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First insights into the performance of the SWOT Level 2 River Single-Pass Vector Data Product in rivers with complex morphology: application to the Bíobío River basin, Chile

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Abstract

Hydrological monitoring in Chile is hindered by sparse and unevenly distributed gauging networks, particularly in mountain basins with limited accessibility. The Surface Water and Ocean Topography (SWOT) mission offers a unique opportunity to complement *in situ* observations through high-resolution radar altimetry. The Biobío River basin presents a demanding environment for SWOT due to its narrow channels, steep gradients, and strong geomorphological heterogeneity.

This study evaluates the performance of the SWOT L2_HR_RiverSP (version C) product in the Biobío basin by comparing satellite-derived water-surface elevations with *in situ* measurements from nine DGA streamflow stations. Standard hydrological metrics (R, NSE, NRMSE, MAE) were applied along with quality filters (wse_u < 0.15; node_q = 0–1). Results show strong spatial variability linked to channel width and morphology: wide reaches (>200 m) exhibit high correlations (R ≈ 0.80) and moderate errors (NRMSE < 0.7), whereas narrow or sinuous segments yielded negative NSE values and substantial dispersion. Geometric inconsistencies in the SWORD database were also identified, along with indications of reduced observational consistency following the transition to version D, although this version was not formally analyzed.

Overall, SWOT shows considerable potential for enhancing hydrological observation in Chile, but its operational application in narrow or morphologically complex rivers requires local validation, geometric correction, and integration with lower-level products (e.g., PIXC) to better interpret observations under challenging fluvial conditions.

Keywords: SWOT, satellite altimetry, river hydrology, validation, Biobío River, SWORD."

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1. Introduction

Rivers play essential ecological, social, and economic roles worldwide, shaping landscapes, supporting biodiversity, and providing critical ecosystem services such as water supply, climate regulation, and aquifer recharge (Zeiringer, Seliger, Greimel, & Schmutz, 2018). In Chile, these functions acquire particular relevance given the country's dependence on rivers for hydropower generation, irrigation, and urban water supply, especially in regions affected by high climatic variability and increasing pressure on water resources (OECD, 2024). However, river systems are among the most threatened globally due to anthropogenic interventions, hydropower development, land-use change, and the accelerating impacts of climate change, all of which modify natural flow regimes and reduce the predictability of extreme hydrological events (Malmqvist and Rundle, 2002; Poff et al., 1997). In Chile, these pressures have intensified hydromorphological alteration in multiple basins (Rojas et al., 2019; Rojas et al., 2014), amplifying the need for robust and spatially extensive hydrological monitoring systems.

Despite this need, traditional hydrological observation in Chile faces severe limitations. The national gauging network exhibits low spatial density, irregular maintenance, gaps in temporal continuity, and insufficient coverage in mountain and remote regions (Mesa Nacional del Agua, 2022; Nicolás Vásquez et al., 2021). These deficiencies hinder the construction of reliable hydrological reference series, the calibration of hydrological models, and the development of adaptive water-management strategies under changing climatic conditions (Fustos et al., 2022; Muñoz et al., 2011; Wade et al., 2025). As recognized in global and Chilean contexts, data scarcity in ungauged or poorly gauged basins remains a major challenge for hydrological research and water-resources planning (Hrachowitz et al., 2013).

The Surface Water and Ocean Topography (SWOT) satellite mission represents a significant advancement in the remote observation of continental waters by providing high-resolution measurements of water surface elevation, width, and slope using Ka-band interferometric radar (Biancamaria et al., 2016). For rivers wider than 50 m, SWOT can achieve vertical accuracies of approximately 10 cm, offering new opportunities for monitoring hydrological variability, calibrating discharge models, and assessing surface-water dynamics (Moreira et al., 2025; Yao et al., 2025). These capabilities are particularly relevant for countries like Chile, where complex topography and accessibility constraints limit the expansion of conventional gauging networks.

However, important knowledge gaps remain regarding SWOT performance in fluvial environments characterized by narrow channels, steep longitudinal profiles, dense riparian vegetation, or high morphological variability. Such conditions are common in Chilean basins influenced by the Andes and the Coastal Range, where sinuosity, confined valleys, islands, and irregular planforms may affect radar detection and lead to systematic errors in water-surface retrievals. International studies have documented challenges in similar settings, showing that river width, geometric complexity, and vegetation can degrade SWOT observations (Andreadis et al., 2025; Andreoli et al., 2012; Zhao et al., 2025). These findings highlight the need for regional validation to determine the mission's reliability in morphologically complex basins and in rivers near or below the nominal width threshold.

The Biobío River basin provides an ideal testbed for this purpose. It is one of the largest and most hydrologically significant basins in Chile, spanning strong physiographic and climatic gradients from the Andes to the Pacific, and containing multiple tributaries with contrasting morphologies (DGA, 2012;

Figueroa et al., 2020). The basin also includes heavily regulated sections influenced by major hydroelectric infrastructure, which can further alter water-surface properties and affect radar backscatter. These conditions make the Biobío a particularly demanding environment for evaluating SWOT performance.

To date, no formal evaluation exists of SWOT river products in Chile, nor in Andean basins with narrow, steep, and geomorphologically heterogeneous channels. This represents a critical gap given the country's dependence on satellite-based observations to complement sparse *in situ* networks.

This study provides a regional validation of the SWOT L2_HR_RiverSP product (version C) in Chile by comparing satellite-derived water-surface elevations with *in situ* measurements from nine streamflow stations operated by the Dirección General de Aguas (DGA).

Although this is a first insight, this study aims to:

(1) Quantify the agreement between SWOT and in situ observations across a range of channel morphologies.

(2) Evaluate how width, sinuosity, and local geomorphology influence detection quality.

(3) Identify geometric discrepancies in the SWORD database and assess their impact on SWOT retrievals.

This study provides insights through evidence-based assessment of SWOT performance in Chile and offers a foundation for the mission's operational use in Andean basins with complex morphology and limited in situ observation.

2. Study Area

2.1 Physiographic characteristics of the Biobío River basin

The Biobío River basin, one of the largest and most important in Chile, covers approximately 23,861 km² between 36°42' and 38°49' S and 71°00' and 73°20' W. Its main river originates in Galletué Lagoon (1,160 m a.s.l.) in the Andes Mountains and flows roughly 380 km before reaching its outlet in the Gulf of Arauco (Pacific Ocean). Among its principal tributaries are the Vergara, Laja, Duqueco, Queuco, and Bureo rivers, all of which contribute substantial discharge to the system (Figueroa, Parra, & Díaz, 2020).

