A Feasibility Assessment on Monitoring Ungauged Mekong River Tributaries Using SWOT Satellite Data

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Key words: SWOT, flooding, river levels, UNSDG, remote sensing

SUMMARY

Accurate water level monitoring of the Mekong River is essential for managing hydrological extremes, yet the current in-situ gauge network leaves vast stretches of the basin unmonitored, creating significant gaps in regional flood forecasting. This observational gap creates uncertainty that directly impacts the region's ability to meet the United Nations Sustainable Development Goals (UNSDGs), particularly SDG 6 (Clean Water) and SDG 13 (Climate Action). This study investigates the feasibility of using the Surface Water and Ocean Topography (SWOT) satellite mission as a supplemental tool to densify the monitoring network across 12 ungauged tributaries (ranging from ~15–600 m in width). Dedicated site investigations at key locations, namely, Chiang Saen and Khong Chiam, identified the challenging ground conditions, such as exposed bedrock, dense vegetation, and remote access that hinder conventional gauge installations and measurements. Consequently, a satellite-based methodology was developed using SWOT Level-2 River Single-Pass Vector Node data. The workflow incorporates a Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm for outlier removal and a slope correction technique to derive water surface elevation (wse) values. Comparisons with four mainstream in-situ stations reveal SWOT wse differences on the order of approximately 28-38 cm root mean square error (RMSE). Using the developed methodology, SWOT-based wse values were achievable for all tributaries wider than 30 m. Furthermore, diverse flow regimes, from synchronous seasonal pulses of large tributaries to independent flash floods in smaller channels and regulated flows driven by upstream dams, were observed. Overall, these findings demonstrate that SWOT can effectively complement sparse in-situ gauge networks, providing a scalable solution for transboundary water monitoring and climate resilience planning.

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1. INTRODUCTION

The Mekong River Basin is subject to severe hydrological variability, oscillating between extreme flood events and prolonged droughts. Effective water resources management requires a comprehensive understanding of the basin's total discharge. However, current monitoring infrastructure is primarily situated along the main river channel with sparse monitoring of tributaries. Existing in-situ instrumentation is generally limited to one gauge in the upstream headwaters and one near the confluence or dam site. This leaves vast stretches of the river unmonitored, masking critical hydrological processes such as local runoff, backwater effects from the mainstream, and flow travel times between the upper and lower catchments (Biancamaria et al., 2016a). The resulting data gaps create significant uncertainty for flood forecasting and water management, directly impacting the region's ability to meet the United Nations Sustainable Development Goals (UNSDGs), specifically SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). Addressing these observational gaps in the Mekong River Basin is critical for achieving specific targets which include integrated water resources management and consistent monitoring of transboundary basins. Importantly, fostering cooperation along the Mekong River is essential, particularly in regions where data sharing between upstream and downstream communities remains a challenge. The ability to detect independent flood pulses in unmonitored Mekong tributaries would directly enhance the regional capacity to reduce disaster risks and protect vulnerable communities. Field site investigations conducted for this study at Chiang Saen and Khong Chiam revealed the practical challenges on the ground contributing to limited in-situ instrumentation. The distance between reliable telemetry stations can be vast; for example, the gap between Khong Chiam and the nearest station at Mukdahan is 161 km. Many remote tributaries exhibit shifting riverbeds and dense vegetation, which can obstruct in-situ infrastructure and pose challenges for access and maintenance. Satellite radar altimetry missions such as Jason-2/3, Sentinel-3, and CryoSat-2 have been used for water level monitoring in large inland water bodies (Boergens et al., 2017; Tourian et al., 2017) and provided long-term water level records for major lakes and wide rivers (>1 km in width). However, application to smaller tributaries (characterized by < 200 m in width) is often limited by larger footprints of the radar pulse, which suffer from land contamination when observing narrow channels (Birkett, 1998; CNES et al., 2020; ESA, 2019; Scharroo, 2020). The Surface Water and Ocean Topography (SWOT) mission utilizes Ka-band radar interferometry to provide high-resolution 2D observations of water surface elevation (wse), width, and slope, specifically targeting river channels wider than 100 m (Biancamaria et al., 2016b; Jet Propulsion Laboratory, 2024). The overall objective of this study is to assess the feasibility of using SWOT data to monitor water levels in sparsely gauged tributaries of the Mekong Basin.

