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A multi-river contactless airborne river bathymetry dataset

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Abstract

High-resolution river bathymetry data are essential for a wide range of hydrological, hydrodynamic, and fluvial geomorphological applications. Unoccupied Aerial Systems (UASs) serve as flexible airborne platforms for carrying a range of sensing instruments, enabling contactless and non-invasive data acquisition, particularly in remote or hard-to-access locations. This paper presents a large, openly available dataset of UAS-borne water penetrating radar (WPR) and sonar/echosounder bathymetric measurements collected from seven rivers across Europe and Africa. The measurements were validated against ground truth reference data, showing good agreement and demonstrating that UAS bathymetric mapping can achieve satisfactory performance under a wide range of natural conditions.

Background & Summary

River bathymetry data are fundamental to a wide range of water-related research and applications¹⁻⁴. Detailed representations of river channel bathymetry support various river management applications, including flood risk assessment, navigational safety, ecological assessment and the monitoring of channel sediment dynamics⁵⁻⁸. Bathymetric data are also an important input for hydrodynamic modelling. Accurate representation of channel cross-sectional geometry is important for reliable simulations of flow depth, water surface elevation, and discharge^{9,10}. In the absence of detailed observations, hydrodynamic models often rely on simplified representations of channel geometry¹¹⁻¹³, which may introduce errors into model simulation¹⁴. When the geometric and roughness parameters are calibrated jointly, inaccurate bathymetric representations will be compensated for calibrated roughness parameters, reducing model reliability^{11,15}.

Bathymetric data are also increasingly important for remote sensing based discharge estimation¹⁶. Remote sensing provides an important means of estimating river discharge over large spatial scales, particularly in ungauged and poorly gauged regions. However, underwater channel geometry, which is unobservable from space, constitutes an important source of uncertainty in the inversion of discharge from remotely sensed water surface observations^{11,17,18}.

Improved availability and sharing of river geometry data, including cross-sectional bathymetry, are therefore important for advancing large-scale remote sensing of river discharge¹⁹.

Bathymetric mapping requires sufficiently high spatial resolution to capture the spatial variability of channel morphology and riverbed characteristics²⁰⁻²². Regular surveys are also needed to capture temporal changes in channel bathymetry caused by sediment erosion, deposition or human activities. Timely and accurate characterization of these spatial and temporal changes are essential for maintaining up-to-date river channel representations, which can support hydrodynamic model calibration and validation, improve discharge estimation, and enhance flood simulation and assessment²³⁻²⁵.

Conventional bathymetric surveys are primarily based on in situ measurements, such as real-time kinematic global navigation satellite system (RTK-GNSS) surveys. Although RTK-GNSS can provide highly accurate elevation measurements, it requires the operator to enter or access the river channel and collect a large number of points manually. It is therefore labour-intensive and often constrained by factors such as water depth, site accessibility, and operational safety. As a result, the spatial resolution, cross-section spacing, and revisit frequency of such surveys are frequently limited^{26,27}. Boat-mounted single-beam or multi-beam swath sonars can provide more continuous measurements of bed elevation. However, boat deployment requires sufficient water depth and practical river access, making such surveys difficult in shallow or remote river reaches^{28,29}.

To overcome the limitations of conventional field surveys, remote sensing approaches have been increasingly developed for river bathymetric mapping. Existing contactless or unoccupied aerial systems (UAS) approaches can be broadly classified into three categories: 1) depth retrieval from airborne or UAS spectral imagery^{4,30-34}; 2) reconstruction of submerged topography from overlapping optical imagery using structure-from-motion (SfM) techniques³⁵⁻³⁸; and 3) direct measurements using bathymetric LiDAR, sonar, or radar systems^{39,40}. The first two approaches estimate bathymetry indirectly from optical observations, and their performance strongly depends on water clarity, bed visibility, water depth, and surface-reflection conditions. Consequently, these optical approaches are generally most effective when the riverbed remains sufficiently visible through the water column^{32,33}, limiting their applicability in turbid or optically challenging river environments.

Among the direct sensing approaches, green bathymetric LiDAR can penetrate the water column and directly measure bed elevation. It has been applied to inland water and river surveys and can provide highly accurate bathymetric information under suitable conditions^{3,41-44}, with penetration depths typically reaching approximately 2-3 Secchi depths and, more recently, up to about 5 Secchi depths⁴⁵. However, green LiDAR systems are relatively costly compared with conventional topographic LiDAR and other UAS-based sensing approaches. In addition, their performance can be influenced by water clarity and suspended sediment concentrations, which restricts their wider application in turbid rivers and repeated large-scale surveys^{33,46}.

