China [16], some of which traverse complex terrain, highlights potential altimeter malfunctions that lead to significant errors (Table 5). Similarly, research on the Inner Niger Delta [44] indicates that multiple river currents or floodplains surrounding VSs can cause major inaccuracies, complicate waveforms, and make range determination more challenging for re-trackers (Table 5). However, despite being located in a floodplain, one VS analyzed by Kittel et al. [15] reported an exceptionally low RMSE (0.14 m). Additionally, Rai et al. [45] estimated monthly discharge at VSs along the Ganga River using data from three satellite altimeter missions—ERS-2 (1995–2007), Jason-2 (2008–2017), and Envisat (2002–2010)—concluding that the temporal resolution of altimetry contributes to discharge estimation uncertainty.

Table 5. Uses Sentinel-3A radar altimetry to summarize research on river water levels.

References	Study area	The river width (m)	Distance to gauging station (Km)	Number of V. S	RMSE (cm)
Bogning et al. (2018) [41]	Ogoou´e River	300–1240	66–133	3	20-40
Normandin et al. (2018) [44]	Inner Niger Delta	380–3760	8–162	16	16-170
Zaidi et al. (2020) [39]	Indus River	-	0.71–3.74	2	43-45
Jiang et al. (2020) [16]	Chinese rivers	70–2000	<3	39	12-639
Scherer et al. (2020) [46]	Lower Mississippi River	-	11.29	1	14
Kittel et al. (2021) [15]	Zambezi basin	35–600	4.8–19.5	2	14-28
Halicki & Niedzielski (2022) [24]	Vistula and Odra basins	40–610	0.49–72.7	34	12-44
Rai et al. (2021) [45]	The Ganga River	130 m to 2 km	<81	7	22 -71
Present study	**The Euphrates River**	**40-200**	**0.750-65**	**4**	**29-39**

Since this study focuses on VSs in a relatively flat region, the impact of topography was not examined. Table 3 presents low and acceptable RMSE values (0.29–0.39 m, with a mean of 0.35 m) and minimal dispersion (RMSE standard deviation = 0.035 m). Contrary to Maillard et al. [43], which suggests land cover significantly affects data quality, our findings indicate no substantial impact, likely due to the similarity of land cover types across most Vs. To assess the accuracy of manually derived altimetry-based water levels, various services, including the European Space Agency (ESA) GPOD, were utilized (Table 5).

The root mean square error (RMSE) estimates in our analysis are lower than those reported by Schwatke et al. [32] for significantly larger inland water bodies. While this finding is promising, caution is warranted, as substantial absolute water elevation discrepancies (exceeding 1 m) may contribute to considerable errors in some virtual stations (VSs) identified by Schwatke et al. [32]. Notably, variability in water elevations surpasses absolute variations observed in Iraqi rivers (Figure 4).

In a recent study, Scherer et al. [46] reanalyzed altimetric water elevations from the DAHITI data center and introduced a novel approach to discharge prediction by integrating remote sensing imagery with satellite altimetry. Their analysis of 20 VSs along the Lower Mississippi River, including a Sentinel-3A VS, demonstrated DAHITI's high accuracy, yielding an RMSE of just 14 cm (Table 5). However, it is important to note that the Mississippi River is one of the largest rivers globally, significantly wider than those in Iraq. Additionally, their study found no correlation between a river width of 200 m and the data used to assess water elevation accuracy (Table 3 and Figure 4).

Our findings align with those of Jiang et al. [16] and Santos da Silva et al. [47], confirming that river width does not influence the accuracy of altimetry-derived surface water heights. Notably, researchers tracking water levels along the Brahmaputra River employed a different approach using retracted Jason-2/3 and Envisat altimetric data. Despite analyzing river segments ranging from 200 to 1000 m in width, they concluded that their methodology is suitable for rivers as narrow as 300 m. An interesting observation is that the presence of tributaries between studied stations does not appear to negatively impact concordance between in situ and VS data.

However, previous studies by Kittel et al. [15] and Biancamaria et al. [48] suggest that major tributaries can complicate comparisons between adjacent stations (Table 5). The low agreement between water heights recorded at the Al-Hamza gauge station and its neighboring VS may be attributed to sandbars along the river stretch (Table 3). This is consistent with the findings of Maillard et al. [43], which indicate that sandbars significantly affect water level estimations in virtual locations. Additionally, while hydraulic structures may hinder hydrograph comparisons, they do not directly affect altimetric measurements [48]. River channel morphology also plays a crucial role in reconstructing water levels within regulated channels. Along the Euphrates River, the presence of extensive sandbar accumulations poses further challenges. Virtual stations with Nash-Sutcliffe efficiency (NSE) values below 0.59 cm (Table 3) were often located in areas with complex river morphology and unfavorable geographic conditions. These findings support the conclusions of Maillard et al. [43], which highlight the influence of sandbars, parallel river channels, and multiple satellite track crossings on altimetric measurement accuracy.