From a morphostructural perspective, the basin is organized into three well-defined physiographic units: the Andes Mountains to the east, the Central Depression in the middle sector, and the Coastal Range to the west. This arrangement creates a marked altitudinal gradient that controls fluvial energy and conditions the dynamics of hydrological and sedimentary processes (DGA, 2012).

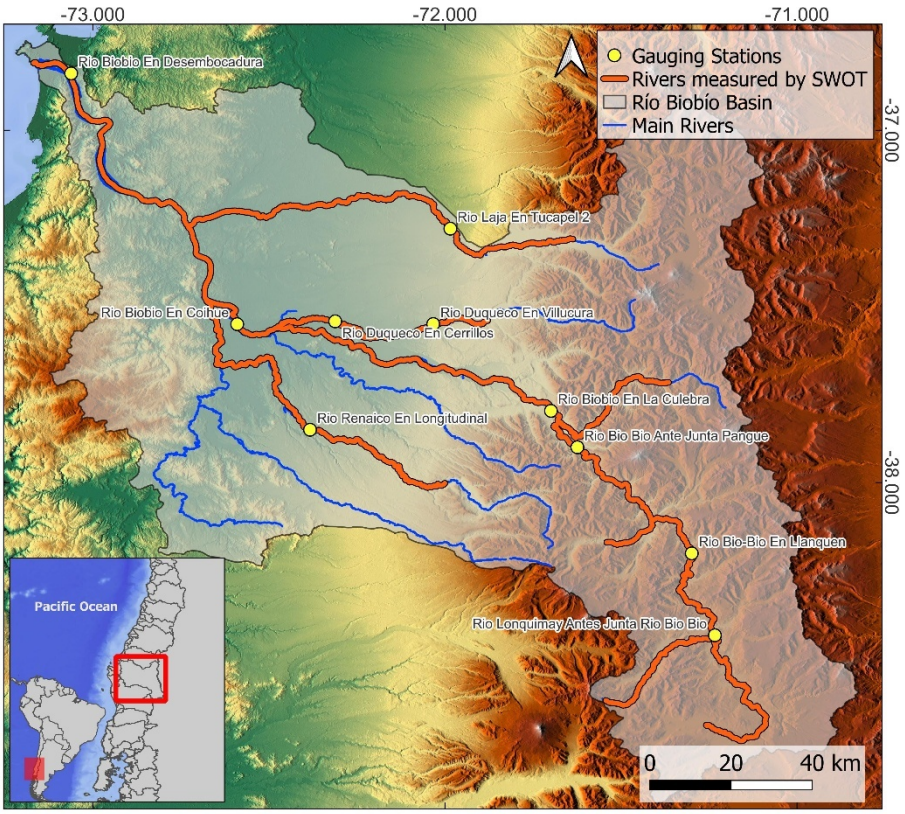

Figure 1. Study Area: Río Biobío Basin

2.2 Morphology, climate, and hydrological regime

The morphology of the basin varies markedly along its course. In the upper basin, narrow glacial valleys with steep slopes predominate; in the middle section, the river crosses a fluviovolcanic plain associated with the Antuco volcano; and in the lower reach, the Biobío flows over a fluvio-marine plain characterized by recent deposits and high sedimentary dynamics.

Climatically, the basin exhibits a pronounced latitudinal and altitudinal gradient. Annual precipitation ranges from about 1,000 mm in the central valley to more than 2,000 mm in the high Andes, with most rainfall occurring during winter. This distribution generates a nivo-pluvial hydrological regime, with winter and spring flow maxima driven by frontal rainfall and snowmelt (DGA, 2012; Figueroa et al., 2020).

The Biobío River is one of the highest-discharge rivers in the country, with an average annual flow of approximately 900 m^3/s at its mouth. This behavior makes it a representative system for validating satellite observations under conditions of strong topographic and climatic contrast.

2.3. Anthropogenic pressure and hydroelectric infrastructure.

The basin has been heavily modified by human activities, particularly through the construction of large-scale hydroelectric power plants such as Ralco, Pangue, and Angostura, which significantly alter the river's natural regime. These facilities regulate flow, reduce seasonal variability, and modify downstream sedimentary and ecological dynamics (Figueroa et al., 2020).

Other sub-basins, such as those of the Laja and Duqueco rivers, also contain regulation systems and reservoirs that increase hydromorphological alteration. Combined with land-use change and projected flow reductions due to climate change, these pressures create a scenario of high hydrological vulnerability (DGA, 2012; Figueroa et al., 2020).

Taken together, these conditions make the Biobío River basin an ideal environment for assessing the accuracy and limitations of satellite products such as SWOT, particularly in rivers with complex morphologies and strong anthropogenic interference.

2 Data and Methodology

2.1. Satellite and geometric data (SWOT, SWORD, Sentinel-2)

The analysis was based on the vector product of the SWOT mission, known as the Level-2 High Rate River Single-Pass Vector Data Product (L2_HR_RiverSP, version C). This dataset provides estimates of water surface elevation (WSE), its associated uncertainty (wse_u), the node quality index (node_q), and other hydrological attributes defined for river reaches and nodes included in the SWORD (SWOT River Database) framework (Altenau et al., 2025).

SWOT's satellite configuration enables near-global coverage, with high-resolution observations (~50–70 m) acquired over 50-km swaths on each side of the orbit. For this study, all observations available from the beginning of version C records were used; the first acquisition cycles for rivers in Chile begin in November 2023. All observations up to April 2025 were included. This cutoff was established because, starting in June 2025, the first results of version D of the RiverSP product are released, whose geometric prior corresponds to SWORD v17b, whereas version C relies on SWORD v17. These two versions exhibit some geometric differences in channel traces, which may introduce inconsistencies when combining products. For this reason, the analysis was restricted exclusively to version C up to April 2025. Version D data were not considered because sufficiently long and stable time series for Chilean basins are not yet available to support a meaningful evaluation, and this study focuses on an initial assessment based on the most stable release currently available, while the mission team continues evaluating the geometric updates introduced in Version D.

Only observations meeting the criteria wse_u < 0.15 and node_q = 0 or 1 were retained to ensure the required minimum quality.

The spatial definition of reaches and nodes is derived from SWORD v17, which contains simplified vector geometries of global river systems. The accuracy of this database is critical for correctly matching satellite observations to actual channel sections; therefore, its geometric validity was assessed as part of the analysis. For this purpose, multispectral Sentinel-2 imagery (Copernicus Programme) was used to visualize river traces at a 10-m resolution. These images enabled verification of the actual channel location and the detection of discrepancies between SWORD geometry and the observed river position, supporting the identification of misalignment or geometric displacement errors in specific reaches of the Biobío and its tributaries.