UAS-mounted sonar and water penetrating radar (WPR) provide additional promising direct measurement approaches for river bathymetry. UAS sonar generally requires the sensor to remain in contact with the water surface during the survey, and deployment is limited by water speed and aquatic vegetation^{40,47}. In contrast, WPR can be operated from the air at low flight

altitudes to detect reflections from the water surface and riverbed without requiring contact with the water. Its performance is generally less affected by submerged vegetation than sonar-based approaches^{40,48}. However, the effective penetration depth of WPR is strongly influenced by water electrical conductivity, as higher conductivity increases electromagnetic attenuation and can limit the detectability of the riverbed.

Overall, UAS borne WPR has shown strong potential as an efficient complement to conventional in situ bathymetric surveys, particularly in river reaches that are difficult or unsafe to access or where boat deployment is impractical^{29,40,48}. Nevertheless, high-quality and openly available bathymetric data remain scarce in practical applications. Compared with terrestrial digital elevation models (DEM), publicly accessible river bathymetry datasets are limited, and multi-site datasets spanning different river types and field conditions are even less common⁴⁹⁻⁵¹. This lack of comprehensive bathymetric datasets not only constrains hydraulic modelling and river management applications, but also further development of UAS-based bathymetric mapping approaches under realistic field conditions.

To address this need, this study presents a GNSS referenced river bathymetry dataset acquired using a UAS-based sensing platform (DJI Matrice 300). The dataset includes 81 cross-sections surveyed across seven rivers in Europe and Africa. Submerged bathymetry was primarily measured using a Zond Aero LF WPR. At selected sites where conditions allowed, independent in situ reference data were also collected and used for technical validation; the comparisons show overall good agreement between UAS-derived bathymetry and field measurements. By covering diverse real-world river environments, the dataset provides a basis for evaluating UAS bathymetric methods across different field conditions.

The released dataset enables the construction of river channel geometry for hydraulic modelling and model-based discharge estimation⁵², and provides cross-sectional information for UAS-based contactless discharge estimation approaches⁵³. By making multi-site, multi-sensor bathymetric cross-sections and associated reference data openly available, this dataset provides a reusable basis for hydraulic modelling, fluvial geomorphological monitoring, bathymetric method validation, and future repeat surveys.

Methods

Study sites and field surveys

Between 29.08.2023 and 30.07.2025, a total of 81 cross sections were surveyed at 7 rivers across Europe and Africa, including Torne River (Sweden), Rönne River (Sweden), Isar River (Germany), Po River (Italy), Orco River (Italy), Ouémé River (Benin), and Ogun River (Nigeria). The locations of the surveyed rivers are shown in Figure 1, while the locations and names of individual cross-sections are presented in Figure 2. The objective of the surveys was to obtain georeferenced bathymetric profiles across the river channels. Once the submerged bathymetry is collected, complete cross-sectional geometry profiles can be derived by combining the topographic information derived from near infrared (NIR) LiDAR surveys or existing DEM (digital elevation model) products.