2. DESCRIPTION OF THE STUDY AREA

This study focuses on four primary gauge stations in the Mekong Basin spatially distributed approximately every 300 km, namely: Chiang Saen, Chiang Khan, Nakhon Phanom, and Khong Chiam (Figure 1). 12 tributaries are grouped into sub-areas corresponding to their nearest mainstream gauge station, shown in Figure 1 (right) with a closer look provided in Figure 2, where the Chiang Saen area includes Ruak, Ing, and Kok rivers; the Chiang Khan area includes Loei and Hueang rivers; the Nakhon Phanom area includes Kam, Xe Bangfai, Hinboun, and Songkhram rivers; and the Khong Chiam area includes Xe Dong, Mun, and Ban Xenoun rivers. These tributaries vary significantly in morphology and channel geometry, ranging from narrow, steep mountainous channels (widths of 15–40 m, e.g., Loei, Ruak) to wider, floodplain-dominated reaches (widths > 100 m, e.g., Mun, Songkhram) (Mekong River Commission, 2024). Table 1 provides a summary of the tributaries detailing their associated mainstream gauge station (the nearest station and distance) and relative location (upstream/downstream).

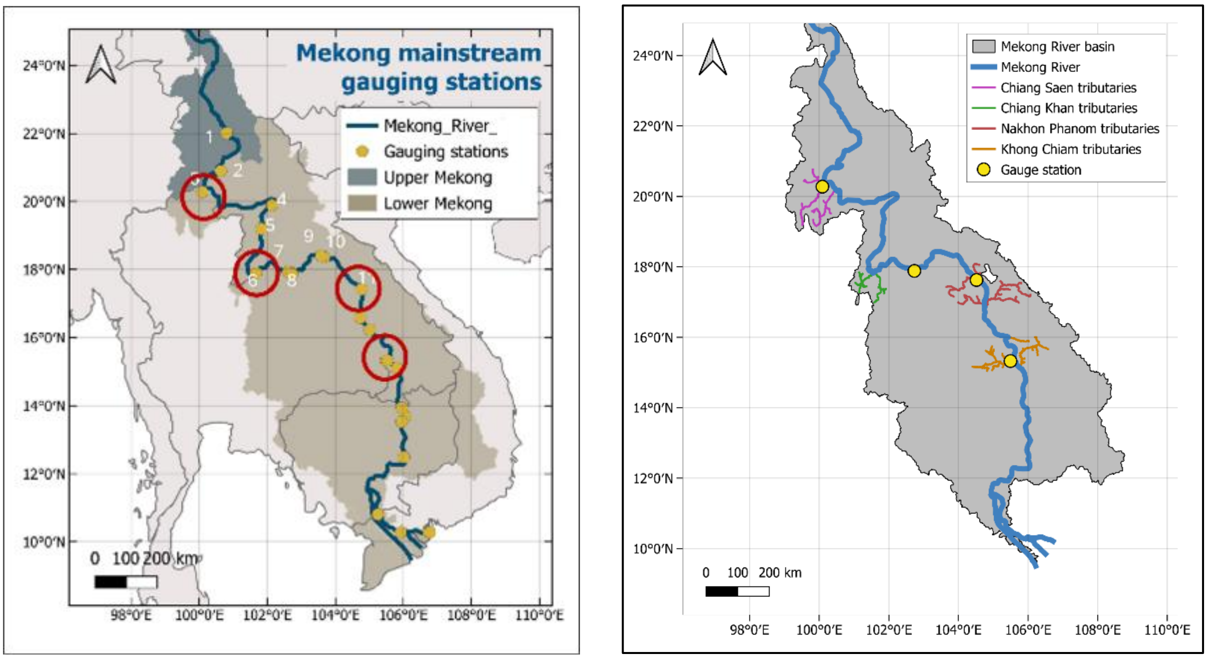

Figure 1: Map illustrating the extent of the Mekong River Basin and the locations of 22 gauge stations (yellow) along the mainstream. Red circled areas represent the four sub-areas of interest (left). Spatial distribution of the tributaries examined in this study (right).