6. Conclusions

The launch of Sentinel-3A and 3B marked significant progress in satellite altimetry, introducing the first open-loop global mission equipped with a synthetic aperture radar altimeter (SARAL). This study assessed the advantages of the Kalman filter by analyzing water levels obtained from two key altimetry databases: DAHITI and Hydroweb.

Altimetry data from four virtual stations along the Euphrates Basin in Iraq were retrieved from the DAHITI database, covering a study area with an average river width ranging from 40 to 200 meters. The dataset spans February 2019 to January 2020. The key findings are as follows:

- The RMSE (Root Mean Square Error) for DAHITI-derived altimetry-based water levels ranges from 0.29 to 0.39 meters.
- Hydroweb altimetry-based surface level measurements for multiple missions yield an RMSE between 0.70 and 0.90 meters.
- The mean Nash-Sutcliffe Efficiency (NSE) for DAHITI-derived water level reconstruction along the Euphrates River is 0.78, with a range of 0.59 to 0.98.
- The NSE for HydroWeb's multi-mission water level reconstruction along the Euphrates River falls within the same range (0.59–0.98).
- No significant correlation exists between river width and water level measurements from Sentinel-3A, RMSE precision, or NSE proficiency.
- Land cover does not significantly influence NSE values or RMSE precision in altimetry-based water level reconstructions.
- Altimeter measurement accuracy is primarily affected by complex topography and unfavorable geographic conditions, including inter-channel sandbars and other morphological features.

This study validated the accuracy of DAHITI-derived data by comparing it with data from other missions and databases. The results demonstrate that DAHITI's enhanced outlier rejection and Kalman filtering techniques, particularly when applied to Sentinel satellite data, contribute to improved accuracy. The validation of DAHITI's water level time series for the Euphrates River showed substantial improvements over in situ data and Hydroweb-derived time series. The findings underscore the potential of the Kalman filter for real-time applications, particularly when integrated with dynamic modelling.

7. Declarations

7.1. Author Contributions

Conceptualization, A.W.B.R. and M.A.; methodology, M.A.; software, M.A.; validation, A.W.B.R. and M.A.; formal analysis, M.A.; investigation, A.W.B.R. and M.A.; resources, M.A.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, A.W.B.R. and M.A.; visualization, M.A.; supervision, A.W.B.R., M.I.H., and M.H.B.H.; project administration, A.W.B.R.; funding acquisition, M.A. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding and Acknowledgments

The authors would like to express their sincere gratitude to the Faculty of Built Environment and Surveying (FABU), Universiti Teknologi Malaysia (UTM), for their invaluable assistance, particularly in providing technical support and facilitating data collection for this study. The authors also gratefully acknowledge the financial support from Universiti Teknologi Malaysia through the UTM Contract MG Grant R.JI30000.7652.4C773 and the UTM Matching Grant Q.J130000.3052.04M83.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Boergens, E., Nielsen, K., Andersen, O. B., Dettmering, D., & Seitz, F. (2017). River levels derived with CryoSat-2 SAR data classification - A case study in the Mekong River Basin. Remote Sensing, 9(12), 1238. doi:10.3390/rs9121238.

[2] Böhm, J., Werl, B., & Schuh, H. (2006). Troposphere mapping functions for GPS and VLBI from ECMWF operational analysis data. Journal of Geophysical Research, 111(B2), B02406. doi:10.1029/2005JB003629.

[3] Michailovsky, C. I., McEnnis, S., & Bauer-Gottwein, P. (2012). River monitoring from space: Monitoring the Niger River using radar altimetry. Hydrology and Earth System Sciences, 16(8), 3139–3148. doi:10.5194/hess-16-3139-2012.

[4] Berry, P. A. M., Garlick, J. D., Freeman, J. A., & Mathers, E. L. (2005). Global inland water monitoring from multi-mission altimetry. Geophysical Research Letters, 32(16), 1–4. doi:10.1029/2005GL022814.

[5] Dawson, G., Landy, J., Tsamados, M., Komarov, A. S., Howell, S., Heorton, H., & Krumpen, T. (2022). A 10-year record of Arctic summer sea ice freeboard from CryoSat-2. Remote Sensing of Environment, 268. doi:10.1016/j.rse.2021.112744.