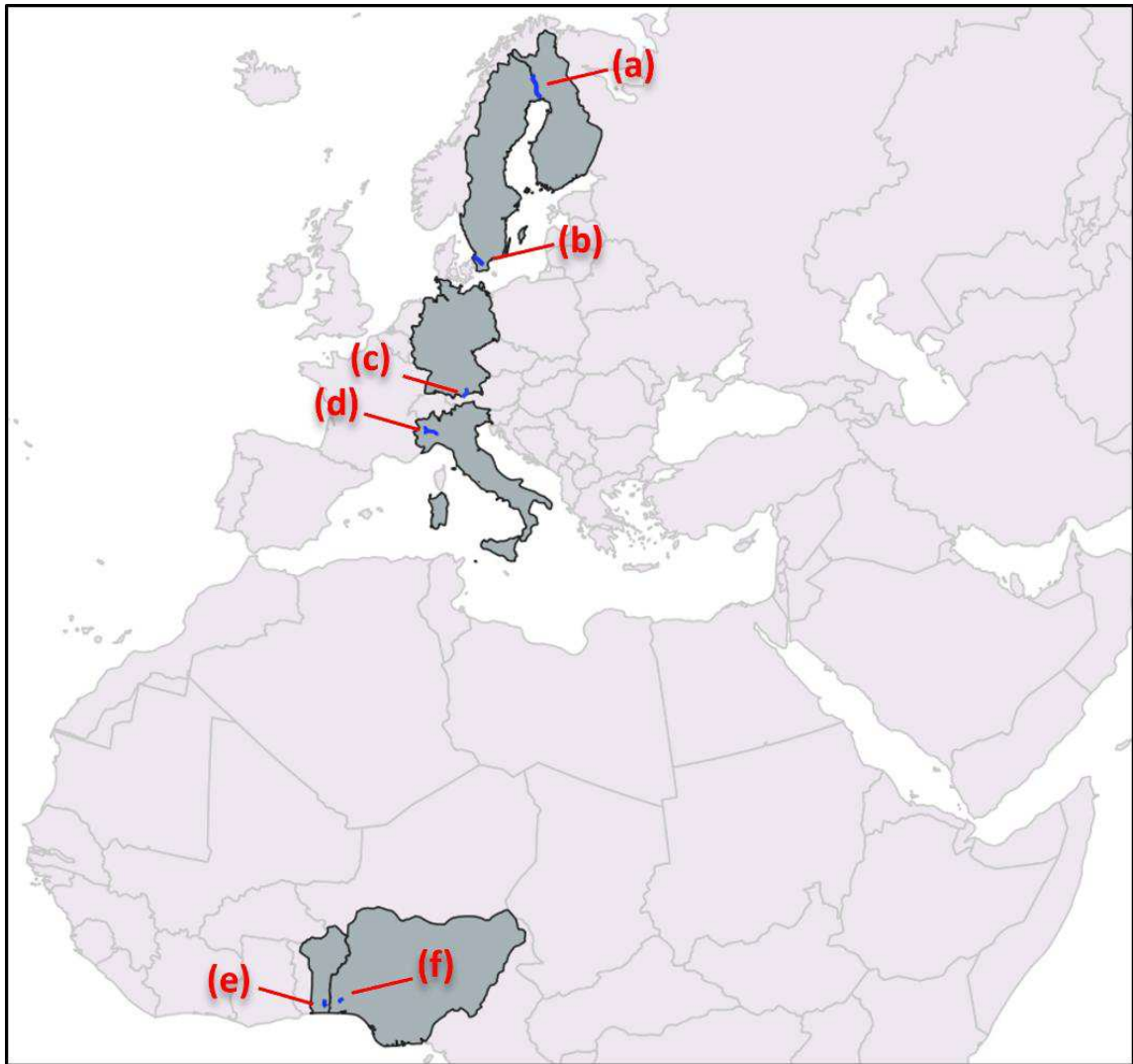


Figure 1. The overview map of the surveyed river reaches.