2.2. In situ data – DGA streamflow stations

As a validation reference, data from streamflow gauging stations administered by the DGA were used. Stations were selected based on their location in rivers observed by SWOT and the availability of records that temporally overlapped with the acquisition dates of the L2_HR_RiverSP product.

Instantaneous discharge records were employed, as these are the only datasets that include water level (stage) estimates with a temporal resolution of 30 minutes. However, not all stations had recent data due to the common delay between measurement dates and public availability in DGA systems. Consequently, in several cases, the time series had to be truncated before 2025, although efforts were made to maximize the temporal overlap with SWOT observations.

The DGA interpolates some values to preserve the 30-minute resolution, but the interpolation method is not specified. In all detected cases, the interpolation did not exceed one day of gap, allowing these values to be included without significantly affecting the fine-scale temporal comparison with SWOT.

In total, nine streamflow stations were selected, distributed along the Biobío River and its main tributaries. This coverage spans a wide range of channel widths and geomorphological conditions, enabling evaluation of the SWOT product's performance across contrasting river environments.

2.3. Temporal matching and vertical reference adjustment.

To compare satellite observations with in situ records, an hourly temporal matching was performed using the SWOT acquisition time as the reference. This procedure was necessary because, in several of the analyzed sites, SWOT provided more than one observation per day (due to different orbital passes affecting the same node or adjacent nodes), and this ensured that the intraday variability captured by SWOT was not lost. Only observations with coincident timestamps were retained, and unmatched cases were excluded without interpolation.

Each DGA station was associated with three SWOT nodes from the L2_HR_RiverSP product (version C), selected based on geographic proximity. Nodes were chosen strictly by horizontal proximity within the same river segment to ensure hydraulic consistency. When no nearby nodes with available data were present, reach-level observations corresponding to the station's location were used instead.

Because SWOT-derived elevations are referenced to the EGM2008 geoid, whereas DGA series report water levels relative to a local (unspecified) gauging datum, a vertical reference adjustment was applied. For this purpose, the mean difference between the overlapping portions of both series was computed and applied as an additive correction, thereby aligning the datasets within a common relative reference frame.

2.4. Quality filters and validation metrics

To ensure the quality of the satellite data, the following filters were applied:

- Only nodes with quality values of node_q = 0 or 1 were retained, as these correspond to valid observations without critical warnings.
- Observations with wse_u ≥ 0.15 were excluded, since high uncertainty values indicate a low level of confidence in the water-surface elevation estimate.

The comparison between SWOT time series and in situ data was carried out using standard hydrological metrics (Alvial Vásquez et al., 2020; Moriasi et al., 2015; López-Pozo et al., 2022), computed using the mean of the three SWOT nodes associated with each station (or the corresponding reach when no nodes were available). The metrics used were:

Table 1. Statistics used to evaluate the consistency between SWOT and in situ data.

Statistic	Formula	Ranges
Standardized standard deviation (σ_e)	$\sigma_e = 1 - \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}{(X_i - \bar{X})^2}}$	(−∞, 1] (≈0 ideal)
Normalized root mean square error (NRMSE)	$nrmse = \frac{\sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}}}{\sigma_x}$	[0, ∞) (less is better)
Mean absolute error (MAE)	$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\lvert \mathrm{X} - \mathrm{Y} \rvert$	[0, ∞) (less is better)
Pearson correlation coefficient (R)	$\rho_{xy} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{Y})^2}^{\,2}\sqrt{\sum_{i=1}^{n}(X_i - \bar{Y})^2}}$	[−1, 1] (|r| high = Good agreement)
Nash–Sutcliffe model efficiency coefficient (NSE)	$nse = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$	(−∞, 1] (1 ideal)
Willmott's index of agreement (d)	$d = 1 - \frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{\sum_{i=1}^{n}(\lvert Y_i - \bar{X} \rvert + \lvert X_i - \bar{X} \rvert)^2}$	[0, 1] (1 ideal)

Let X_i denote the in-situ water-level observations (DGA), used as the reference series, and Y_i the corresponding SWOT-derived water-surface elevations.

NSE < 0 indicates poorer performance than the mean, NRMSE provides a normalized error measure, MAE reflects absolute deviations, and the Willmott index (d) quantifies relative agreement, with values approaching 1 indicating strong consistency. These metrics allow assessing both the agreement in shape and magnitude between the series, as well as the presence of systematic biases. In all cases, the statistics were interpreted according to the ranges reported in the hydrological literature.

2.5. Spatial analysis and geomorphological assessment

To evaluate the spatial consistency of SWOT observations, the density and quality of the data were examined along different reaches of the river. Patterns of data loss, dispersion, and coverage gaps were investigated and linked to physical channel characteristics such as width, riparian vegetation, and morphology. Offsets were identified visually when the SWORD centerline clearly deviated from the observable water surface.

In some reaches with poor performance, a detailed inspection was carried out using Sentinel-2 imagery and the channel geometry recorded in the SWORD database, with the aim of identifying possible alignment errors, mislocated nodes, or “dark water” conditions that may hinder radar detection.

2.6. Uncertainty analysis of the SWOT product

In addition to the validation against in situ data, an independent evaluation of the uncertainty reported by the L2_HR_RiverSP product (wse_u) was conducted for all nodes within the Biobío River basin.

In the uncertainty analysis, all available nodes inside the basin boundary were considered, without restricting the sample to those associated with gauging stations. The wse_u < 0.15 filter was not applied, in order to capture the full distribution of uncertainty in the product. However, the node quality criterion was maintained, retaining only observations with node_q = 0 or 1, thereby ensuring a minimum level of geometric and instrumental reliability. Estimated channel widths for each node were also incorporated, as SWOT uncertainty depends strongly on channel morphology, particularly in narrow, sinuous, or densely vegetated rivers.

3. Results

3.1. Statistical validation of SWOT observations

The results obtained from the comparison between SWOT L2_HR_RiverSP satellite observations and in situ records from the DGA are summarized in Table 2. Nine gauging stations distributed across different reaches of the Biobío River basin were evaluated, using standard hydrological metrics to quantify the agreement between both data sources.

Table 2. Comparison of SWOT measurements with in situ observations.

