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UAWOS - Unmanned Airborne Water Observing System

Deliverable 4.2:

Copernicus and Tero water level validation

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1. Overview and Summary

This document summarizes the outcomes from Task 4.2: Copernicus water level service validation.

The main aim of the task was the validation and enhancement of inland water observations from satellite EO using UAS hydrometry. A secondary objective was the assessment of the WSE estimates in virtual stations as a preparatory activity to Task 4.3 Estimating discharge at virtual stations. The considered validation sites were virtual stations of interest in the Po, Torne Ælv and Isar river.

This document constitutes deliverable D4.2 of the Horizon Europe project “UAWOS – Unmanned Airborne Water Observing System”, contract number 101081783.

2. Data and methods

2.1. UAV data

This work employs UAV altimetry data from two different instruments: by the NRA24 radar altimeter and LX_80 radar altimeter. The Geolux LX-80 altimeter radar is a frequency modulated continuous wave radar sensor that works in W-band, at frequencies between 77 GHz and 81 GHz (further details are provided in UAWOS_D2.1 - Radar Altimetry Payload [1]); and the NRA-24 altimeter radar, that operates in K-band, in the 24 GHz-ISM frequency band. All the data used in the project can be found in the UAWOS dataset repository.

For 2024 Torne and Isar river campaign the the WSE measured by the NRA24 radar altimeter instrument has been used. Whereas for the 2024 Po and all 2025 campaigns, the data from the LX_80 radar was found to be more accurated.

2.2. Satellite data from VS

This work employs the Tero-VS and Tero-WL near-real-time operational chains developed by Lobelia to retrieve inland water surface elevation from satellite radar altimetry. These processing systems are designed to exploit multi-mission datasets for dynamic monitoring of lakes and rivers, where in-situ measurements are often sparse or unavailable.

The Tero-VS component is responsible for defining virtual stations — fixed geographic locations where repeated altimeter ground tracks intersect inland water bodies. To identify these candidate locations, Tero-VS spatially intersects the JRC Global Surface Water Occurrence dataset with the nominal ground tracks of Sentinel-3, Sentinel-6, and Jason missions. A buffer offset is applied to each track to account for possible orbital drift and geolocation uncertainties. Wherever buffered ground tracks overlap areas classified as surface water, a virtual station is created and stored with metadata such as geographic extent, associated tracks, and mission availability. These virtual stations serve as gateways for systematic data extraction in the subsequent processing step.

The Tero-WL component ingests these virtual stations and retrieves all Level 2 altimetry measurements from the above missions that fall within or intersect each station's footprint. For every returned measurement point, a water surface elevation value is computed after applying the standard set of geophysical and environmental corrections included in Level 2 products. These typically include wet and dry tropospheric path delays, solid Earth and ocean tide corrections, geoid and reference ellipsoid models and instrumental and orbit corrections. Although originally designed for open-ocean conditions, over-land processing benefits from the multi-mission redundancy, allowing for regular sampling of lakes and wide rivers at sub-weekly time scales depending on the mission configuration.

After initial processing, all valid observations within a virtual station are grouped by acquisition day. To reduce noise caused by heterogeneous surface conditions, retracker performance, or mixed land–water waveforms, an Interquartile Range (IQR) filter is applied to each daily group. Points falling outside the IQR bounds are discarded as potential outliers. The remaining filtered points are then averaged, yielding a single representative daily water surface elevation estimate for that satellite pass. This approach balances noise reduction with retention of temporal variability, resulting in clean and consistent time series for each virtual station.

It is important to note that inland altimetry is generally more robust in characterizing relative changes in water surface elevation (e.g., rising or falling water levels) than in providing absolute elevation values. Absolute differences can arise due to geoid model uncertainties, mission-specific instrumental biases, variations in retracker performance over inland water, and differing reference ellipsoids across missions. For this reason, inter-mission harmonization or comparison with in-situ water level gauges is typically required to correct for vertical biases and establish a consistent baseline. As a consequence, single-point comparisons may appear offset even when relative temporal dynamics are accurately captured.

In its final form, the processing pipeline provides harmonized multi-mission inland water elevation time series suitable for hydrological applications such as water balance studies, reservoir monitoring, and assimilation into hydrological models.

2.3. SWOT data

SWOT is a joint NASA, CNES, Canadian Space Agency mission that monitors Earth's surface water and oceans WSE at a global scale. The SWOT satellite was launched on December 16, 2022, and provides water elevation data using state-of-the-art radar interferometry technology, observing lakes, rivers and wetlands and detecting ocean features covering more than 90% of Earth's surface water. Traditional satellite altimetry estimates water level accurately, but spatial coverage is limited to virtual stations (where satellite track crosses a water body) due to the limited spatial coverage under the satellite track. SWOT provides near-global 2D mapping every 21 days, this capability allows to estimate WSE along the river course and thus to estimate river slope [2] [3].

We have used the SWOT Level 2 Water Mask Pixel Cloud Data Product, Version C for our purposes [4] [5]. The Pixel Cloud product provides high-resolution, geolocated observations of terrestrial surface water pixels, derived from high-resolution radar observations collected by the Ka-band Radar Interferometer (KaRIn) on the SWOT satellite. Version D of this same product began to be distributed in May 2025, but at the time of writing this deliverable the reprocessing of data from previous dates is still not completed.

The Pixel Cloud product classifies each geolocated point into different types of surfaces, as listed in Table 4. This data comes with flags dealing with the quality of the surface classification, the geolocation process, the interferogram, among others. When working with wider rivers such as the Torne or the Po, SWOT WSE data has been filtered to only consider high-coherence measurements using all these flags to remove unreliable or inaccurate information. For narrower rivers such as the Isar or the Orco, SWOT has more difficulties detecting the water surfaces and data is usually less clean than in open water. For these reasons, a lesser strict filtering has been applied in these scenarios by including low-coherence measurements and only considering the geolocation quality flag to maximize the number of points available.

Class	Definition
1	Land
2	Land near water
3	Water near land
4	Open water
5	Dark water
6	Low-coherence water near land
7	Open low-coherence water

Table 1: Definitions of numeric surface classification values for the Pixel Cloud product [4].

2.4. In situ data

To compare the satellite derived WSE data, we use gauge stations in-situ data, provided by: the Finnish Environment Institute, the Finnish Permit and Control Authority, the Finnish Life Centres, the Finnish Meteorological Institute and the Finnish Flood Centre in cooperation with expert organisations in the water sector, and downloaded from vesi.fi [6]; and from the Agenzia Interregionale per il fiume Po [7]. These providers were chosen due to the proximity of the in-situ stations to one or several of the studied virtual stations, and the ability to correct the river slope differences between them. These datasets provide hourly water level data at the location of the gauge stations.

Because the in-situ gauge stations are not located at exactly the same positions as the virtual stations, the Tero-WL and DAHITI water level time series were adjusted using SWOT-derived river slopes to account for elevation differences and to ensure consistency with the in-situ reference levels.

The validation was conducted using the following performance metrics: Pearson's correlation coefficient (Pearson's CC), bias, unbiased Mean Absolute Error (uMAE), and unbiased Root Mean Square Error (uRMSE).