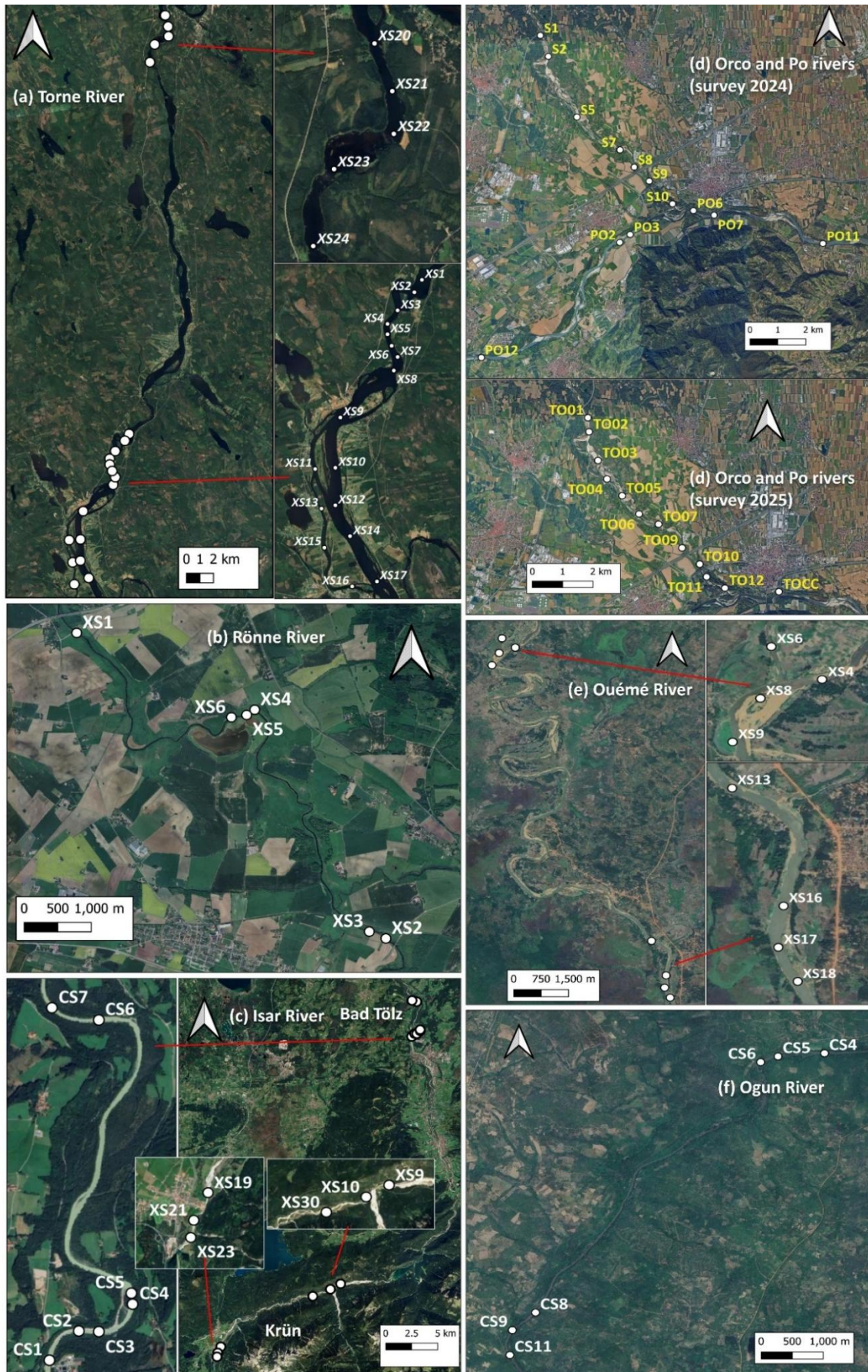


Figure 2. Detailed overview of the surveyed cross-sections, with the corresponding name of each cross-section shown on the map.

UAS platform and survey workflow

The submerged portions of the riverbed were mainly surveyed using UAS-borne WPR Zond Aero LF, while the Sonar ECT400S was used as the primary comparison dataset, as sonar represents an established reference technology for bathymetric measurements⁴⁸. During the Rönne River survey, additional legacy or reference configurations, including WPR Gekko 80, Sonar ECT 400 and Deeper CHIRPplus were also operated for comparison, the detailed intercomparison of these sensors is presented by Zhou (2025)⁴⁸. Table 1 list the comparison of key characteristics between Sonar / Echosounder, WPR and green LiDAR.

Table 1. Comparison of key characteristics of UAS-borne Sonar/Echosounder, WPR, and green LiDAR for river bathymetric surveys.

	Sonar / Echosounder	Ground (Water) Penetrating Radar (GPR, WPR in this paper)	Green LiDAR
Cost of payload	~€10k	~€10k	~€100k
Postprocessing effort	Medium, can be automatized	High, not fully automatic	High, can be automatized
Autonomy/flight height	Tethered and in contact with water	≤ 0.5 m above water	> 30 m above water
Depth range	Up to 100 m	~ 5 m, frequency dependent	Limited by turbidity, 2-3Secchi depths
Resolution	Centimeters	Centimeters to decimeters, frequency dependent	Centimeters
Penetration into bed sediments	No	Yes	No
Deployment in strong currents	Limited in strong current	Yes	Yes
Sensitivity to turbidity	None	None	Typically ~2-3 Secchi depths, recent studies report up to 5 Secchi depths ⁴⁵ . River Secchi depth is commonly 0.2 – 0.5 meters
Sensitivity to salinity	Low, can be corrected for	High, <1000 $\mu\text{S}/\text{cm}$	None
Sensitivity to water temperature	High, can be corrected for	None	None
Sensitivity to bottom type / color	Medium	High	High
Sensitivity to aquatic vegetation	High, frequency dependent	Low	High

The primary UAS platform used to acquire this dataset was the DJI Matrice 300, which provided sufficient payload capacity and RTK-enabled navigation for the Zond AERO LF WPR and ECT400S sonar systems. Additional platforms, including DJI Matrice 600 and the HydroHex were used for selected reference and comparison measurements. On the DJI Matrice 300 RTK and DJI Matrice 600, bathymetric payloads, rover GNSS receiver and altitude control components (True Terrain Follow, TTF) were integrated through the UgCS SkyHub onboard computer. SkyHub facilitates sensor configuration, control and storage of georeferenced raw data from supported sensors. In combination with TTF mode, it also enables accurate, and efficient operations compare to HydroHex, which was operated manually.