[6] Nilsson, B., Andersen, O. B., Ranndal, H., & Rasmussen, M. L. (2022). Consolidating ICESat-2 Ocean Wave Characteristics with CryoSat-2 during the CRYO2ICE Campaign. Remote Sensing, 14(6), 1300. doi:10.3390/rs14061300.

[7] Heorton, H., Tsamados, M., Armitage, T., Ridout, A., & Landy, J. (2021). Cryosat-2 significant wave height in polar oceans derived using a semi-analytical model of synthetic aperture radar 2011-2019. Remote Sensing, 13(20), 4166. doi:10.3390/rs13204166.

[8] Lian, T., Xin, X., Peng, Z., Li, F., Zhang, H., Yu, S., & Liu, H. (2022). Estimating Evapotranspiration over Heterogeneous Surface with Sentinel-2 and Sentinel-3 Data: A Case Study in Heihe River Basin. Remote Sensing, 14(6), 1349. doi:10.3390/rs14061349.

[9] Shen, M., Duan, H., Cao, Z., Xue, K., Qi, T., Ma, J., Liu, D., Song, K., Huang, C., & Song, X. (2020). Sentinel-3 OLCI observations of water clarity in large lakes in eastern China: Implications for SDG 6.3.2 evaluation. Remote Sensing of Environment, 247, 111950. doi:10.1016/j.rse.2020.111950.

[10] Wan, Y., Zhang, R., Pan, X., Fan, C., & Dai, Y. (2020). Evaluation of the significant wave height data quality for the sentinel-3 synthetic aperture radar altimeter. Remote Sensing, 12(18), 3107. doi:10.3390/RS12183107.

[11] Morris, A., Moholdt, G., Gray, L., Schuler, T. V., & Eiken, T. (2022). CryoSat-2 interferometric mode calibration and validation: A case study from the Austfonna ice cap, Svalbard. Remote Sensing of Environment, 269, 112805. doi:10.1016/j.rse.2021.112805.

[12] McCarthy, D. D., & Petit, G. (2004). IERS Conventions (2003) (IERS Technical Note No. 32). International Earth Rotation and Reference Systems Service. Available online https://iers-conventions.obspm.fr/archive/2003/tn32.pdf (accessed on May 2025).

[13] Bosch, W., Dettmering, D., & Schwatke, C. (2014). Multi-mission cross-calibration of satellite altimeters: Constructing a long-term data record for global and regional sea level change studies. Remote Sensing, 6(3), 2255-2281. doi:10.3390/rs6032255.

[14] Li, P., Li, H., Chen, F., & Cai, X. (2020). Monitoring long-term lake level variations in middle and lower Yangtze basin over 2002-2017 through integration of multiple satellite altimetry datasets. Remote Sensing, 12(9), 1448. doi:10.3390/RS12091448.

[15] Kittel, C. M. M., Jiang, L., Tøttrup, C., & Bauer-Gottwein, P. (2021). Sentinel-3 radar altimetry for river monitoring – a catchment-scale evaluation of satellite water surface elevation from Sentinel-3A and Sentinel-3B. Hydrology and Earth System Sciences, 25(1), 333–357. doi:10.5194/hess-25-333-2021.

[16] Jiang, L., Nielsen, K., Dinardo, S., Andersen, O. B., & Bauer-Gottwein, P. (2020). Evaluation of Sentinel-3 SRAL SAR altimetry over Chinese rivers. Remote Sensing of Environment, 237, 111546. doi:10.1016/j.rse.2019.111546.

[17] Biancamaria, S., Schaedele, T., Blumstein, D., Frappart, F., Boy, F., Desjonquères, J. D., Pottier, C., Blarel, F., & Niño, F. (2018). Validation of Jason-3 tracking modes over French rivers. Remote Sensing of Environment, 209, 77–89. doi:10.1016/j.rse.2018.02.037.

[18] Förste, C., Bruinsma, S., Shako, R., Marty, J. C., Lemoine, J. M., Flechtner, F., ... & Balmino, G. (2014). EIGEN-6C3stat: A high-resolution global gravity field model including GOCE data. GFZ Data Services, Potsdam, Germany.

[19] Le Gac, S., Boy, F., Blumstein, D., Lasson, L., & Picot, N. (2021). Benefits of the Open-Loop Tracking Command (OLTC): Extending conventional nadir altimetry to inland waters monitoring. Advances in Space Research, 68(2), 843–852. doi:10.1016/j.asr.2019.10.031.