2.5. River slope correction

When different WSE from satellite virtual stations, UAV measurements or in-situ measurements are not taken at the same location, there's the need of correcting the river slope. As can be seen in Figure 1, Tero-WL data points vary in space due to satellite's orbit drift over time. This results in water level values dependent on the position of the data point along the river course. Therefore, this correction is needed for both correcting the existent bias among missions and to compare the Tero-WL data with the other water level sources.

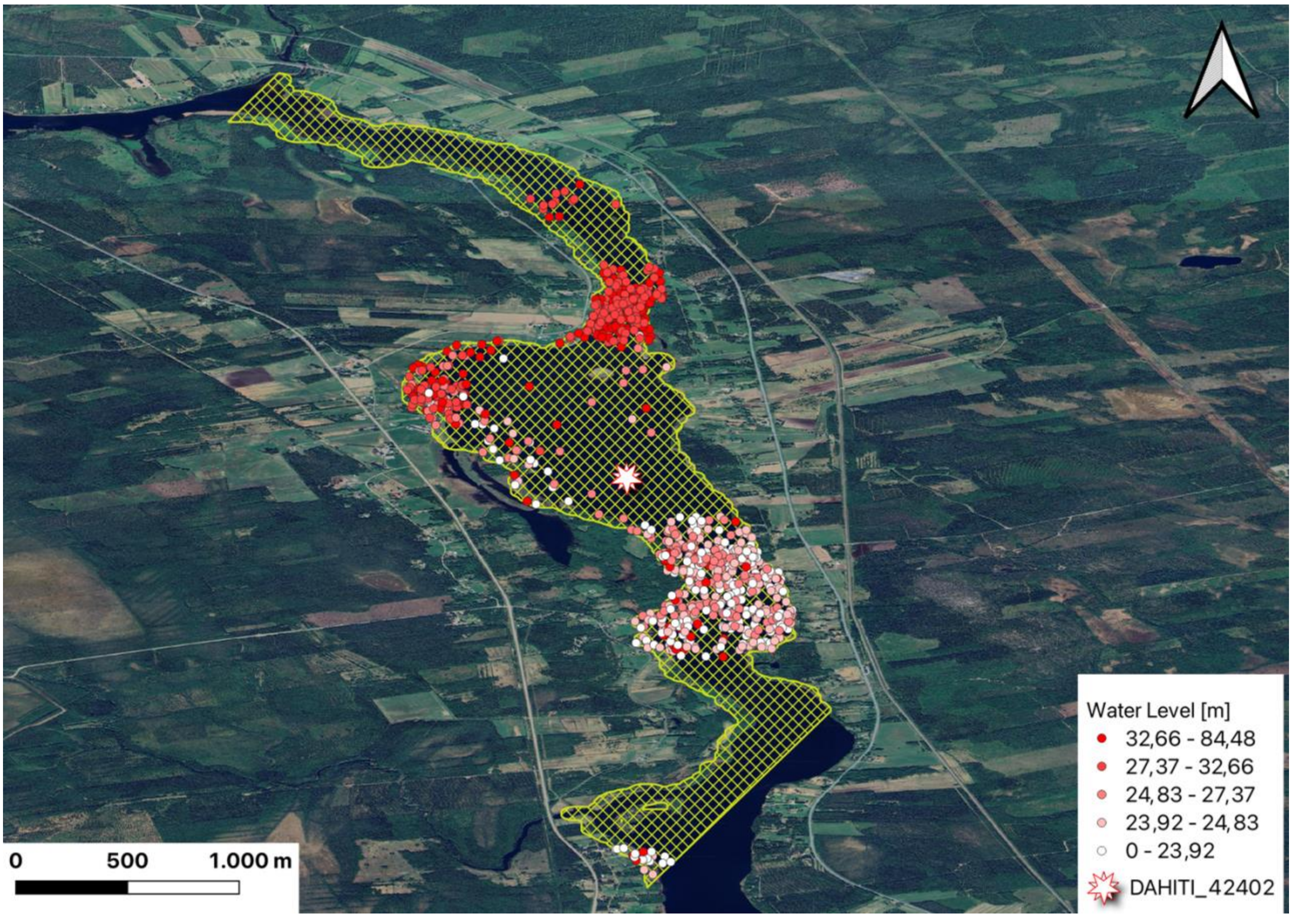

Figure 1: S3B_136 virtual stations and Tero-WL data points over it.

The estimation of river slope has been performed using data from the SWOT mission.

To estimate the SWOT derived slope, the average WSE from several SWOT passes is used. First, WSE is computed as the average of all SWOT measurements at a 50m radius (slightly higher than the 200m used in the SWOT river node product) around points separated also by 50m along the river centerline. This is performed separately for each SWOT pass available and then all of them are averaged one more time to obtain the final time-averaged WSE. To avoid unphysical results, we force the slope to be monotonically decreasing. UAV data is then projected to the same centerline. Steps are described in Figure 2.

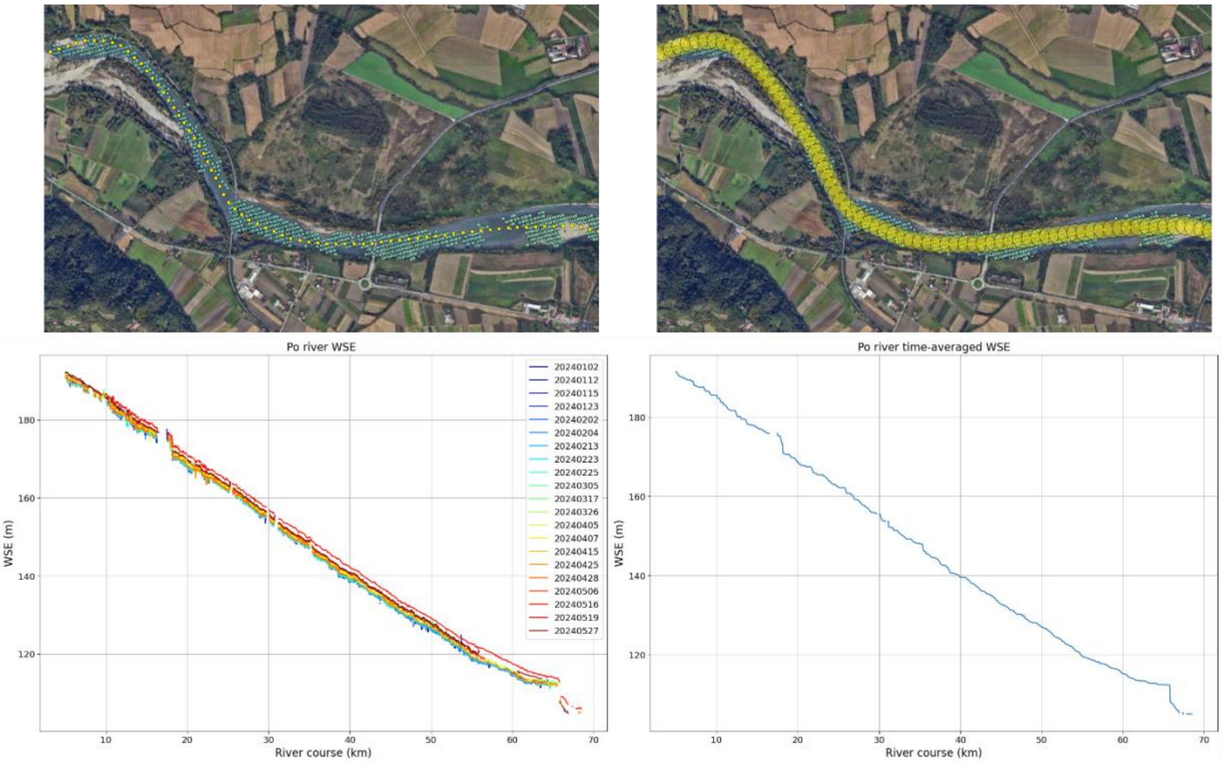

Figure 2: Steps followed to obtain the time-average SWOT WSE slope. Starting from the original data (top left), we perform the average of all SWOT points at 50m around points separated by 50m along the river centerline (top right). This is repeated for several dates (bottom left), and finally the average of all slopes is computed avoiding unphysical results (bottom right).