The bathymetric measurements were georeferenced using an onboard RTK/PPK (Real Time Kinematic / Post-Processed Kinematic) GNSS (Global Navigation Satellite System) system,

Emlid Reach M2 rover GNSS receiver was used. During operation, a locally deployed GNSS base station transmitted correction data to the rover receiver through NTRIP (Networked Transport of RTCM via Internet Protocol) connection. Because these corrections were transmitted over the Internet, reliable mobile broadband connectivity was required. Starlink was used at remote survey sites where 4G LTE coverage was insufficient. A True Terrain Follow system from SPH Engineering was additionally integrated through SkyHub to control the flight height relative to the water surface. This was particularly important for WPR surveys, during which the UAS generally needed to maintain a height of less than approximately 0.5 m above the water surface to obtain high-quality radar signals. The overall conceptual illustration of the workflow is shown in Figure 3.

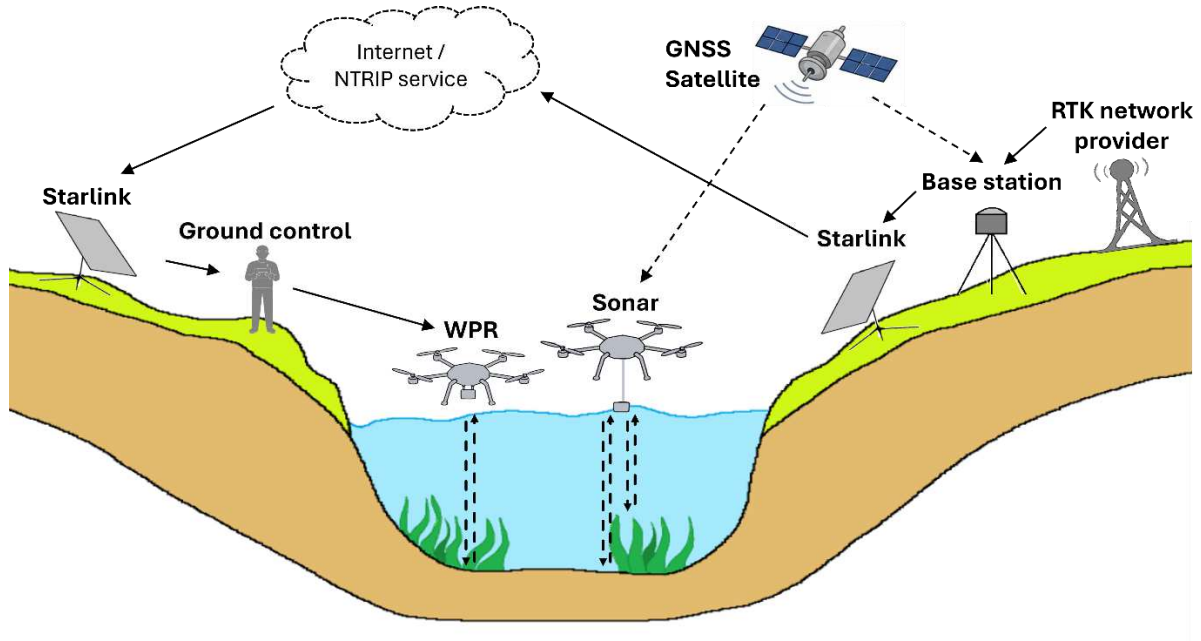


Figure 3. Conceptual illustration of the UAS-based bathymetric survey workflow.

UAS bathymetry measurements

The derivation of riverbed elevation consists of two components: the retrieval of water depth and the determination of water surface elevation (WSE). For WPR, Water depth is derived from the different propagation paths of electromagnetic waves from the water surface and the riverbed. When the emitted radar wave reaches air-water interface, part of signal is reflected by the water surface, while the remaining energy propagates through the water column and subsequently reflected by the riverbed. The two-way travel time between the water-surface and the riverbed reflections thus represents the propagation time within the water column, and water depth can be calculated as:

$$d = \frac{v_w(t_b - t_s)}{2} \quad (1)$$

where d is water depth, t_b and t_s are the travel time with the water-surface and riverbed reflections respectively. v_w is the propagation speed of electromagnetic wave in the water. During the processing workflow, the water surface reflection is first identified as reference, and

riverbed reflection is subsequently picked for each radar trace to derive the corresponding water depth.