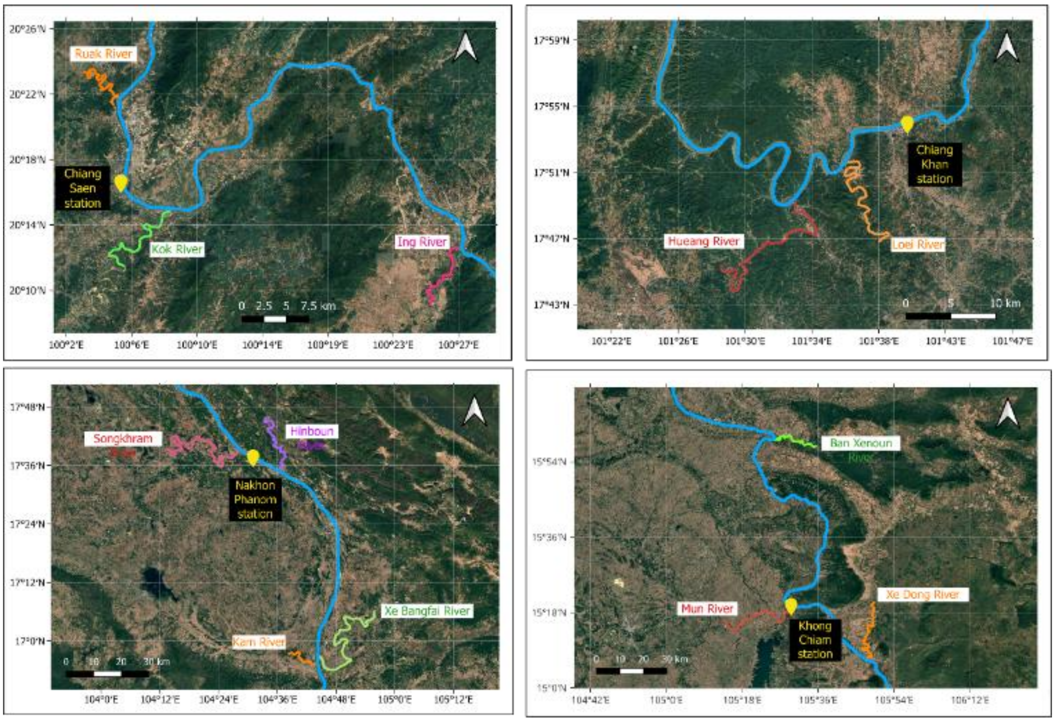

Figure 2: Maps of tributaries corresponding to mainstream gauge stations: Chiang Saen (top-left), Chiang Khan (top-right), Nakhon Phanom (bottom-left), and Khong Chiam (bottom-right)

Table 1: Summary of the 12 selected tributaries ordered from upstream to downstream

Tributary	Width (m)	Associated main station and Distance (km)	Relative location
Ruak	30-60	Chiang Saen (10)	Upstream
Kok	60-250	Chiang Saen (6)	Downstream
Ing	30-60	Chiang Saen (65)	Downstream
Loei	15-30	Chiang Khan (20)	Upstream
Heuang	30-60	Chiang Khan (9)	Upstream
Songkhram	80-120	Nakhon Phanom (9)	Upstream
Hinboun	40-60	Nakhon Phanom (10)	Downstream
Xe Bangfai	140-160	Nakhon Phanom (90)	Downstream (east)
Kam	110-120	Nakhon Phanom (90)	Downstream (west)
Xe Dong	100-120	Khong Chiam (100)	Upstream
Mun	330-600	Khong Chiam (4)	Downstream
Ban Xenoun	30-100	Khong Chiam (40)	Downstream

3. SITE INVESTIGATIONS

Effective monitoring of the Mekong River water levels relies on a combination of established in-situ networks and supplementary site assessments. This section details the current gauge infrastructure and presents insights from two dedicated site investigations conducted in December of 2023 and 2025, that highlighted operational challenges in ungauged regions.

3.1 Current In-Situ Water Level Monitoring

The primary source of hydrological data for the basin is the network managed by the Mekong River Commission (MRC) (MRC, 2024). In-situ water level data were obtained from the MRC, consisting of manual gauge stations and 15-minute interval recordings collected via automated telemetry stations (Figure 3) available from 2008 to present. To facilitate direct comparison with SWOT satellite observations, this study utilizes data from 2023 onwards, aligning with the operational timeline of the SWOT mission. A critical data processing component involved standardizing the vertical reference system. Original MRC records are provided as water levels relative to a station-specific "zero gauge." These were converted to orthometric heights (referenced to the Thai national datum, Kolak-1915) by adding the zero-gauge elevation provided in the station metadata. To ensure consistency with SWOT products, the gauge data were transformed to EGM2008 by applying a vertical offset of 0.86 m, derived from regional geoid separation analysis (Dumrongchai & Duangdee, 2019).

Figure 3: In-situ monitoring infrastructure at Khong Chiam and Chiang Saen documented during the site investigations. Khong Chiam (December 18, 2023): (A) Traditional manual staff gauge requiring visual inspection; (B) Automated telemetry station. Chiang Saen (December 19, 2025): (C) Traditional manual staff gauge requiring visual inspection; (D) Automated telemetry station.

The seasonal fluctuation of the Mekong River is typically illustrated by the transition between the wet (May–October) and dry (November–April) seasons as shown in Figure 4. However, the in-situ gauge record exhibits intermittent data gaps resulting from instrument failure or maintenance (Gao et al., 2018). Gap filling methods may be used (see eg., Ekeu-wei et al., 2018), however in this study, gaps were excluded and the validation process relied solely on the observed data.