Gauging Station	σ_e	**nRMSE**	MAE	R	NSE	d	N° obsv	Start Date	Max width river (m)
Río Biobío Ante Junta Pangue	-1.58	2.27	0.99	0.42	-4.50	0.52	16	20-01-2024	42
Río Biobío en Coihue	-0.15	1.10	0.42	0.46	-0.27	0.68	18	14-05-2025	270
Río Biobío en Desembocadura	-0.12	0.28	0.11	0.97	0.92	0.98	27	10-12-2023	2389
Río Biobío en Llanquén	-0.48	1.46	0.79	0.34	-1.18	0.60	61	29-11-2023	54
Río Biobío en la Culebra	-4.59	4.83	0.60	0.61	-24.45	0.38	12	09-12-2024	67
Río Duqueco en Cerrillos	0.71	1.24	1.19	0.19	-0.63	0.40	20	12-04-2024	39
Río Duqueco en Villucura	0.25	0.69	0.22	0.71	0.51	0.81	25	29-11-2023	48
Río Laja en Tucapel 2	-0.27	0.71	0.28	0.83	0.48	0.89	29	20-01-2024	67
Río Lonquimay Antes Junta Rio Biobío	0.54	0.69	0.78	0.51	0.75	0.02	38	2023-12-09	36

Río Renaico en Longitudinal	-0.56	1.09	0.17	0.69	-0.27	0.78	15	28-11-2023	39

As shown in Table 2, there is a relationship between channel width and the performance of the satellite product, although this relationship is not strictly linear. Good results were observed in some relatively narrow reaches, whereas in other, even wider sections, the agreement was less optimal. This suggests that local morphology and hydraulic complexity influence the performance of SWOT as much as the effective river width.

In stations located in wider reaches, such as Biobío en Desembocadura (2,389 m) and Laja en Tucapel 2 (67 m), correlation coefficients were high (R ≈ 0.97 and R ≈ 0.83, respectively), and relative errors (NRMSE ≈ 0.28 and 0.71) remained below 0.75. These values, together with positive NSE scores (≈ 0.92 for Biobío en Desembocadura and ≈ 0.48 for Laja en Tucapel 2), indicate an acceptable representation of hydrological dynamics by SWOT in these reaches.

In contrast, stations associated with narrow or geomorphologically complex rivers, such as Duqueco en Cerrillos (39 m) and Biobío en La Culebra (67 m), showed negative NSE values and substantial dispersion between the series (e.g., NRMSE ≈ 1.24 at Duqueco en Cerrillos and ≈ 4.83 at Biobío en La Culebra). These results reflect the limited detection capacity of the satellite radar under such conditions, where the signal is more sensitive to channel irregularities and to the partial loss of water pixels.

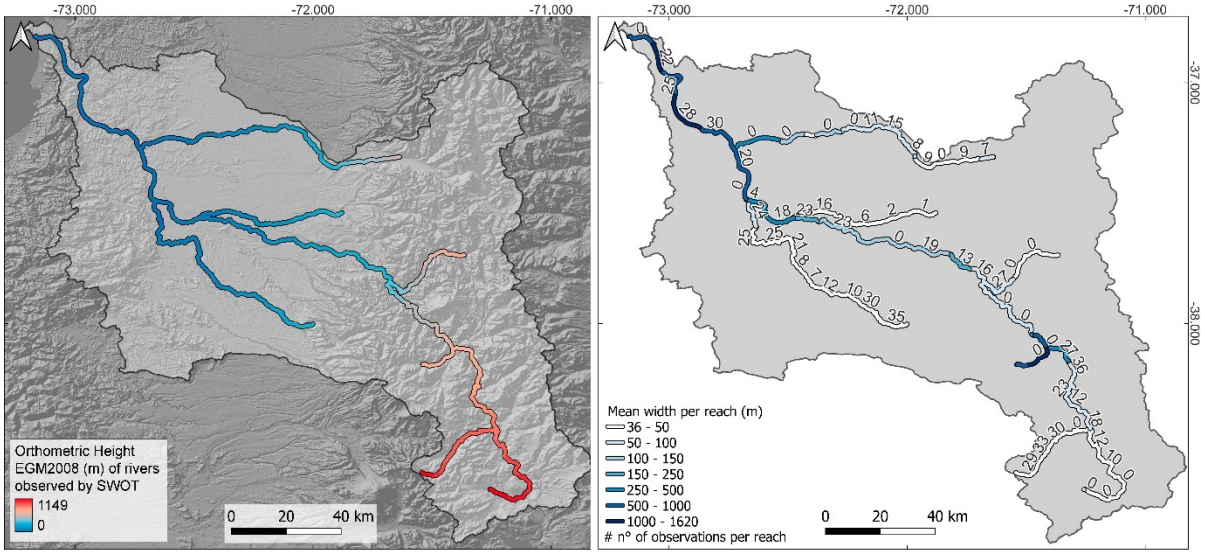

Figure 2. (Left) Water surface elevation of rivers observed by SWOT. (Right) Average channel width of SWOT-measured reaches and number of observations per reach.