Once the water depth is derived, water surface elevation (WSE) is further needed to convert the depth into bed elevation. Where available, WSE was measured directly using ground-based RTK-GNSS. For a fully contactless approach, WSE can also be estimated from the UAS altitude recorded by the onboard RTK and the predefined flight height above the water surface. Using the TTF system, the UAS can maintain an approximately constant distance above the water surface at the prescribed height during flight. Accordingly, WSE can be calculated as:

$$WSE = z_{GNSS} - \Delta z_{GNSS-TTF} - D_{TTF} \quad (2)$$

where z_{GNSS} is the height of GNSS antenna reference point from RTK or PPK. $\Delta z_{GNSS-TTF}$ is the offset between GNSS antenna and TTF altimeter radar, for RTK is 0.21m and for PPK is 0.36m. It should be noted that offset of 0.21 m / 0.36 m are specific to the UAS platform and payload configuration used in this study. This offset should be remeasured if the platform or mounting configuration is changed. D_{TTF} is the distance between altimeter radar and water surface. Based on field experience, a distance of less than 0.5 m generally provided a stronger radar reflection, and 0.4 m was used during the surveys.

Finally, the riverbed elevation is calculated as:

$$z_{riverbed} = WSE - d \quad (3)$$

Figure 4 illustrates the measurement principle for deriving water depth and WSE from the UAS-borne WPR. Sonar bathymetry follows a similar principle but uses acoustic rather than electromagnetic waves. Unlike WPR, the sonar transducer needs to remain in contact with water body and water depth is determined from two-way travel time of acoustic pulse between the riverbed and transducer⁴⁸.

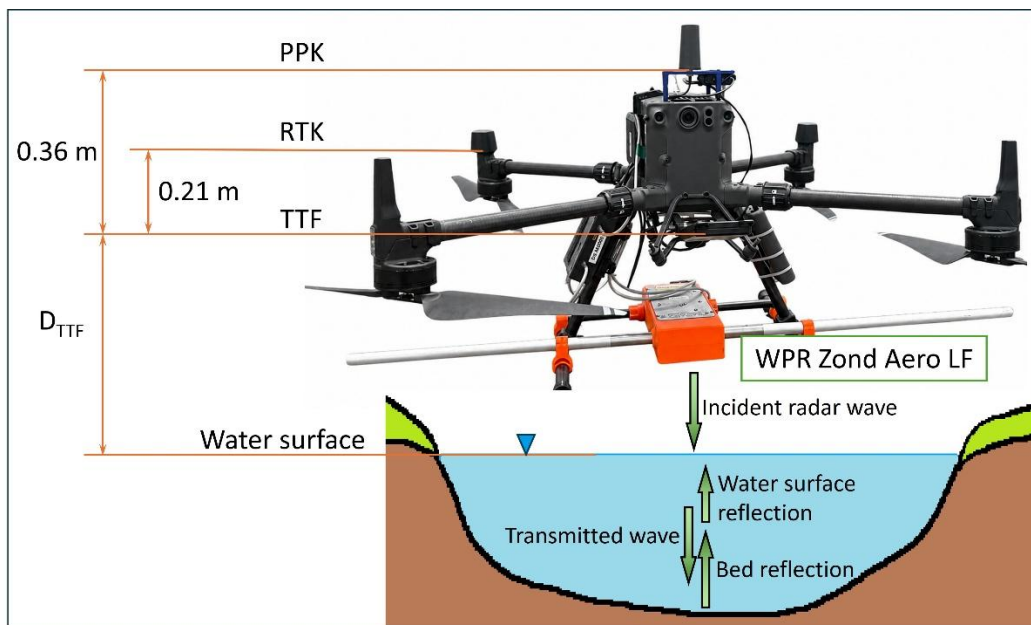


Figure 4. Schematic of UAS-borne WPR bathymetry measurements.