3.2 Site Challenges

To understand the practical limitations of expanding the existing in-situ gauge network, site investigations were conducted in the Khong Chiam district, Ubon Ratchathani Province, Thailand, on December 18, 2023, and the Chiang Saen district, Chiang Rai Province, Thailand, on December 19, 2025 (locations shown in Figure 5). A geospatial information system (GIS) enabled approach was used to document river conditions along a 7.8 km transect at Khong Chiam (137 geotagged photographs) and a 9.7 km transect at Chiang Saen (81 geotagged photographs) (Wiboonwipa & Fotopoulos, 2024). The geotagged imagery documented fluctuating riverbanks characterized by dense vegetation (shown in Figure 6) and exposed bedrock. Furthermore, thick cloud cover prevalent during the wet season may inhibit some satellite measurements (Neumann et al., 2023). An analysis of Sentinel-5P data availability indicates that thick cloud cover exceeding 70% occurs on average 56 days per year in the Mekong Basin area. These obstructed days are concentrated during the peak monsoon months, creating significant data gaps when water level monitoring is critical. Dense vegetation along the riverbanks may absorb/scatter satellite observations resulting in substantial observational data gaps (Neuenschwander et al., 2020). Additional challenges are incurred from satellite observations with large footprints that exceed the width of narrow tributaries.

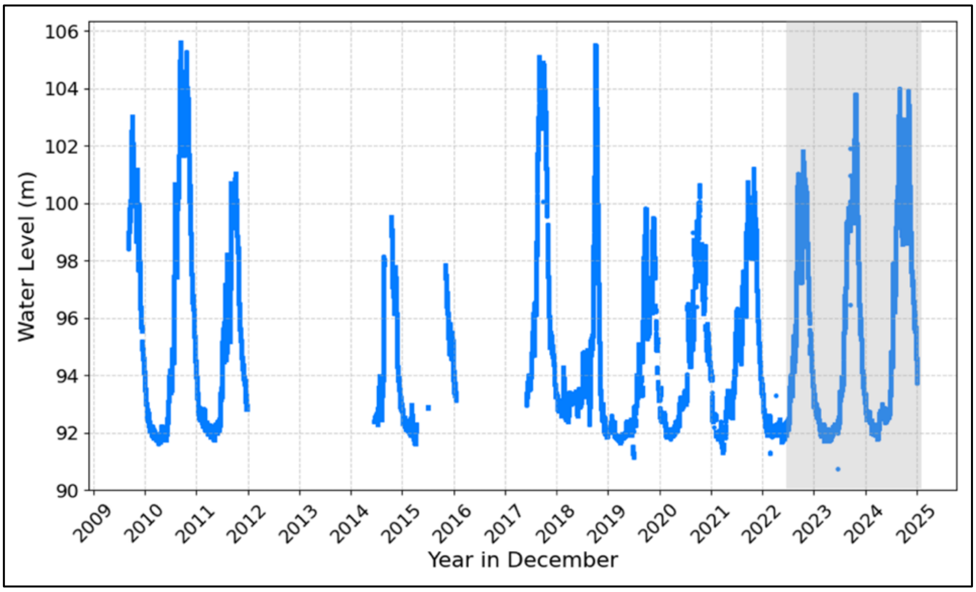

Figure 4: Seasonal variation of water level at Khong Chiam station (2008-2025 from in-situ telemetry station data provided by the Mekong River Commission (MRC). The shaded region indicates the temporal extent of the data analyzed in this study (2023 onwards).

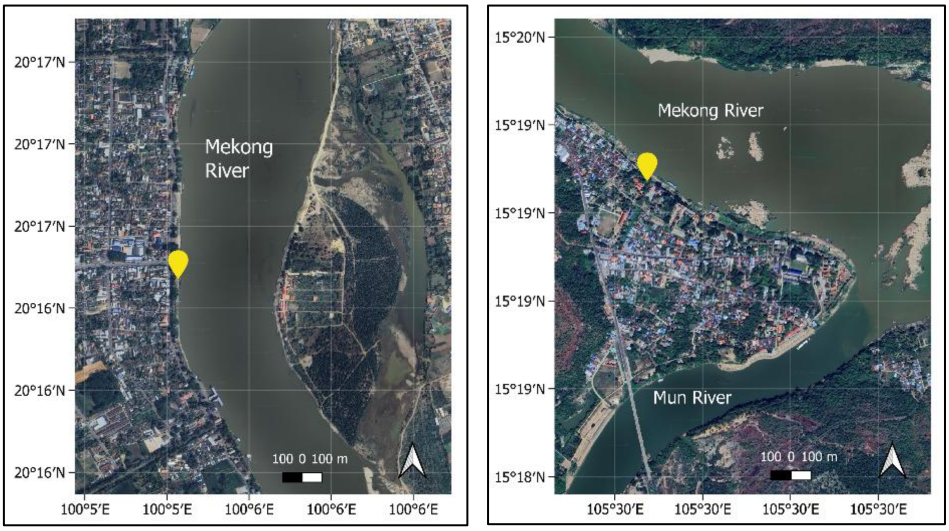

Figure 5: Maps showing the location of the Chiang Saen mainstream gauge station (left) and the Khong Chiam station (right)