3. Validation of satellite against UAV measurements

The validation of conventional altimetry datasets satellite presents significant challenges, primarily due to the very limited availability of suitable data points. Field campaigns must be conducted under specific and stable hydrological and meteorological conditions, which makes it difficult to acquire measurements coincident with satellite overpasses that have very low repetity frequency (e.g. for Sentinel 3 every 35 days). Furthermore, conventional altimetry satellites orbit suffer a drift from nominal track (+/- 1km) that makes very difficult to obtain colocated insitu measurements.

The unprecedented increase in data availability provided by SWOT (Surface Water and Ocean Topography) fundamentally transforms this validation landscape. SWOT's wide-swath KaRIn interferometric altimeter delivers near-continuous spatial coverage of rivers and lakes larger than ~50–100 m in width, producing dense grids of water surface elevation measurements at unprecedented spatial resolution. Instead of relying on a single nadir track intersecting a water body every several weeks, SWOT offers orders-of-magnitude more observations, enabling validation strategies that are both more flexible and more statistically robust. Furthermore, SWOT's high spatial resolution allows comparisons not only at point locations (as in nadir altimetry) but also across river reaches, enabling the validation of hydrodynamic gradients, slope patterns, and spatial consistency of water surface elevation within a single overpass. This markedly increases the number of usable matchups and reduces the logistical constraints traditionally associated with field campaigns.

For the 2024 campaigns, the WSE measured by the NRA24 radar altimeter instrument has been used to validate SWOT data for the same day whenever it is available. For 2025, the data from the LX_80 radar was used instead.

When this comparison is not possible because there are no collocated observations, we have analyzed the slope derived from the UAV radar altimeter measurements and the SWOT derived slope (as estimated in section 2.5).

3.1. Tero WL Sentinel 3 WSE validation

Using conventional altimetry, only the 2024 Po River field campaign met the necessary temporal and environmental requirements for this validation. The positions of the data points used in this comparison are shown in Figure 3.

For this field study, the closest available field measurement to the satellite observation was selected, and the difference between the two water surface elevation values was computed after using the same geoid and correcting for along-river height using the SWOT-derived river slope. Consequently, the reported difference of 3.107m does not include elevation effects along the river. However, the mean distance between the satellite track and the closest UAV-derived point is around 270 m, while the elevation difference estimated from the SWOT-derived slope is only 6.1 cm. Such a small height difference over this distance likely reflects the low spatial precision of SWOT measurements and the averaging applied to derive the river slope, meaning that fine-scale topographic variations are not fully captured. Therefore, part of the residual 3.107m discrepancy could be attributed to local river topography, in addition to residual bias and the inherent limitations of single, non-coincident field validations.

As discussed in Section 2.2, water surface elevation data derived from satellite altimetry are most reliable for capturing relative changes rather than absolute values, since biases can be corrected across missions or using in-situ data. This emphasizes that single-point comparisons should be interpreted with caution.

Figure 3: Po River field study data and coincident satellite data point.

3.2. SWOT's WSE validation

When comparing the UAV radar altimeter WSE with SWOT WSE for the same day, we need to take into account that measurements from both datasets have different footprints, i.e., SWOT satellite's footprint is about 20m, and UAV altimeter measurements is of around 0.5m. To address this spatial gap, for every SWOT measurement we select the surrounding UAV data points at a 20 m radius and average the reported UAV WSE, similarly to what was done for the time-averaged WSE slope. This averaging process also helps reduce the amount of noise present in data. This is only performed for those data points at a distance to the centerline of 20 m or less.

Once this correspondence between UAV radar altimeter and SWOT measurements is achieved, we calculate the bias, the mean absolute error (MAE) and coefficient of determination (R2) between both sources. SWOT provides WSE measurements with respect to the WGS 84 ellipsoid, while the UAV campaigns are referenced to different height reference systems. Orco and Po datasets use the ITALGEO05 quasi-geoid, Torne data is provided with respect to the RH2000 height reference system, and Isar data uses the DHHN2016 height reference system. For the purpose of the comparisons, all data has been set to the EGM 2008 geoid.

For the available field studies, we found analogous SWOT satellite passes for:

- the Orco River on 2025-04-08.
- the Torne River on 2024-09-05.
- the Isar River on 2024-02-24 and on 2025-07-29.

Figure 4 shows the WSE data from SWOT and the trajectories made by the UAV at the study sites after filtering.