Sensor applicability and operational limitations

The sonar transducer must remain in direct contact with the water. During UAS surveys, the transducer is therefore suspended beneath the UAS using a tether. This configuration restricts sonar operations to relatively slow flowing conditions because strong currents may displace or tilt the transducer. For sonar sensor equipped with housing attachment, a maximum flow velocity is 1.5 m/s and 0.8 m/s for sensor without housing attachment. Sonar measurements can also be affected by submerged vegetation²⁹. WPR determines water depth from the travel time of electromagnetic waves. In contrast to sonar, WPR does not require direct contact with the water and can therefore provide a fully contactless bathymetric measurement. WPR is generally less sensitive than single-beam sonar to submerged vegetation and is consequently the preferred solution where contactless surveying is required⁴⁰. Its limitation is the electric conductivity of water. Based on the operational experience, WPR performance becomes strongly limited when water electrical conductivity exceeds approximately 300–400 $\mu\text{S}/\text{cm}$, although the practical limit also depends on radar frequency for depth penetrating ability, water depth and site-specific conditions, particularly bottom type.

Reference bathymetry observations

Besides UAS bathymetry, independent ground-based reference data were also collected to evaluate the accuracy of the UAS bathymetry. These reference observations included boat-mounted acoustic Doppler current profiler (ADCP) measurements and RTK GNSS surveys measurements. The availability of the different measurement types at each cross section is summarized in Table 2. In addition, EPSG codes adopted for the horizontal and vertical coordinate reference systems, the operating frequencies of the UAS-WPR and the water electric conductivity for the surveyed cross-sections are also listed in Table 2.

Table 2. Names, locations, survey dates, data availability, EPSG codes, WPR operating frequencies, and water electrical conductivity for each surveyed cross-section.

River	Cross-section name	Location		Survey date	UAS bathymetry					Insitu reference bathymetry	
					Water penetrating radar (WPR)		Sonar			ADCP	RTK-GNSS
		Lon	Lat		Zond Aero LF	Gekko 80	ECT400	ECT400S	DeeperC HIRPpluss		
Isar River (Krün)	XS9	11.44	47.56	27/02/2024	x						
	XS10	11.43	47.56	27/02/2024	x						x
	XS19	11.29	47.51	27/02/2024	x						x
	XS21	11.28	47.50	25/02/2024	x						x
	XS23	11.28	47.50	26/02/2024	x						x
	XS30	11.41	47.55	27/02/2024	x						x
Isar River (Bad Tölz)	CS1	11.54	47.78	29/07/2025	x					x	x

	CS2	11.54	47.78	29/07/2025	x		
	CS3	11.55	47.78	30/07/2025	x		
	CS4	11.55	47.78	30/07/2025	x		
	CS5	11.55	47.79	30/07/2025	x		
	CS6	11.55	47.81	30/07/2025	x		
	CS7	11.54	47.81	30/07/2025	x		
Ogun River	CS4	3.35	7.31	12/05/2025	x		
	CS5	3.35	7.31	13/05/2025	x		
	CS6	3.34	7.31	13/05/2025	x		
	CS8	3.31	7.26	14/05/2025	x		
	CS9	3.31	7.25	15/05/2025	x		
	CS11	3.31	7.25	15/05/2025		x	
Orco River	Orco S1	7.81	45.24	14/07/2024	x		
	Orco S2	7.81	45.23	14/07/2024	x		
	Orco S5	7.83	45.21	14/07/2024	x		
	Orco S7	7.85	45.20	14/07/2024	x		
	Orco S8	7.86	45.20	14/07/2024	x		
	Orco S9	7.86	45.19	14/07/2024	x		
	Orco S10	7.87	45.19	15/07/2024	x		
	TO01	7.81	45.24	9/04/2025	x		x
	TO02	7.81	45.23	9/04/2025	x		
	TO03	7.82	45.22	9/04/2025	x		
	TO04	7.82	45.22	9/04/2025	x		x
	TO05	7.83	45.21	8/04/2025	x		
	TO06	7.84	45.21	8/04/2025	x		x
	TO07	7.84	45.20	8/04/2025	x		x
	TO09	7.85	45.20	9/04/2025	x		
	TO10	7.86	45.19	10/04/2025	x		
	TO11	7.86	45.19	10/04/2025	x		