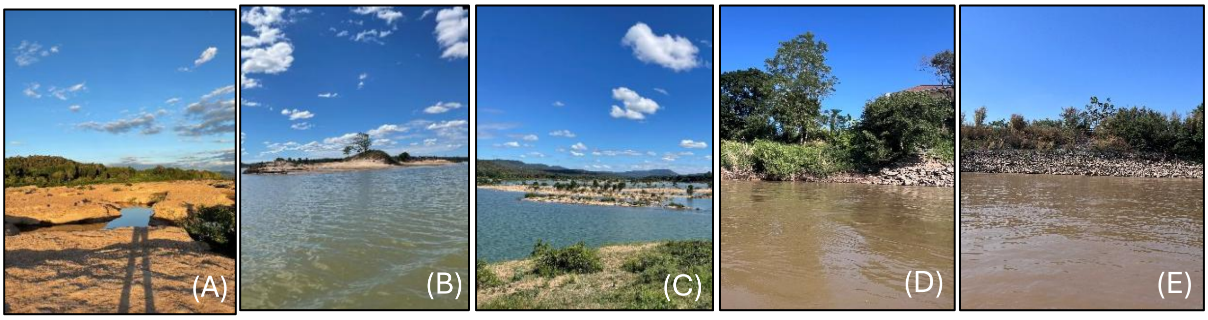

Figure 6: Photographs from the site investigation at Khong Chiam (December 2023) and Chiang Saen (December 2025) illustrating environmental site challenges. Khong Chiam: (A) Exposed riverbed and vegetation. (B) and (C) Exposed bedrock in the middle of the river. Chiang Saen: (D) and (E) Vegetated riverbanks

4. DESCRIPTION OF DATA AND METHODOLOGY

In response to observational limitations along tributaries, SWOT mission data was employed to determine if gaps could be filled using the available measurements. SWOT utilizes a Ka-band Radar Interferometer (KaRIn) to acquire wide-swath measurements (two 50-km swaths separated by a 20-km gap), generating 2D water surface elevation grids with a 50 m × 50 m resolution (Fu et al., 2012). This study utilizes the Level-2 River Single-Pass Vector (L2_HR_RiverSP) Node product, which aggregates hydraulic parameters—including wse, width, and slope (referenced to EGM2008) into vector nodes spaced at approximately 250 m intervals along the river centerline (Altenau et al., 2021). While the nominal revisit cycle is 21 days, overlapping swaths in the study area increase temporal sampling by up to 13–17 days. The diverse range of channel widths of the Mekong provide an ideal test bed for assessing the KaRIn instrument's observational limits. The accuracy of KaRIn is dependent on the signal-to-noise ratio, which degrades as channel width decreases. Narrow channels approach the SWOT measurement grid size, making them prone to terrain layover, where the return signal is a mixture of water specular reflection and surrounding terrain scattering (Frasson et al., 2017). By validating retrievals across varying widths—from the broad mainstream to the narrow tributaries—the threshold where these land contamination effects render water level retrieval unreliable can be assessed (Biancamaria et al., 2016).

For the tributary analysis, a specific data extraction procedure was applied to ensure data quality and avoid signal contamination within the mixing zone between the mainstream and tributaries (Benda et al., 2004; Domeneghetti et al., 2021; Jiang et al., 2017). SWOT data points were explicitly selected from a river reach starting 3 km upstream from the confluence and extending for 2 km (i.e., capturing the reach from 3 to 5 km upstream) shown in Figure 7. This spatial selection ensures that the satellite observations capture the independent flow dynamics of the tributary rather than the mixing zone of the mainstream.

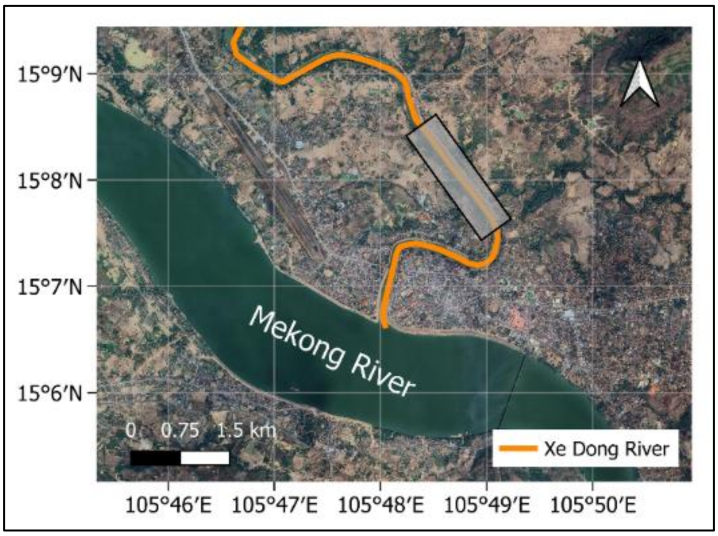

Figure 7: Illustration of the highlighted tributary reach defined for SWOT data extraction. The box indicates the specific 2-km river segment, located 3 km upstream from the confluence.