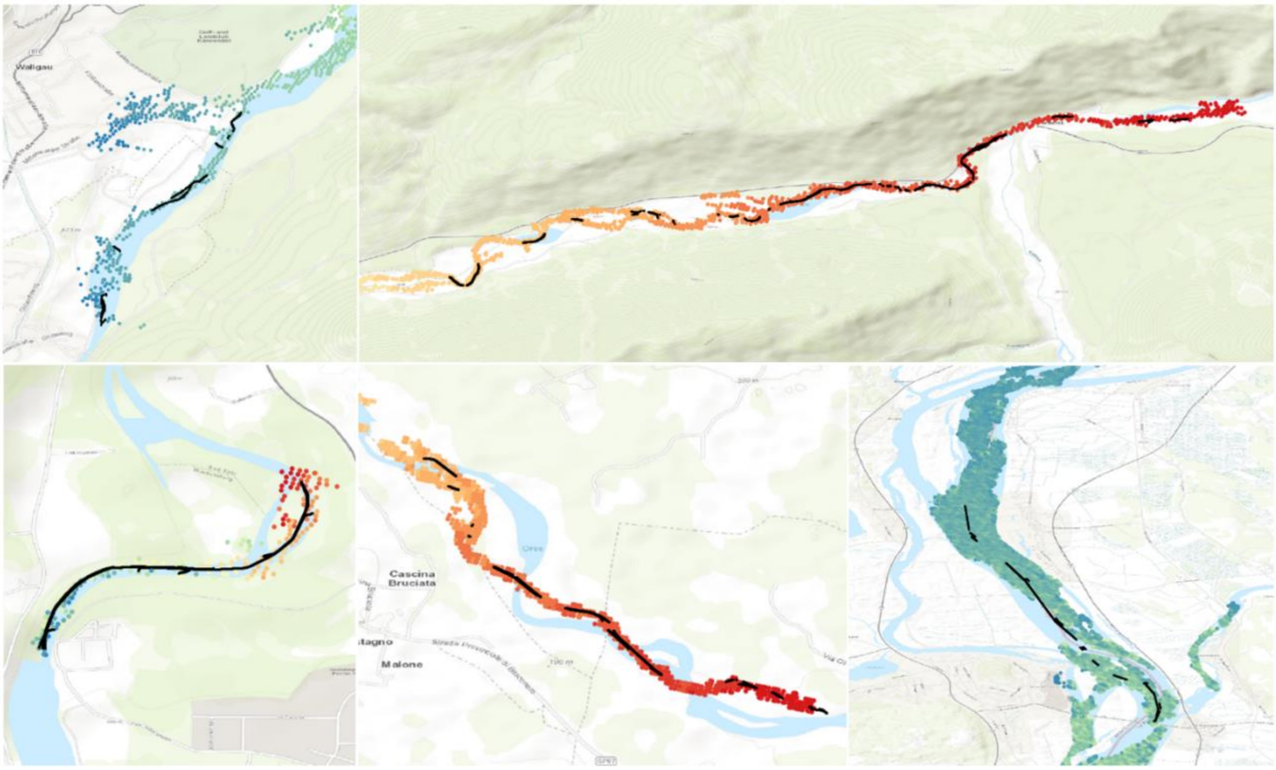

Figure 4: WSE data points from SWOT colored by WSE for each study site, along with the UAV trajectories post-filtering. From left to right and from top to bottom: Isar 2024 (first zone), Isar 2024 (second zone), Isar 2025, Orco 2025 and Torne 2024.

As an example, in Figure 5 we can see the UAV measurements plotted against their equivalent SWOT averaged data points for Orco River data measured during the field campaign on April 8, 2025. In red, we can see the line of best fit for the set of points, with a slope of 0.95. The MAE between the two measurements is 0.470 m, the coefficient of determination is R^2=0.959 and the bias is 0.23 m.

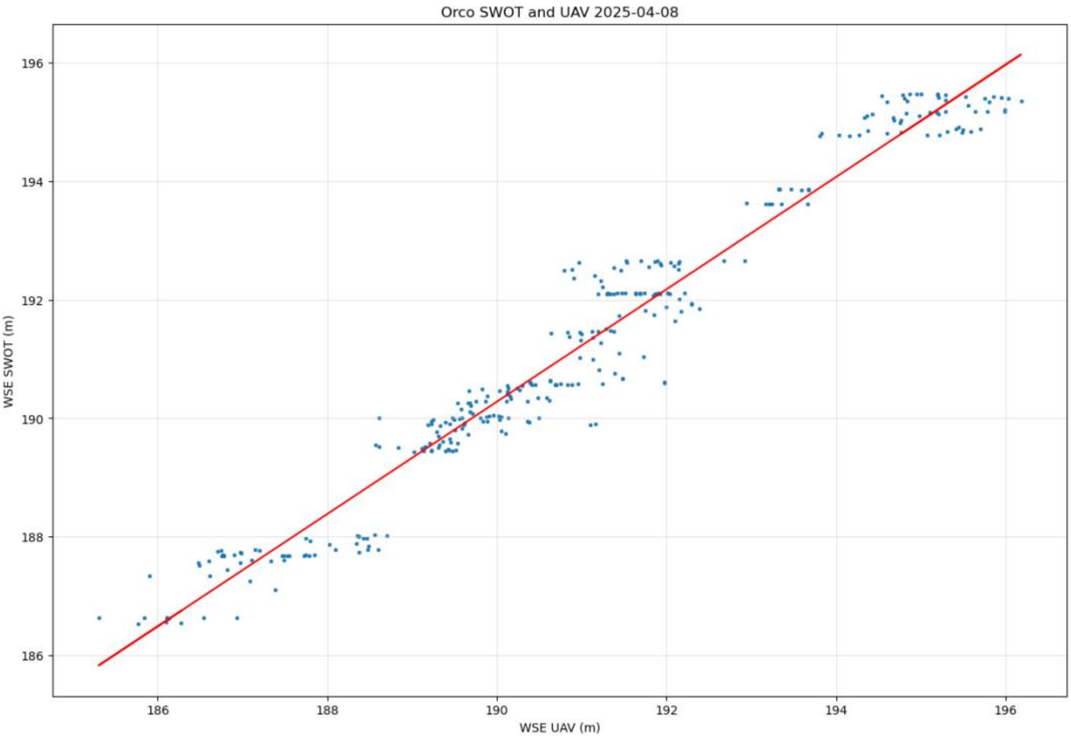

Figure 5: UAV radar altimeter against SWOT WSE during the Orco campaign on April 8, 2025. In red, best fitting line for the set of points.

A summary of the results for all the different campaigns that took place can be seen in Table 2. All parameters lie in a very similar range, with the sole exception of the 2024 Torne campaign, where the data presented no correlation due to the noise in SWOT data, the small range of values for the WSE and the presence of some outliers in the UAV WSE data that required to be removed. Nevertheless, the congruence between the two data sources is clear when working with all the points obtained along the whole river course.

Campaign	Bias (m)	R^2	Slope	MAE (m)
Isar 2024 zone 1	-0.30	0.949	0.89	0.487
Isar 2024 zone 2	-0.35	0.996	1.01	0.395
Torne 2024	0.10	0.027	0.13	0.252
Orco 2025	0.23	0.959	0.95	0.470
Isar 2025	-0.04	0.858	0.96	0.340

Table 2: Summary of the different metrics obtained for all the campaigns with collocated SWOT and UAV observations.

Despite this, a notable difference between the UAV and SWOT measurements can be observed when working on a smaller scale. Looking closely at the collected data, it can be seen that the UAV altimeter captures much finer details of the subtle slope changes that occur along the river course that SWOT is uncapable of detecting due to its resolution and intrinsic noise. Data from the 2025 Orco campaign is the best example of this phenomenon. In Figure 6 we can see the SWOT and UAV data points obtained on April 8, 2025 zoomed at a specific point of the Orco river. The UAV radar altimeter can detect the rapids that occur due to the riffle-pool structures present in the river that are absent in the 50 m averaged SWOT slope. The order of magnitude of SWOT noise is too large for these features to be resolved, and in fact it creates unphysical results where the WSE increases along the river course, which would require to be corrected.