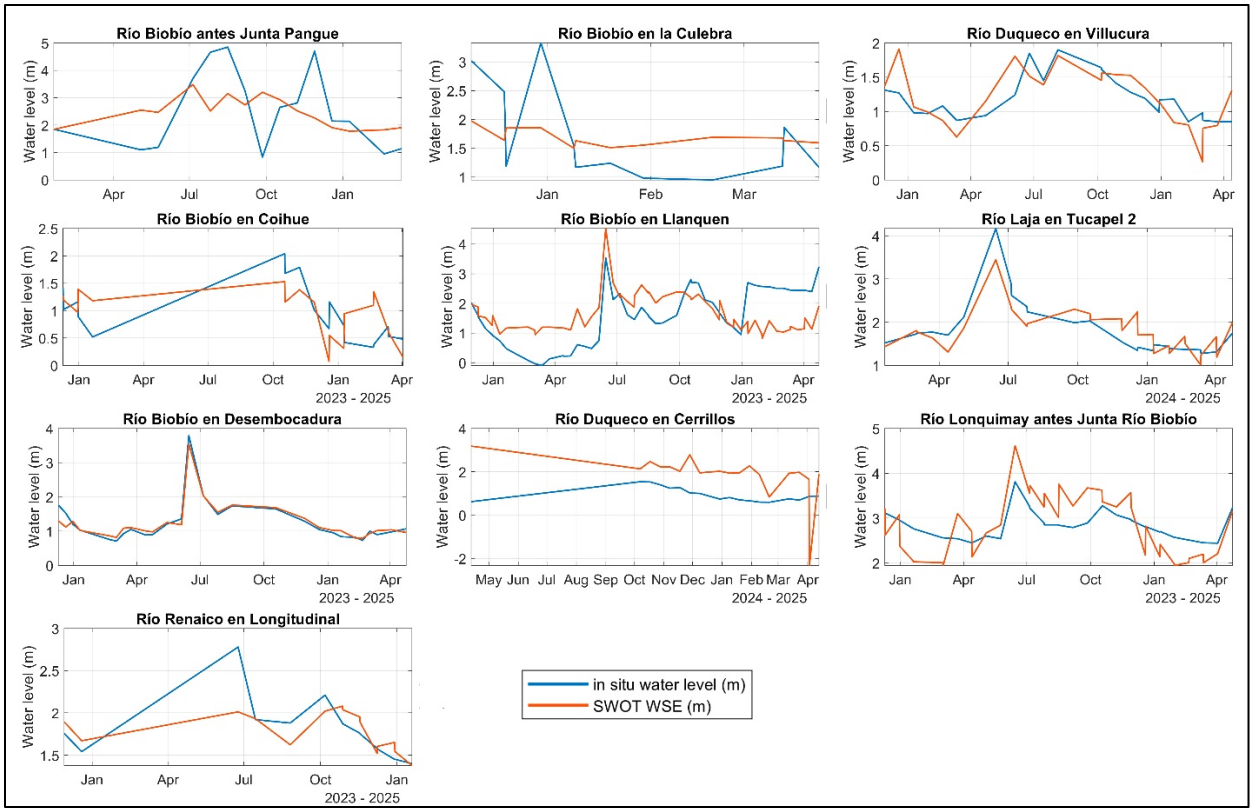

Figure 3. Time series at selected sites for the comparison between SWOT data and in situ water level measurements

A particular case is the station Lonquimay Antes Junta Río Biobío, for which no temporally matching data were available, neither at the node level, as shown in Figure 4, nor for the respective reach. In this scenario, the three closest nodes of the Biobío River, located immediately downstream of the confluence, were used as an approximation to evaluate the hydrological evolution at this point. Although this comparison is not strictly correct, it provides a reasonable reference for the river dynamics, considering that both rivers exhibit similar responses up to the confluence zone due to their comparable morphologies and shared climatic conditions. Despite being different rivers, a high correlation was obtained ($R \approx 0.78$), which is a strong indication that the mission is able to capture hydrological dynamics even in very narrow reaches (<50 m). This reach is characterized by its narrowness and dense riparian vegetation, conditions that hinder satellite detection of the water surface and may explain the reduced performance observed. Although the Biobío reach immediately downstream of the confluence contains more SWOT observations, a direct hydrological comparison is not possible due to the absence of gauging stations in that area.

Other reaches, such as Biobío en Coihue and Biobío Ante Junta Pangue, showed only partial reproduction of the temporal signal, with moderate correlations ($R \approx 0.46$ and 0.42), but negative NSE values and substantial magnitude errors (NRMSE ≈ 1.10 and 2.27). These patterns are consistent with the presence of river islands, riparian vegetation, or irregular channel geometries that are not adequately represented in SWORD, which can introduce errors in the assignment of water surfaces and reduce agreement between SWOT and in situ series.

A reduction in the quality and consistency of observations was detected starting in May 2025, coinciding with the transition of the SWOT product from version C to version D. This update introduced new height

calibrations and adjustments to reach geometries, which may have generated discontinuities in the time series at certain sites. These observations were not included in the calculation of the statistical metrics.

3.2. Spatial variability in SWOT observation coverage and quality

Beyond the metric differences between stations, a high degree of spatial variability was observed in the coverage and quality of satellite observations along the river channels. This heterogeneity appeared even within the same river, where adjacent reaches exhibit markedly different densities of valid observations, as illustrated in Figure 2.

For example, in the Laja River, certain narrow reaches contained a considerable number of observations with acceptable uncertainty, whereas other, wider downstream sections showed significantly lower coverage. Figure 4 highlights this abrupt alternation, indicating that the variability cannot be explained solely by channel width. In some areas, channel depth remains constant or even increases, suggesting the influence of additional factors such as water-surface roughness (“dark water”), reduced flow velocity, or riparian vegetation.

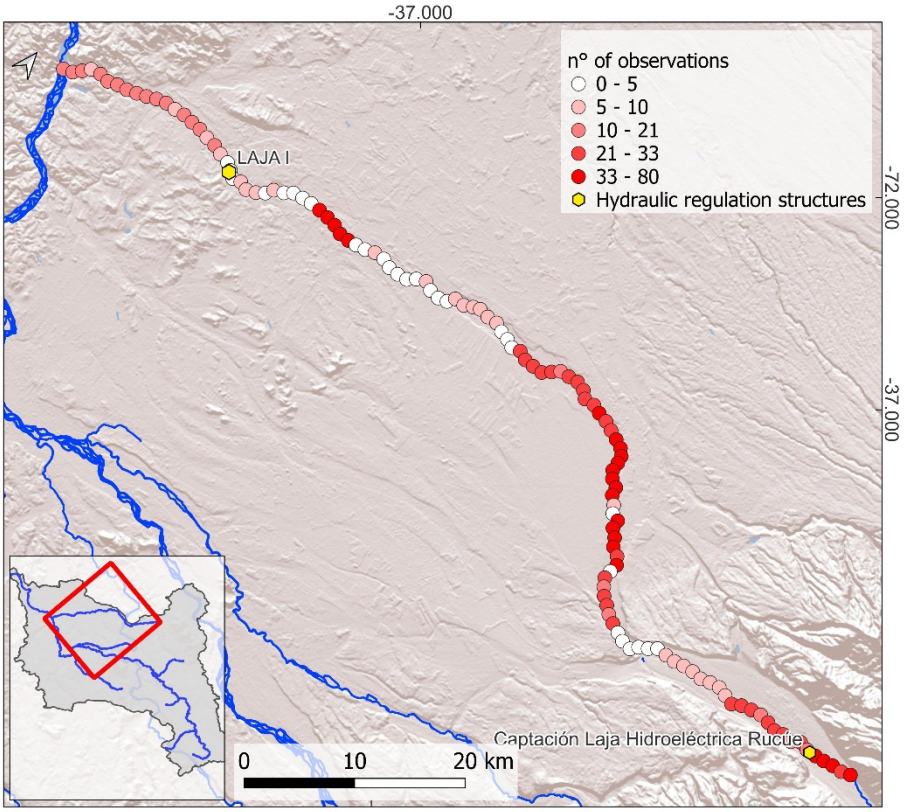

Figure 4. Number of SWOT node observations in the Laja River.