A three-stage processing workflow was developed which involved outlier detection using DBSCAN (Sawant, 2014), dynamic slope correction, and a statistical assessment comprising mainstream validation and tributary-mainstream correlation analysis. The clustering process is governed by two key parameters; namely how close data points must be to one another to be considered neighbors in the same cluster and the specified minimum number of points required to form a cluster. For this study, parameters were empirically optimized such that points within 0.2 m were assigned to the same cluster with a minimum specified number of points equal to 5. The tributaries exhibit a distinct water surface slope that varies with the hydrological regime (see Figure 8, minimum, maximum, mean and median elevations shown). This slope introduces a spatial gradient that must be accounted for when aggregating satellite measurements, as simple averaging combines elevation points that are systematically higher (upstream) and lower (downstream) than the reference location (Frasson et al., 2017). To address this, a dynamic slope-correction algorithm was implemented. This method defines a virtual station at the tributary confluence to monitor the outflow into the mainstream (Tourian et al., 2016). Using the spatially filtered observations described in Section 2.3, the instantaneous water surface slope for each SWOT overpass was computed via linear regression (Nielsen et al., 2022).

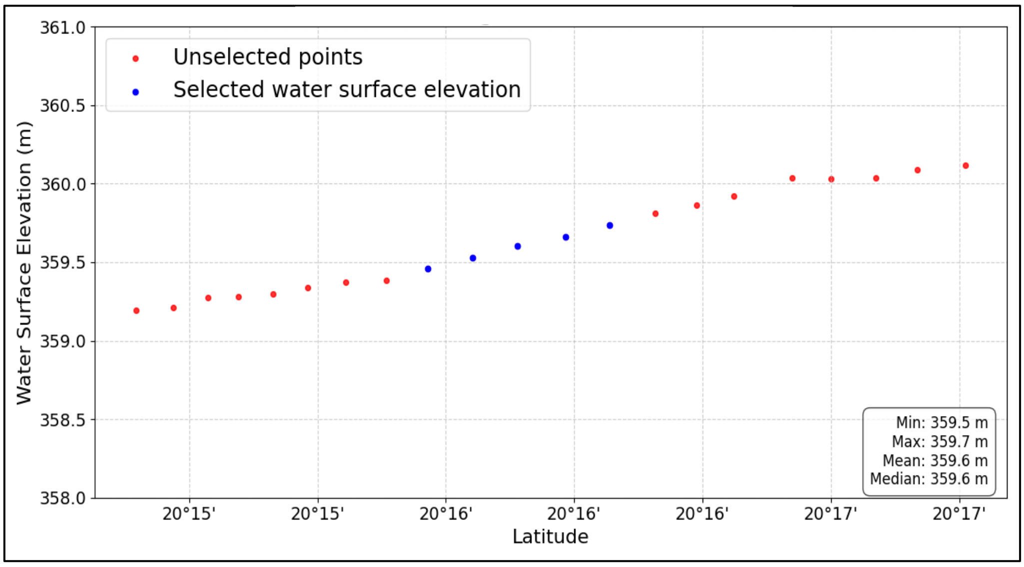

Figure 8: Longitudinal profile of SWOT Water Surface Elevation (wse) at the Chiang Saen reach on 26 November 2024, illustrating the consistent water surface slope. Blue dots represent the valid wse measurements selected after filtering. Red dots indicate unselected data points.

To accurately calculate the water surface slope, it is necessary to account for the actual flow direction of the river. Simple latitude/longitude grids can be misleading in complex channel geometries, especially where tributaries flow east-west rather than north-south. To mitigate geometric distortion in sinuous reaches where the flow paths have many curves and turns, the algorithm dynamically aligns the projection axis with the primary flow direction. This ensures that the slope is calculated correctly relative to the virtual station, consistent with the river centerline logic standardized in the SWOT River Database (SWORD). (Altenau et al., 2021). The upstream measurements are projected onto the virtual station datum using the derived slope as follows:

$$H_{vs} = H_{trib} - (S \times \Delta L) \tag{3}$$

Where H_{vs} is the water surface elevation at the virtual station, H_{trib} is the observed water surface elevation at the tributary, S is the calculated slope, and ΔL is the spatial offset from the virtual station. Since direct validation of the satellite-derived water levels was not possible, analysis was conducted in two distinct phases, namely (i) a mainstream validation performed at the four gauge stations to quantify the baseline accuracy of the proposed processing workflow, and (ii) a hydrologic connectivity assessment applied to the ungauged tributaries to evaluate flow synchronization (Betterle et al., 2019; Pavlin et al., 2021; Xingyuan et al., 2023). To verify the reliability of the proposed processing method (DBSCAN filtering and slope correction), the workflow was applied to the adjacent mainstream of the Mekong River at the