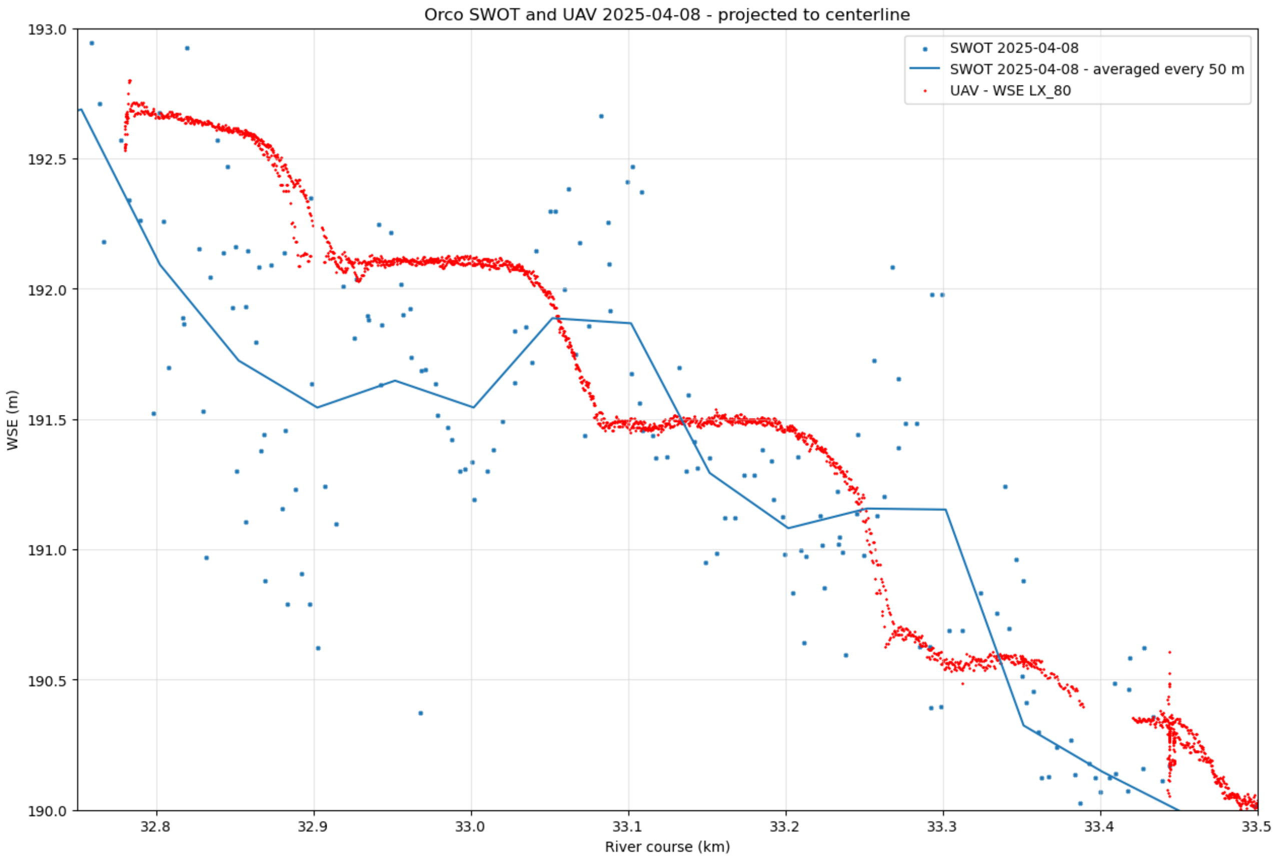

Figure 6: SWOT WSE for April 8, 2025 (blue points), SWOT estimated river slope for that same day (line in blue) and UAV radar altimeter WSE (red).

3.3. SWOT River Slope

The comparison between the UAV river slope and SWOT derived slope has been performed when there is no collocated UAV and SWOT data, completely or partially throughout the whole field study. To compute the metrics that compare the two sources, we used all the filtered UAV data and selected those SWOT time-averaged slope points that are closest to any of the UAV points. Results can be observed in Table 3. Like in the previous case, both datasets agree when dealing with the entire river.

Campaign	Bias (m)	R^2	Slope	MAE (m)
Torne 2024	0.48	0.996	1.00	0.666
Po 2024	-0.67	0.992	1.01	0.698
Orco 2024	-0.33	0.997	1.00	0.505
Orco 2025	-0.16	0.998	0.99	0.360

Table 3: Summary of the different metrics obtained for the non-collocated field campaigns against the time-averaged SWOT WSE data.

Looking at the finer details shows a similar effect to that seen when working with data from the specific campaign date. As can be observed in Figure 7, the SWOT 2025 time-averaged slope is still not able to capture the small changes in WSE that the UAV altimeter detects. Figure 9 shows that this occurrence takes place repeatedly throughout the river's course.

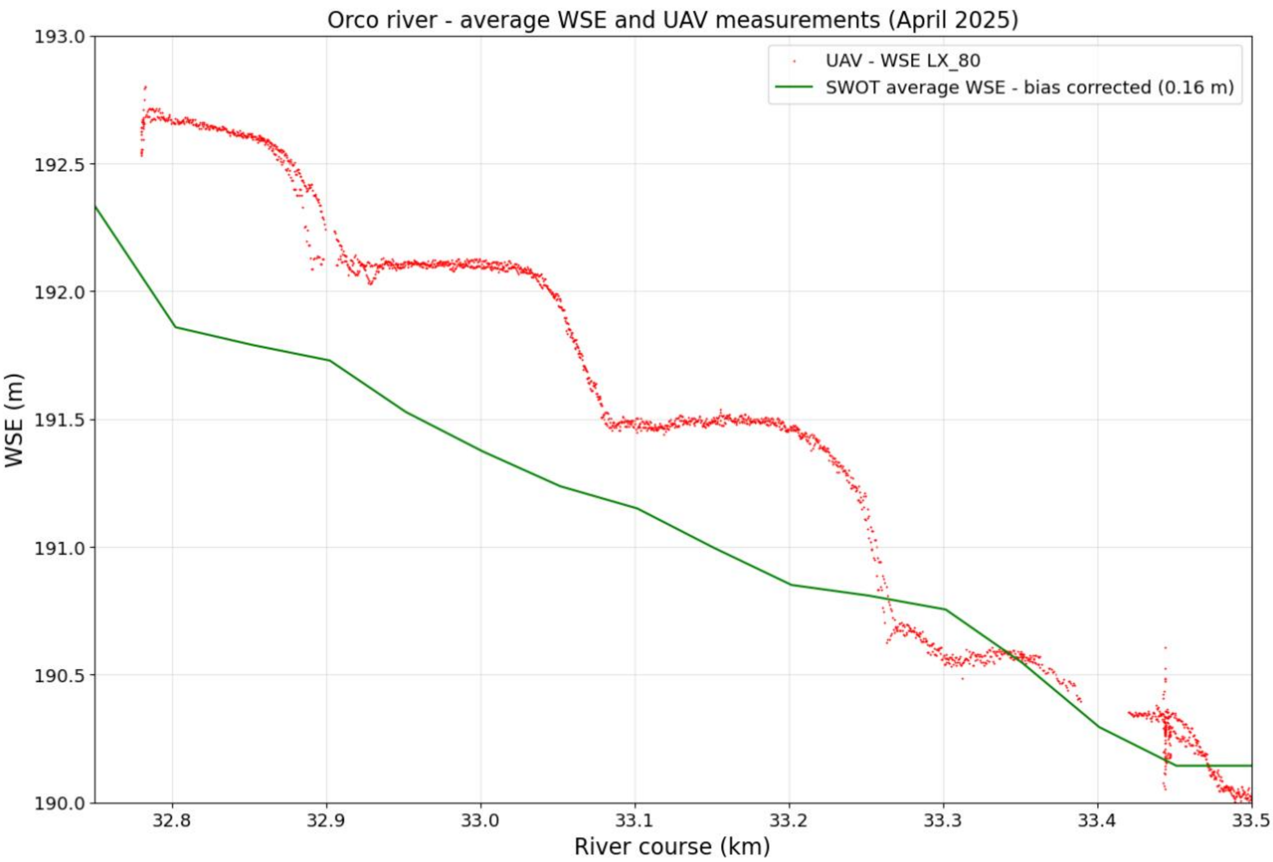

Figure 8: Detail of the SWOT 2025 time-averaged river slope (green) and UAV radar altimeter WSE (red) for the 2025 river Orco campaign.