In hydraulically regulated areas, such as the reach upstream of the LAJA I Hydroelectric Plant, channel widening was associated with a smoother water surface, which may reduce the radar backscatter detectable by SWOT. Similarly, at the confluence of the Lonquimay River with the Biobío, a higher number of SWOT observations is recorded in the Biobío, even though the Lonquimay exhibits comparable morphological conditions.

In addition, a general increase in the number of available observations was identified after the transition of the SWOT product from version C to version D, although no formal comparative analysis was performed. Many of the nodes with lower data density shown in Figure 4 do not account for the dates of this update, suggesting that the new geometric calibrations or filtering algorithms may have improved effective detection in certain fluvial contexts.

3.3. Temporal variability

In certain reaches with a sufficient number of observations, it was possible to examine the temporal evolution of water levels observed by SWOT in comparison with in situ measurements from the DGA. The best results were obtained at Biobío en Desembocadura and Laja en Tucapel 2, although temporal patterns could also be identified, albeit with lower quality, in stations such as Biobío en Llanquén and Duqueco en Villucura, where the time series exceeded 20 valid observations.

In the case of Biobío en Llanquén, the overall performance metrics were R = 0.34, NSE = –1.18, and NRMSE = 1.40. Nevertheless, periods of good visual agreement between both datasets were identified, particularly between June and October 2024, as shown in Figure 3.

For Río Biobío Ante Junta Pangue (R = 0.42), SWOT partially reproduced the temporal shape of the signal, although with substantial magnitude errors. The limited number of available observations increases the statistical uncertainty of the resulting metrics.

Taken together, the analyzed stations showed appreciable temporal variability in the quality of the match between satellite observations and in situ records, as evidenced by differences in correlation levels and scatter throughout the time series.

3.4. Geometric analysis and positioning errors (Sentinel-2)

In addition to the validated stations, a geometric and quantitative assessment was conducted for river reaches without DGA coverage, using SWOT observations and Sentinel-2 optical products. The objective was to identify physical or geometric factors that could explain the low density or quality of satellite observations, as well as possible misalignments between the SWORD database and the actual position of the river channel.

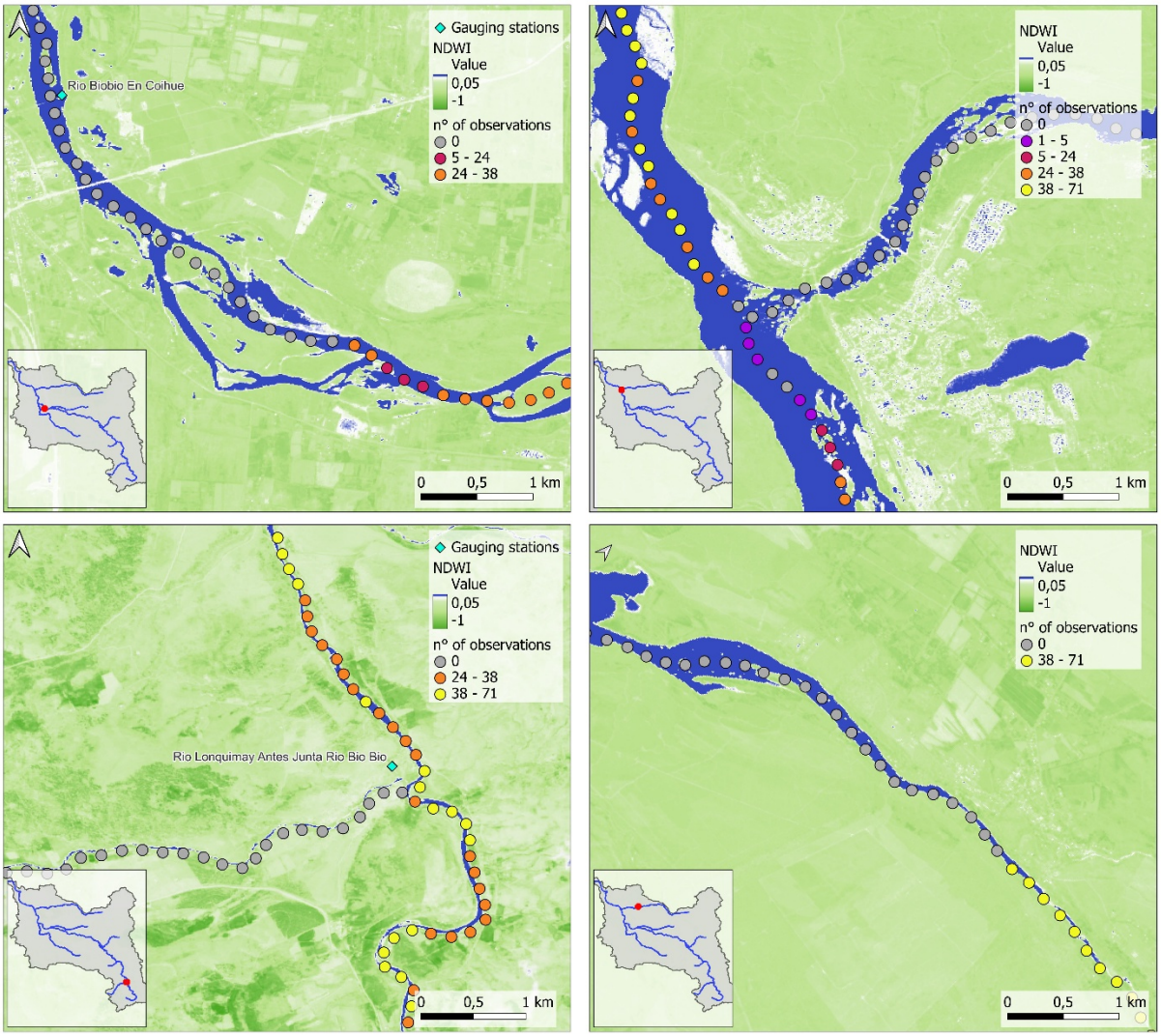

Figure 5. River positions captured by Sentinel-2 in 2015 and the corresponding SWORD Prior Database node locations. Río Biobío en Coihue (upper left), Laja–Biobío confluence (upper right), Río Lonquimay Antes Junta Río Biobío (lower left) and Laja River (lower right).