Chiang Saen, Chiang Khon, Nakhon Phanom, and Khong Chiam stations. The comparison with calibrated MRC gauges was performed using RMSE and the mean difference between the SWOT wse and in-situ water levels, to establish the baseline accuracy of SWOT measurements of water level. Hydrologic connectivity (quantified using Pearson's correlation coefficient, r) analysis was performed to assess the flow dynamics of the ungauged tributaries. See eq. (4):

$$r = \frac{\sum_{i=1}^{N}\left[\left(H_{trib,i} - \bar{H}_{trib}\right)\cdot\left(H_{main,i} - \bar{H}_{main}\right)\right]}{\left(\sqrt{\sum_{i=1}^{N}(H_{trib,i} - \bar{H}_{trib})^2}\right)\cdot\left(\sqrt{\sum_{i=1}^{N}(H_{main,i} - \bar{H}_{main})^2}\right)}, \quad (4)$$

Where N denotes the total number of concurrent observations shared between the two datasets, and i represents the index for each individual time step. The terms $H_{trib,i}$and $H_{main,i}$ refer to the specific water surface elevation measured at time i for the tributary and the mainstream station, respectively. $\bar{H}_{trib}$and $\bar{H}_{main}$ represent the arithmetic means calculated from the entire water level time series for the tributary and the mainstream, respectively. This metric evaluates the temporal synchronization between the tributary water levels (H_{trib}) and the SWOT-derived water levels at the nearest mainstream station (H_{main}). It is used to distinguish between tributaries that are temporally synchronous with the main stream (high correlation) and those exhibiting independent, asynchronous flow patterns (Kossieris et al., 2024).

5. RESULTS AND DISCUSSION

The workflow developed for this study demonstrated consistent agreement across the basin, with RMSE values between SWOT-derived wse and in-situ gauge water levels ranging from 0.28 m (Khong Chiam) to 0.38 m (Chiang Khan) and mean offsets ranging between -0.1 m and +0.3 m. The high data density (40 to 54 matched pairs per station) demonstrates the utility of SWOT data for extended monitoring at adjacent tributaries and the operational limits of SWOT for providing measurements of wse in narrow, vegetated channels. The analysis of the 12 tributaries (Figure 2) established a river width of 30 meters as the operational lower limit for reliable monitoring in this environment. Tributaries wider than 30 m, specifically the Ruak (30–60 m; Figure 9 right) and Ing (Figure 10 left), yielded consistent time series that captured seasonal pulses. Conversely, the Loei River (15–30 m; Figure 9 left) yielded only a single valid data point over two years, indicating that channels narrower than 30 m currently preclude reliable SWOT water level monitoring. This finding provides a critical guideline for surveyors and local authorities planning future satellite-based monitoring campaigns. The analysis of the Mun River revealed a strong negative correlation (r = -0.72) with the mainstream Mekong. While the Mekong followed the natural seasonal pulse, the Mun's water levels were inverted, directly reflecting the operation of the upstream Pak Mun Dam (Baird et al., 2020).

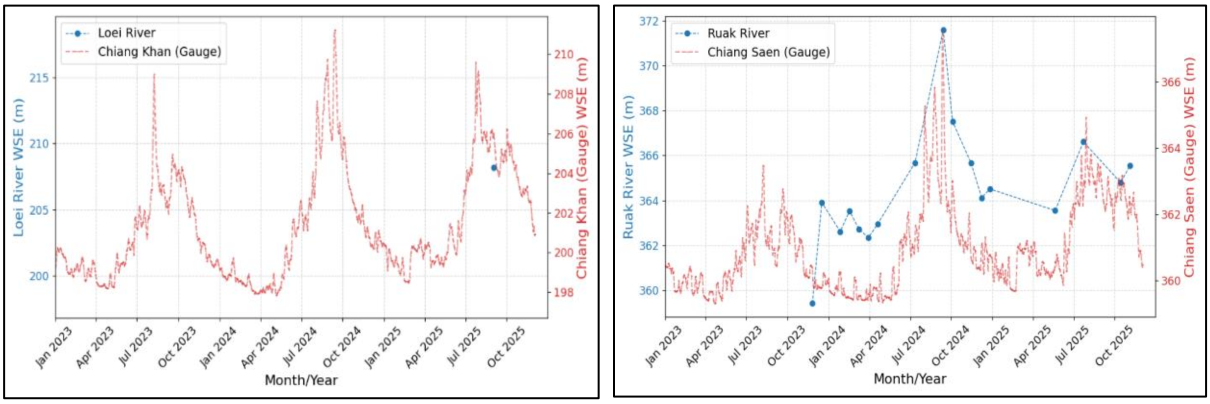

Figure 9: SWOT WSE time series demonstrating the feasibility limit. The narrow Loei River (15-30 m), where monitoring failed (left). The wider Ruak River (30-60 m), where seasonal trends were successfully captured (17 matched days), suggesting the >30 m feasibility threshold (right).