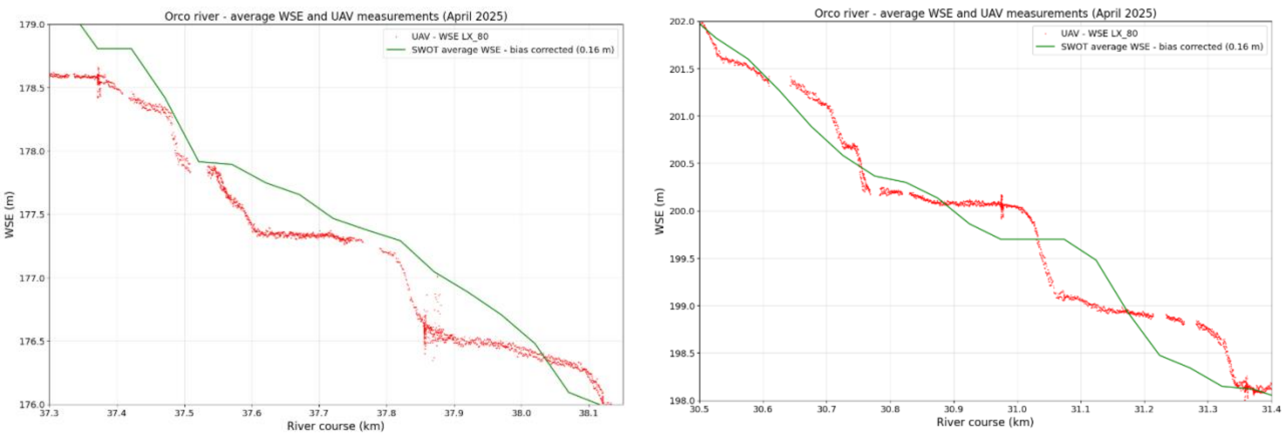

Figure 9: Detail of the SWOT 2025 time-averaged river slope (green) and UAV radar altimeter WSE (red) for the 2025 river Orco campaign at two different points.

4. Assessment of WSE in view of river discharge estimation

Within this task we have also evaluated the availability and accuracy of the satellite measurements that could potentially be used to estimate river discharge following UAWOS T4.1 Rating Curve estimation using UAS hydrometry.

4.1. Virtual stations and data availability

The following UAWOS study areas have been chosen to check the data availability, from 2020 to 2025, and compare it with other operational services such as DAHITI and CLMS (Copernicus Land Monitoring Service). These areas have been chosen for several reasons, the most decisive being the width of the river, the geometry of the satellite pass with respect to the river's course and data availability. In the following figures there can be seen the existing virtual stations for each of the operational services. Tero-VS virtual stations are displayed as areas with the name and pass number of the satellite it corresponds to, while DAHITI's and CLMS's are displayed as single points where these two services reference their measurements to. In the tables can be seen the number of data points for each virtual station and service.

Po river:

Figure 10: Po River virtual stations.

Virtual Station	Tero-WL	DAHITI	CLMS
S3B_43	70	NA	NA
S3A_293	75	NA	NA
S6_44	318	NA	NA
S3A_43 / DAHITI_38577	58	46	NA
S3B_350 / DAHITI_38576	38	131 (Including SWOT)	NA

Table 4: Po river virtual stations data availability VS DAHITI and CLMS.

Upper Isar river:

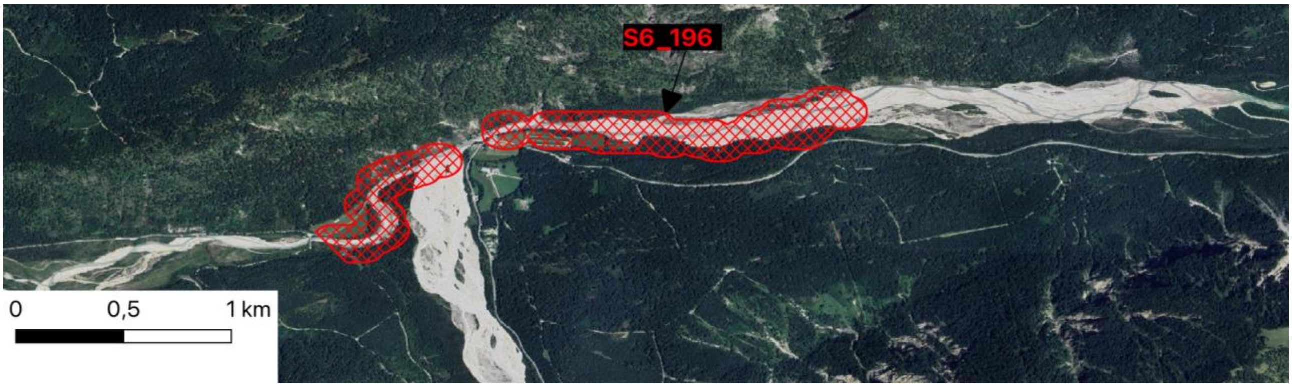

Figure 11: Upper Isar River virtual stations.

Virtual Station	Tero-WL	DAHITI	CLMS
S6_196	86	NA	NA

Table 5: Upper Isar river virtual station data availability VS DAHITI and CLMS.

Orco river:

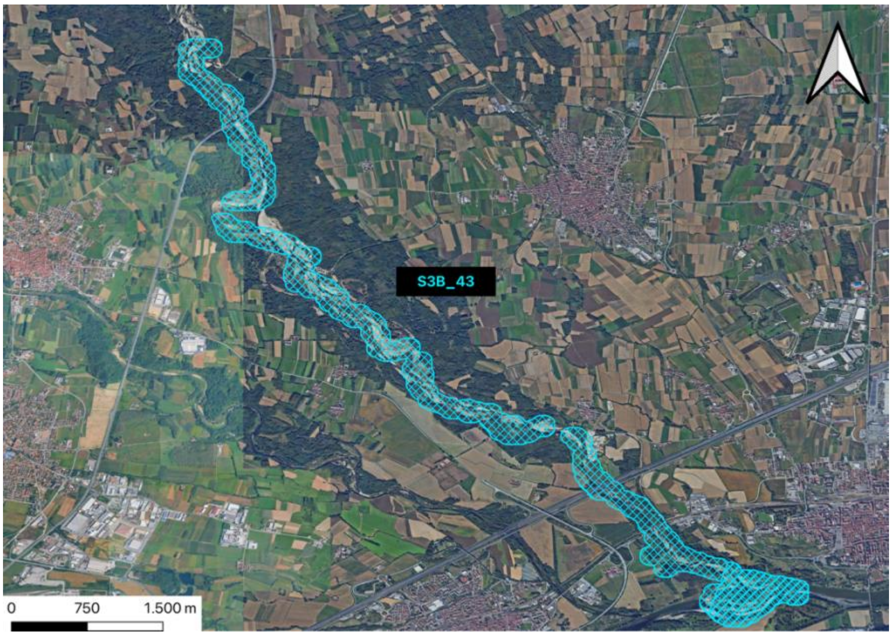

Figure 12: Orco River virtual stations.