In the lower section of the Laja River, an abrupt alternation was observed between reaches with more than 30 detections per year (and over 60 detections for the full period of available records) and others with fewer than 10 valid detections, even though the average channel width remains relatively constant at around 30–60 m. This discontinuity is not associated with local hydrological variations but rather with differences in georeferencing and geometric segmentation of reaches in the SWORD v17 database.

As can be seen in figure 5, at the confluence of the Laja and Biobío rivers, the number of valid observations decreased by more than 68% over the final 29 km before the junction, despite channel width increasing from 50–100 m to more than 200 m. Conversely, at the confluence of the Lonquimay River with the Biobío, the number of SWOT observations in the Biobío is approximately ten times higher than in the Lonquimay, even though both exhibit similar mean widths (≈ 45 m) but different slopes (0.15% for the Lonquimay and 0.38% for the Biobío at the confluence). These contrasts confirm the influence of reach geometry and flow orientation on the radar's detection capability.

Figure 5 illustrates these patterns and reveals localized geometric errors in the SWORD database, particularly in the Lonquimay River, where satellite nodes show displacements of 10 to 100 m relative to the actual river trace observed in Sentinel-2 imagery. These misalignments cause between 10% and 12% of SWOT observations to be assigned to incorrect channel sections, reducing effective coverage and distorting the reported mean water-surface elevations.

3.5. Relationship between uncertainty and channel width

The data showed a clear relationship between channel width and the uncertainty associated with water-level estimation (wse_u), as illustrated in the scatterplot in Figure 6. The narrowest rivers exhibited the highest uncertainties and the greatest dispersion. In the <50 m class, wse_u reached a mean of 0.222 m with a high standard deviation (0.314 m) and maximum values exceeding 25 m, indicating the presence of severe errors associated with narrow, sinuous, or vegetated geometries where PIXC processing tends to degrade. This uncertainty decreases progressively across wider classes: 0.129 m of uncertainty in 50–100 m wide rivers, 0.116 m of uncertainty in 100–250 m wide rivers, and 0.106 m of uncertainty in >250 m wide rivers, reflecting that SWOT operates with greater stability in wider channels. Nevertheless, even in wide rivers, a significant number of outliers were observed (up to 5.03 m), demonstrating that the signal is not entirely free of extreme noise, although its relative frequency is much lower.

Table 3. Descriptive statistics of channel width and wse_u uncertainty by width classes, with and without outliers.

Node measured river width (m)

Width class	count	mean	std	min	25%	50%	75%	max
< 50 m	24585	27.92	14.61	0.00	16.35	30.01	40.59	50.00
50–100 m	25311	72.60	14.24	50.00	60.19	71.37	84.47	100.00
100–250 m	27965	159.31	42.29	100.01	122.31	151.96	192.00	249.98
> 250 m	36635	750.64	654.70	250.01	380.76	598.33	885.72	39804.24

Node wse u (m)

Width class	count	mean	std	min	25%	50%	75%	max
< 50 m	24585	0.22243	0.31385	0.09001	0.11376	0.14121	0.21740	25.09399
50–100 m	25311	0.12853	0.07581	0.09004	0.10182	0.11034	0.13173	3.26356
100–250 m	27965	0.11630	0.08345	0.09001	0.09561	0.10071	0.11342	3.27203
> 250 m	36635	0.10615	0.07211	0.09000	0.09188	0.09348	0.09886	5.03176

Node measured river width (m) outliers removed

Width class	count	mean	std	min	25%	50%	75%	max
< 50 m	22055	29.98	13.44	0.01	20.07	31.94	41.43	50.00
50–100 m	23159	72.96	14.22	50.00	60.58	71.99	84.84	100.00
100–250 m	25296	160.53	42.35	100.01	123.34	153.94	193.53	249.98
> 250 m	31460	782.12	594.99	250.01	394.29	631.14	956.66	38948.39

Node measured river width (m) outliers removed

Width class	count	mean	std	min	25%	50%	75%	max
< 50 m	22055	0.15729	0.06154	0.09001	0.11202	0.13347	0.18316	0.37280
50–100 m	23159	0.11513	0.01895	0.09004	0.10124	0.10848	0.12331	0.17658
100–250 m	25296	0.10339	0.01090	0.09001	0.09530	0.09939	0.10792	0.14013
> 250 m	31460	0.09434	0.00392	0.09000	0.09172	0.09292	0.09545	0.10933

After removing outliers using the IQR method, a more moderate characterization of the uncertainty inherent to the SWOT product is obtained. Mean wse_u values decreased systematically across all width classes, but the most notable change occurs in narrow rivers: in the <50 m class, the mean decreases from 0.222 m to 0.157 m, and the standard deviation drops from 0.314 m to only 0.062 m, indicating that much of the extreme error corresponds to anomalous cases rather than the typical performance of the algorithm. In wide rivers (>250 m), the uncertainty excluding outliers is even more constrained, with a mean of 0.094 m and a standard deviation of only 0.0039 m, confirming an extremely stable signal when channel geometry favors detection.

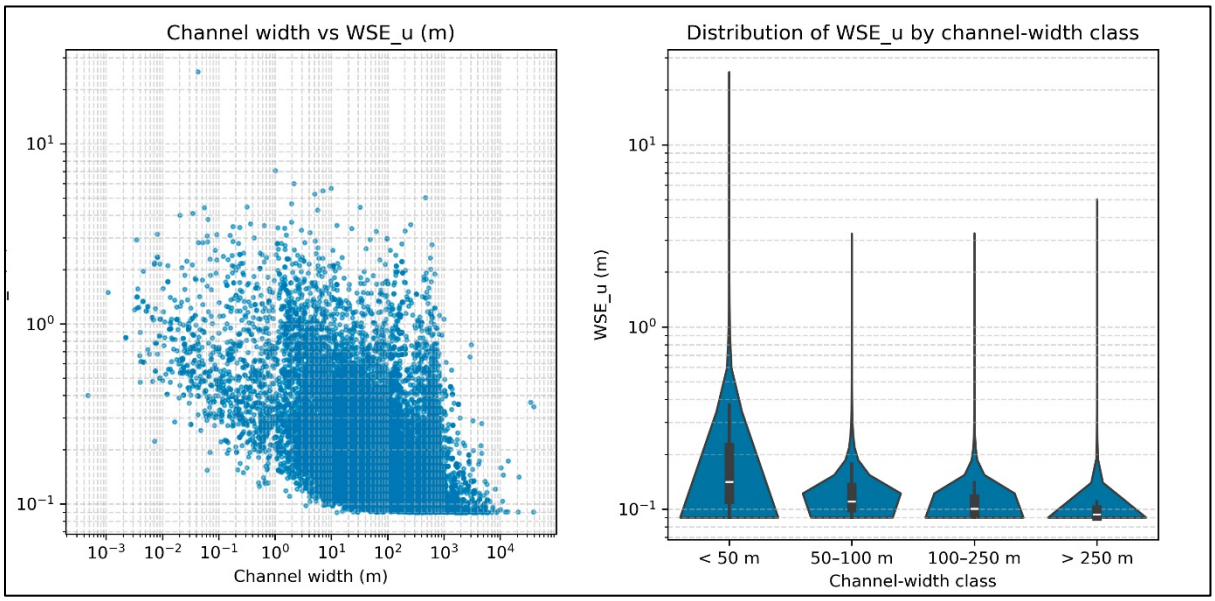

Figure 6. Scatterplot illustrating the variation of WSE_u uncertainty as a function of channel width: global dispersion (left) and violin plots by width class (right).