Smaller tributaries such as the Hueang and Ruak exhibited independent flow signals (r = 0.86) characterized by sharp, short duration rises that were not reflected in the mainstream gauge records. By capturing these asynchronous flood pulses, SWOT measurements can complement current monitoring efforts by providing additional data in critical regions. This capability directly supports UNSDG 13.1 (Strengthen Resilience to Climate-Related Hazards), enhancing the region's adaptive capacity providing information for local authorities to identify flood risks in specific communities that are currently blind spots in regional forecasting models.

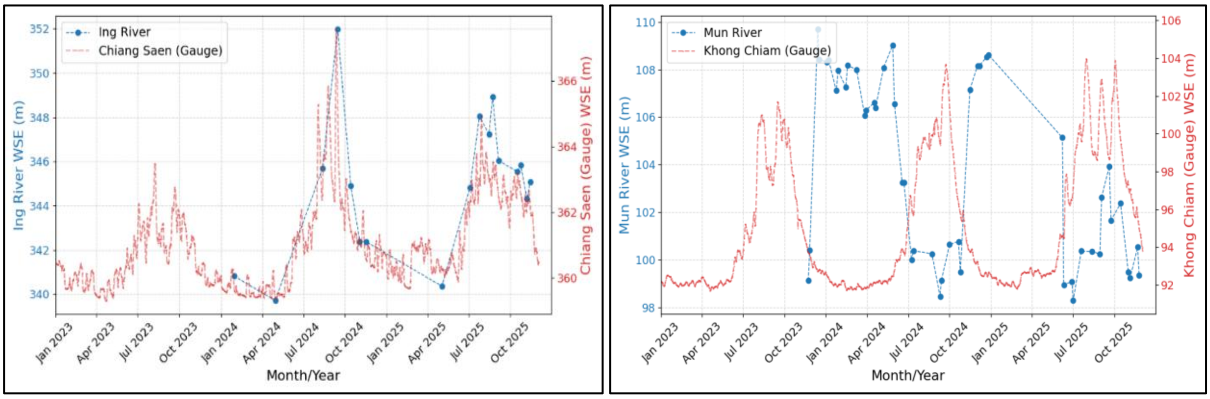

Figure 10: Evidence of independent flow behavior. Synchronous flow: The Ing River tracks the mainstream seasonal pulse (r = 0.99) (left). Asynchronous flow: The Mun River exhibits an inverted signal (r = -0.72), reflecting upstream dam operations invisible to the mainstream gauge network (right).

The ability to bridge these critical observational gaps directly advances the UNSDGs by ensuring that "no one is left behind," particularly in data-scarce regions. By providing an independent, transboundary source of hydrological data such as the operational status of the Pak Mun Dam, SWOT supports SDG 6.5 (Integrated Water Resources Management), fostering cooperation among riparian communities. Furthermore, the demonstrated capacity to detect rapid flood pulses in ungauged tributaries strengthens SDG 13.1 (Climate Resilience), offering a pathway to early warning systems for vulnerable communities that currently lie outside the reach of the conventional monitoring network.

6. CONCLUSIONS

This study assessed the feasibility of using SWOT satellite altimetry data to monitor water levels in 12 ungauged tributaries of the Mekong River Basin. Using a workflow that combines DBSCAN outlier filtering and slope correction, the empirical analysis demonstrates that SWOT is operationally viable for tributary channels in this area that are wider than 30 meters; this is of note as the original mission requirements are specified for water surfaces wider than 100 meters. The results further demonstrate that SWOT provides sufficient sensitivity to distinguish diverse flow behaviors, evidenced by the detection of asynchronous flash-flood pulses in the Ruak River and the regulated, inverted flow patterns of the Mun River driven by dam operations. While operational limits were reached on the Loei River (~ width of 15–30 m), the method proved applicable for the remaining 11 tributaries, which represent most of the network. This study provides a foundational framework for integrating satellite observations into national monitoring grids, enhancing the understanding of transboundary flow dynamics and supporting basin-wide resilience initiatives. Monitoring ungauged tributaries directly advances the United Nations Sustainable Development Goals (UNSDGs) by providing independent, scalable hydrological data that enhances transboundary water resource management (SDG 6.5) and strengthens climate resilience through improved early warning systems for flash floods in narrow channels (SDG 13.1). Bridging these observational gaps ensures vulnerable communities are included in regional risk assessments, embodying the core UNSDG principle of leaving no one behind.

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