Virtual Station	Tero-WL	DAHITI	CLMS
S3B_43	67	NA	NA

Table 6: Orco river virtual station data availability VS DAHITI and CLMS.

Ogun river:

Virtual Station	Tero-WL	DAHITI	CLMS
S6_135	214	NA	NA

Table 7: Ogun River virtual stations data availability VS DAHITI and CLMS.

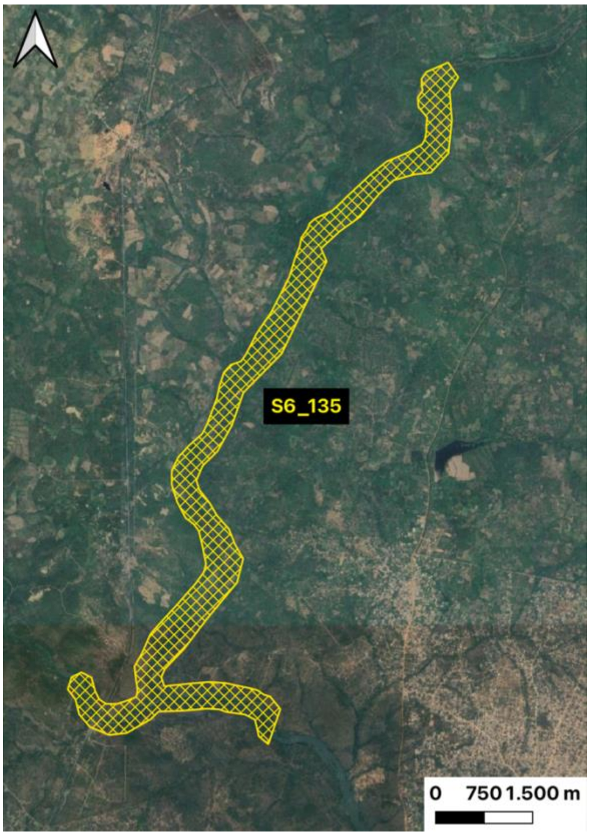

Figure 13: Ogun River virtual stations.

Ouémé river:

Virtual Station	Tero-WL	DAHITI	CLMS
S6_122_a	150	NA	NA
S6_122_b / DAHITI_9249	238	193	NA
DAHITI_38402 (ENVISAT)	NA	84*	NA
DAHITI_38403 (ENVISAT)	NA	83*	NA

Table 8: Ouémé River virtual stations data availability VS DAHITI and CLMS. (*) These measurements were taken before the study period.

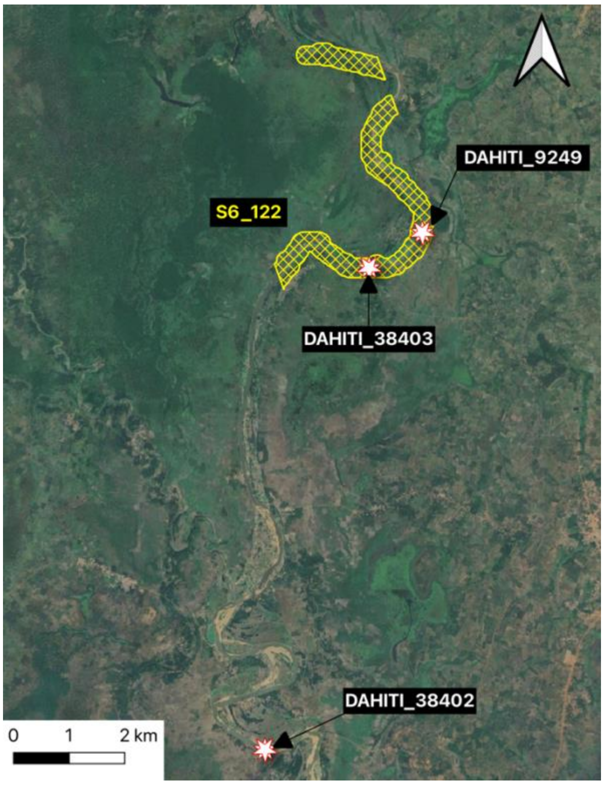

Figure 14: Ouémé River virtual stations.

Torne river:

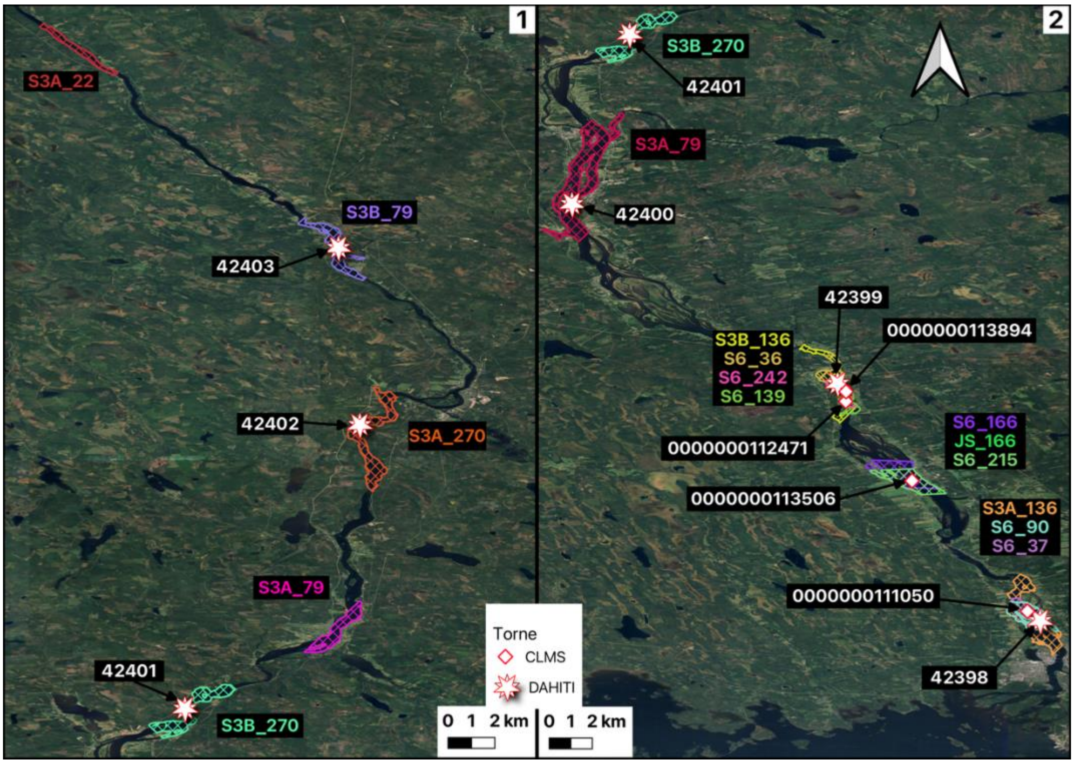

Figure 15: Torne River virtual stations.