Figure 6 shows the relationship between channel width and wse_u uncertainty across all available observations. In the scatterplot, the dispersion of wse_u is considerably higher in narrow rivers, particularly in the <50 m class, where values exhibit a wide range and a clear concentration of high-uncertainty points. As channel width increases, the point cloud progressively narrows, indicating a general reduction in variability, although high values persist across all classes. This pattern is also reflected in the violin plots, where the distributions are wider in channels narrower than 50 m and become more compact in the broader width classes, while still retaining the presence of outliers. Taken together, both visualizations show that uncertainty decreases overall as channel width increases, but extreme variability is not completely eliminated from the dataset.

4. Discussion

The performance of the SWOT L2_HR_RiverSP product in the Biobío River basin shows clear spatial variability controlled by channel width, morphology, and geometric accuracy of the SWORD database. In wide and morphologically stable reaches, SWOT achieved its best results, with correlations above 0.80 and relatively low normalized errors. For example, the Biobío en Desembocadura, a reach exceeding two kilometers in width, reached R = 0.92 with an NRMSE of 0.28, while the Laja en Tucapel 2, although considerably narrower, still achieved R = 0.83 with an NRMSE below 0.75. These results are consistent

with global findings that document stronger SWOT performance in wide, regular channels (Andreadis et al., 2025; Du et al., 2023; Zhao et al., 2025).

Performance declined sharply in narrow or geomorphologically complex rivers. Stations such as Duqueco en Cerrillos and Biobío en La Culebra, both with widths well below 100 m, showed negative NSE values and normalized errors exceeding 1, confirming the known limitations of SWOT in channels narrower than 100 m (Andreadis et al., 2025; Gehring et al., 2023). Although moderate correlations were sometimes observed, such as R = 0.61 at La Culebra, the magnitude of the errors indicates a strong sensitivity to sinuosity, vegetation, and confined topography.

Intermediate performance appeared in reaches like Biobío en Coihue and Biobío en Llanquén, where correlations ranged between 0.30 and 0.50 and errors remained moderate to high. At Llanquén, agreement improved notably during a specific seasonal window between June and October 2024, suggesting that hydrodynamic conditions, such as discharge variability and surface roughness, can affect radar detectability, in line with observations in other basins (Desrochers et al., 2021).

Significant heterogeneity was also observed in the number of valid SWOT detections, particularly in the Laja River, where some reaches accumulated over 60 valid observations while adjacent sections had fewer than 10, despite similar widths. Reductions in detection density of more than 60 percent were also observed near the Laja-Biobío confluence. These discontinuities are consistent with “dark water” effects associated with regulated flows, which reduce radar backscatter (Lobry et al., 2019).

Geometric inconsistencies in the SWORD v17 database played a critical role in several reaches. In the Lonquimay River, Sentinel 2 imagery indicated displacements on the order of tens of meters between actual river traces and SWORD node positions. These misalignments can shift SWOT detections entirely outside the true channel, explaining between 10 and 12 percent of erroneous observations in affected segments, consistent with similar issues reported elsewhere (Altenau et al., 2021; Larnier et al., 2024).

The uncertainty analysis further supports these findings. Narrow rivers typically exhibited mean uncertainties near 0.22 m, with large dispersion and occasional extreme values reaching several meters, while wide rivers showed considerably lower and more stable uncertainties, generally near 0.10 m. After removing statistical outliers, uncertainties in narrow channels dropped substantially but remained higher than in wider ones, indicating intrinsic limitations related to width, vegetation, and local geomorphology.

Temporal consistency also showed signs of degradation after the product transition from version C to version D in mid 2025, likely due to changes in geometric priors. These observations were excluded from the core performance statistics.

Overall, the results confirm that SWOT has significant potential to complement hydrological monitoring in Chile, especially in basins with limited in situ data. However, its performance depends strongly on channel width, morphology, hydraulic regulation, and the geometric reliability of SWORD. The Biobío basin, with its combination of wide lowland rivers and narrow Andean tributaries, provides an effective testbed for understanding these dynamics. As in other regions, operational use of SWOT in Chile will require local validation, geometric correction of river traces, and complementary analyses using lower level products such as PIXC (Desrochers et al., 2021; Dhote et al., 2025; Signorile et al., 2024).

5. Conclusions

Our results demonstrate that the performance of the SWOT L2_HR_RiverSP product in the Biobío basin is controlled primarily by channel width, local morphology, and the geometric accuracy of SWORD. Wide river sections, exceeding 200 m, consistently produced high correlations and moderate errors, whereas narrow or sinuous reaches yielded negative NSE values and large dispersion, confirming a strong morphological constraint on SWOT detectability. Geometric inconsistencies in SWORD and the reduced stability observed after the transition to version D further reveal that channel misalignment and evolving priors remain critical sources of uncertainty in complex fluvial environments.

These findings indicate that, although SWOT represents a transformative opportunity for hydrological monitoring in countries like Chile where in situ networks are sparse and unevenly distributed, its operational use in steep, narrow, or heavily regulated rivers requires rigorous local validation. The systematic influence of width, vegetation, sinuosity, and hydraulic alteration highlights the need for integrating SWORD refinement and lower-level products such as PIXC to diagnose and mitigate observation failures.

This study provides the first basin-scale evaluation of SWOT performance in Andean river systems and establishes a quantitative foundation for future high resolution altimetry-based SWOT hydrological monitoring in Chile. Expanding the analysis across additional climatic and hydrological conditions, and testing the robustness of new product versions, will be essential to ensure reliable, long-term use of SWOT in data-scarce and geomorphologically complex regions.

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Generative AI was used to assist in the translation of this manuscript from Spanish to English.

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