[20] Steunou, N., Picot, N., Sengenes, P., Noubel, J., & Frery, M. L. (2015). AltiKa Radiometer: Instrument Description and In–Flight Performance. Marine Geodesy, 38(sup1), 43–61. doi:10.1080/01490419.2015.1006381.

[21] Zhang, X., Jiang, L., Kittel, C. M. M., Yao, Z., Nielsen, K., Liu, Z., Wang, R., Liu, J., Andersen, O. B., & Bauer-Gottwein, P. (2020). On the Performance of Sentinel-3 Altimetry Over New Reservoirs: Approaches to Determine Onboard A Priori Elevation. Geophysical Research Letters, 47(17), 2020 088770. doi:10.1029/2020GL088770.

[22] Scharroo, R., & Smith, W. H. (2010). A global positioning system–based climatology for the total electron content in the ionosphere. Journal of Geophysical Research: Space Physics, 115(A10). doi:10.1029/2009JA014719.

[23] Revel, M., Zhou, X., Modi, P., Crétaux, J.-F., Calmant, S., & Yamazaki, D. (2024). AltiMaP: Altimetry mapping procedure for hydrography data. Earth System Science Data, 16(1), 75–88. doi:10.5194/essd-16-75-2024.

[24] Halicki, M., & Niedzielski, T. (2022). The accuracy of the Sentinel-3A altimetry over Polish rivers. Journal of Hydrology, 606, 127355. doi:10.1016/j.jhydrol.2021.127355.

[25] Jiang, L., Zhao, Y., Nielsen, K., Andersen, O. B., & Bauer-Gottwein, P. (2023). Near real-time altimetry for river monitoring—a global assessment of Sentinel-3. Environmental Research Letters, 18(6), 064022. doi:10.1088/1748-9326/acdd16.

[26] Fernandes, M. J., Lázaro, C., Nunes, A. L., & Scharroo, R. (2014). Atmospheric corrections for altimetry studies over inland water. Remote Sensing, 6(6), 4952–4997. doi:10.3390/rs6064952.

[27] Jiang, L., Nielsen, K., Andersen, O. B., & Bauer-Gottwein, P. (2017). CryoSat-2 radar altimetry for monitoring freshwater resources of China. Remote Sensing of Environment, 200, 125–139. doi:10.1016/j.rse.2017.08.015.

[28] Kalman, R. E. (1960). A New Approach to Linear Filtering and Prediction Problems. Journal of Basic Engineering, 82(1), 35–45. doi:10.1115/1.3662552.

[29] Yang, Y., & Gao, W. (2006). An Optimal Adaptive Kalman Filter. Journal of Geodesy, 80(4), 177–183. doi:10.1007/s00190-006-0041-0.

[30] Eicker, A., Schumacher, M., Kusche, J., Döll, P., & Schmied, H. M. (2014). Calibration/Data Assimilation Approach for Integrating GRACE Data into the WaterGAP Global Hydrology Model (WGHM) Using an Ensemble Kalman Filter: First Results. Surveys in Geophysics, 35(6), 1285–1309. doi:10.1007/s10712-014-9309-8.

[31] Gruber, C., Moon, Y., Flechtner, F., Dahle, C., Novák, P., König, R., & Neumayer, H. (2014). Submonthly GRACE Solutions from Localizing Integral Equations and Kalman Filtering. In: Rizos, C., Willis, P. (eds) Earth on the Edge: Science for a Sustainable Planet. International Association of Geodesy Symposia, vol 139. Springer, Berlin, Germany. doi:10.1007/978-3-642-37222-3_51.

[32] Schwatke, C., Dettmering, D., Börgens, E., & Bosch, W. (2015). Potential of SARAL/AltiKa for Inland Water Applications. Marine Geodesy, 38(SUP1), 626–643. doi:10.1080/01490419.2015.1008710.

[33] Tourian, M. J., Saemian, P., Ferreira, V. G., Sneeuw, N., Frappart, F., & Papa, F. (2023). A copula-supported Bayesian framework for spatial downscaling of GRACE-derived terrestrial water storage flux. Remote Sensing of Environment, 295, 113685. doi:10.1016/j.rse.2023.113685.

[34] Wang, Y., Li, C., Cui, Y., Cui, Y., Xu, Y., Hora, T., ... & Long, D. (2024). Spatial downscaling of GRACE-derived groundwater storage changes across diverse climates and human interventions with Random Forests. Journal of Hydrology, 640, 131708. doi:10.1016/j.jhydrol.2024.131708.