Virtual Station	Tero-WL	DAHITI	CLMS
S6_37 / 0000000111050	216	NA	113
S6_242 / 0000000113894	447	NA	99
S6_215 / 0000000113506	442	NA	105
S6_139 / 0000000112471	445	NA	79
S6_90	171	NA	NA
S6_166	445	NA	NA
S6_63	175	NA	NA
S3B_270 / DAHITI_42401	68	43	NA
S3A_136 / DAHITI_42398	245	117	NA
S3B_136 / DAHITI_42399	71	64	NA
S3A_79 / DAHITI_42400	68	98	NA
S3A_270 / DAHITI_42402	63	63	NA
S3B_79 / DAHITI_42403	72	58	NA
S3A_22	65	NA	NA

Table 9: Torne River virtual stations data availability in the Tero-VS, DAHITI and CLMS services.

As shown in the previous figures and tables, Tero-VS identifies a substantially larger number of virtual stations than the other services, and Tero-WL provides denser water level time series over the studied period for all CLMS virtual stations and for most of the DAHITI ones. This difference primarily stems from the higher flexibility of the Tero-VS framework and the multi-mission support implemented in Tero-WL. Unlike DAHITI and CLMS, which rely on predefined and precomputed virtual stations, Tero-VS allows the dynamic generation of new virtual stations at user-defined locations. This capability enables Tero-WL to exploit all available satellite passes intersecting a given river reach, thereby maximizing data availability, particularly in areas where multiple missions overlap.

In contrast, DAHITI and CLMS are limited to their existing virtual station catalogs and cannot incorporate new locations without reprocessing their entire datasets. As a result, their spatial coverage and temporal sampling are inherently constrained by prior design choices. Tero-WL's multi-mission approach further enhances data density by combining observations from different altimetry missions, leading to improved temporal resolution when multiple satellites sample the same area.

It is worth noting that the only virtual station for which Tero-WL shows a significantly less dense time series is the S3B_350/DAHITI_38576 station on the Po River (Figure 10). This exception is explained by DAHITI's integration of the Surface Water and Ocean Topography (SWOT) mission observations to increase time series density. Although SWOT data have only been available since August 2023, the wide-swath nature of the instrument provides a much denser sampling than conventional nadir altimetry, allowing DAHITI to rapidly enhance data availability at this location.

4.2. Tero-WL and DAHITI validation against in-situ measurements

The validation of the Tero-WL and DAHITI products was performed using available in-situ water level observations from the Matkakoski (Torne River) and Casale Monferrato (Po River) gauge stations. These stations were selected due to their close proximity to corresponding virtual stations available in both the Tero-WL and DAHITI datasets. No suitable in-situ measurements were found near any of the CLMS virtual stations; therefore, this service was excluded from the validation analysis

Table 10 and Table 11 present the comparison between Tero-WL and DAHITI water level products using in-situ observations as reference. Overall, the results indicate that Tero-WL generally achieves better performance than DAHITI across most validation metrics. Tero-WL tends to show higher Pearson's correlation coefficients and lower unbiased error metrics (uMAE and uRMSE), suggesting a better capability to capture water level variability and temporal dynamics.

At the Matkakoski station (Table 10), DAHITI achieves a slightly lower uRMSE compared to Tero-WL, indicating marginally better performance in terms of overall error dispersion. Nevertheless, Tero-WL shows lower uMAE and a higher Pearson's correlation coefficient, implying a more accurate representation of water level variations despite a somewhat higher uRMSE. This suggests that while DAHITI may reduce large deviations, Tero-WL provides a more consistent and correlated signal with the in-situ measurements.

At the Casale Monferrato station (Table 11), DAHITI exhibits an almost negligible bias, while Tero-WL shows a moderate systematic offset. However, when considering the remaining metrics, Tero-WL consistently outperforms DAHITI, especially in terms of uMAE and uRMSE. Since bias correction is commonly applied to satellite altimetry–derived water level datasets prior to operational use, the superior unbiased error metrics of Tero-WL indicate a higher intrinsic data quality. The near-zero bias observed in DAHITI is likely related to bias correction steps already included in its processing chain.

The multi-track comparison further highlights the robustness of Tero-WL. For both Sentinel-3A and Sentinel-3B passes, Tero-WL products show higher correlation coefficients and substantially lower unbiased error metrics than the corresponding DAHITI datasets. In contrast, DAHITI products, despite exhibiting nearly zero bias, often display weak correlation and larger dispersion errors. These results reinforce the conclusion that, once bias correction is applied, Tero-WL delivers more reliable and higher-quality water level estimates than DAHITI in most validation scenarios.

Metric	Tero-WL	DAHITI
Pearson's CC	0.5479	0.5299
Bias	0.7708	1.3325
uMAE	0.6180	0.7465
uRMSE	0.9493	0.8890

Table 10: Matkakoski in-situ validation results.

Metric	Tero-WL S3A_43	DAHITI_38577	Tero-WL S3B_350	DAHITI_38576
Pearson’s CC	0.627	0.049	0.545	0.605
Bias	-0.649	-0.006	-0.676	0.001
uMAE	0.283	0.429	0.290	0.375
uRMSE	0.351	0.626	0.348	0.602

Table 11: Casale Monferrato in-situ validation results.

5. Conclusions

The findings of this task demonstrate that UAS-based hydrometry is an essential tool for the validation and enhancement of satellite-derived inland water observations. UAV data provides the high-fidelity baseline required to identify and correct the inherent limitations of both conventional and wide-swath (SWOT) altimetry.

UAS platforms successfully addressed the critical bottlenecks of satellite validation. While conventional altimetry (e.g., Sentinel-3) is hindered by low revisit frequencies and orbital drift, the deployment of the UAV altimetry sensors could allow for spatial and temporal synchronization overcoming river slope issues by providing colocated in-situ measurements and capturing water surface elevation (WSE) at satellite overpasses, something rarely achievable with fixed gauging stations. UAV altimetry data can be used to derive high precision WSE and river slope.

The comparison with SWOT slope estimates shows high correlation between UAV altimetry and SWOT. However, a mean absolute error of around 0.5 m has been consistently observed that should be attributed to SWOT being less accurate. Indeed, this study proves that UAS data is necessary to resolve unphysical noise and enhance satellite accuracy. UAV altimetry sensors detected fine-scale riffle-pool structures and rapids (as seen in the Orco River) that are entirely invisible to SWOT’s 50 m averaged slope.

Finally, the assessment of the WSE estimates in virtual stations as a preparatory activity for estimating discharge at virtual stations indicates that Tero-WL provides a more comprehensive and temporally dense dataset than DAHITI and CLMS, particularly for monitoring river water levels where multi-mission observations are available. In-situ validation supports Tero-WL’s higher reliability in capturing temporal variability, while the field study underscores the challenges and limitations of absolute height validation, emphasizing the importance of bias correction and careful interpretation. Overall, Tero-WL demonstrates clear advantages in both spatial coverage and temporal resolution, making it a robust tool for river water level monitoring.

6. References

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