[35] Low, W. Y., Aziz, M. J. A., Idris, N. R. N., & Rai, N. A. (2023). Robust battery state-of-charge estimation with improved convergence rate based on applying Busse's adaptive rule to extended Kalman filters. Journal of Power Electronics, 23(10), 1529–1541. doi:10.1007/s43236-023-00652-w.

[36] Sulistioadi, Y. B., Tseng, K. H., Shum, C. K., Hidayat, H., Sumaryono, M., Suhardiman, A., Setiawan, F., & Sunarso, S. (2015). Satellite radar altimetry for monitoring small rivers and lakes in Indonesia. Hydrology and Earth System Sciences, 19(1), 341–359. doi:10.5194/hess-19-341-2015.

[37] Machefer, M., Perpinyà-Vallès, M., Escorihuela, M. J., Gustafsson, D., & Romero, L. (2022). Challenges and Evolution of Water Level Monitoring towards a Comprehensive, World-Scale Coverage with Remote Sensing. Remote Sensing, 14(15), 3513. doi:10.3390/rs14153513.

[38] Tourian, M. J., Elmi, O., Chen, Q., & Sneeuw, N. (2021). Global monitoring of inland water dynamics using satellite altimetry and hydrological modeling. Remote Sensing of Environment, 264, 112582. doi:10.1016/j.rse.2021.112582.

[39] Zaidi, A. Z., Vignudelli, S., Khero, Z., Ghauri, B. M. K., Muzaffer, R., Naeem, B., Panhwar, V., Zafar, S., & ul Haque, S. (2021). Indus river water level monitoring using satellite radar altimetry. Advances in Space Research, 68(2), 641–651. doi:10.1016/j.asr.2020.03.044.

[40] Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models Part I-A discussion of principles. Journal of Hydrology, 10(10), 282–290. doi:10.1016/0022-.

[41] Bogning, S., Frappart, F., Blarel, F., Niño, F., Mahé, G., Bricquet, J. P., Seyler, F., Onguéné, R., Etamé, J., Paiz, M. C., & Braun, J. J. (2018). Monitoring water levels and discharges using radar altimetry in an ungauged river basin: The case of the Ogooué. Remote Sensing, 10(2), 350. doi:10.3390/rs10020350.

[42] Biancamaria, S., Frappart, F., Leleu, A. S., Marieu, V., Blumstein, D., Desjonquères, J. D., Boy, F., Sottolichio, A., & Valle-Levinson, A. (2017). Satellite radar altimetry water elevations performance over a 200 m wide river: Evaluation over the Garonne River. Advances in Space Research, 59(1), 128–146. doi:10.1016/j.asr.2016.10.008.

[43] Maillard, P., Bercher, N., & Calmant, S. (2015). New processing approaches on the retrieval of water levels in Envisat and SARAL radar altimetry over rivers: A case study of the São Francisco River, Brazil. Remote Sensing of Environment, 156, 226–241. doi:10.1016/j.rse.2014.09.027.

[44] Normandin, C., Frappart, F., Diepkilé, A. T., Marieu, V., Mougin, E., Blarel, F., Lubac, B., Braquet, N., & Ba, A. (2018). Evolution of the performances of radar altimetry missions from ERS-2 to Sentinel-3A over the Inner Niger Delta. Remote Sensing, 10(6), 833. doi:10.3390/rs10060833.

[45] Rai, A. K., Beg, Z., Singh, A., & Gaurav, K. (2021). Estimating discharge of the Ganga River from satellite altimeter data. Journal of Hydrology, 603, 126860. doi:10.1016/j.jhydrol.2021.126860.

[46] Scherer, D., Schwatke, C., Dettmering, D., & Seitz, F. (2020). Long-term discharge estimation for the lower Mississippi river using satellite altimetry and remote sensing images. Remote Sensing, 12(17), 2693. doi:10.3390/RS12172693.

[47] Santos da Silva, J., Calmant, S., Seyler, F., Rotunno Filho, O. C., Cochonneau, G., & Mansur, W. J. (2010). Water levels in the Amazon basin derived from the ERS 2 and ENVISAT radar altimetry missions. Remote Sensing of Environment, 114(10), 2160–2181. doi:10.1016/j.rse.2010.04.020.

[48] Biancamaria, S., Lettenmaier, D.P., & Pavelsky, T.M. (2016). The SWOT Mission and Its Capabilities for Land Hydrology. Remote Sensing and Water Resources. Space Sciences Series of ISSI, Volume 55, Springer, Cham, Switzerland. doi:10.1007/978-3-319-32449-4_6.