	TO12	7.87	45.18	10/04/2025	x					
Po River	Po 2	7.85	45.17	15/07/2024	x					
	Po 3	7.85	45.17	15/07/2024	x					
	Po 6	7.88	45.18	15/07/2024	x					
	Po 7	7.89	45.18	15/07/2024	x					
	Po 11	7.94	45.17	15/07/2024	x					
	Po 12	7.79	45.13	15/07/2024	x					
	TOCC	7.90	45.18	10/04/2025	x					
Ouémé River	XS4	2.41	7.00	9/05/2025	x					
	XS6	2.40	7.00	9/05/2025	x					
	XS8	2.40	7.00	9/05/2025	x					
	XS9	2.40	6.99	9/05/2025	x					
	XS13	2.45	6.91	8/05/2025	x					
	XS16	2.45	6.90	8/05/2025	x					
	XS17	2.45	6.90	8/05/2025	x					
	XS18	2.45	6.89	8/05/2025	x					
Rönne River	XS1	13.02	56.18	29/08/2023		x	x	x	x	x
	XS2	13.09	56.13	30/08/2023	x		x	x	x	x
	XS3	13.09	56.14	30/08/2023	x	x	x	x	x	x
	XS4	13.06	56.17	31/08/2023	x	x	x	x	x	x
	XS5	13.06	56.17	31/08/2023	x	x	x	x	x	x
	XS6	13.06	56.17	31/08/2023	x	x	x	x	x	x
Torne River	XS1	23.75	66.51	6/09/2024	x					
	XS2	23.74	66.50	7/09/2024	x					x
	XS3	23.73	66.50	7/09/2024	x				x	x
	XS4	23.72	66.49	6/09/2024	x		x		x	x
	XS5	23.71	66.49	6/09/2024	x				x	x
	XS6	23.72	66.49	7/09/2024	x					x
	XS7	23.72	66.48	6/09/2024	x					x

XS8	23.72	66.48	6/09/2024	x			x
XS9	23.66	66.46	6/09/2024	x			x
XS10	23.65	66.44	7/09/2024	x			x
XS11	23.63	66.44	4/09/2024	x			
XS12	23.64	66.43	7/09/2024	x	x	x	x
XS13	23.63	66.43	4/09/2024	x			
XS14	23.65	66.42	5/09/2024	x		x	x
XS15	23.63	66.41	5/09/2024	x			
XS16	23.65	66.40	4/09/2024	x			
XS17	23.67	66.40	5/09/2024	x		x	x
XS19	23.69	66.38	5/09/2024	x	x		x
XS20	23.91	66.79	8/09/2024	x			x
XS21	23.92	66.78	8/09/2024	x			x
XS22	23.91	66.77	8/09/2024	x			
XS23	23.89	66.77	8/09/2024	x			x
XS24	23.88	66.76	8/09/2024	x	x	x	x

Table 2 (continued).

River	Cross section	EPSG code		Frequency (MHz)	Water electric conductivity (µS/cm)
		Horizontal	Vertical		
Isar River (Krün)	XS9	25832	7837	150	
	XS10	25832	7837	150	
	XS19	25832	7837	150	
	XS21	25832	7837	150	
	XS23	25832	7837	150	
	XS30	25832	7837	150	
Isar River (Bad Tölz)	XS1	25832	7837	150	194
	XS2	25832	7837	150	194
	XS3	25832	7837	150	194
	XS4	25832	7837	150	194
	XS5	25832	7837	150	194

	XS6	25832	7837	150	194
	XS7	25832	7837	150	194
Ogun River	CS4	32631	5773	150	
	CS5	32631	5773	150	
	CS6	32631	5773	150	
	CS8	32631	5773	150	
	CS9	32631	5773	150	
	CS11	32631	5773	150	
Orco	Orco S1	32632	6893	150	
	Orco S2	32632	6893	150	
	Orco S5	32632	6893	150	
	Orco S7	32632	6893	150	
	Orco S8	32632	6893	150	
	Orco S9	32632	6893	150	
	Orco S10	32632	6893	150	
	TO01	32632	6893	150	
	TO02	32632	6893	150	
	TO03	32632	6893	150	
	TO04	32632	6893	150	
	TO05	32632	6893	150	
	TO06	32632	6893	150	
	TO07	32632	6893	150	
	TO09	32632	6893	150	
	TO10	32632	6893	150	
	TO11	32632	6893	150	
	TO12	32632	6893	150	
Po	Po 2	32632	6893	150	
	Po 3	32632	6893	150	
	Po 6	32632	6893	150	
	Po 7	32632	6893	150	
	Po 11	32632	6893	150	
	Po 12	32632	6893	150	
	TOCC	32632	6893	150	
Ouémé River	XS4	32631	3855	150	
	XS6	32631	3855	150	
	XS8	32631	3855	150	
	XS9	32631	3855	150	
	XS13	32631	3855	150	

	XS16	32631	3855	150	
	XS17	32631	3855	150	
	XS18	32631	3855	150	
Rönne River	XS1	3006	5613		
	XS2	3006	5613	150	208
	XS3	3006	5613	100	200
	XS4	3006	5613	150	160
	XS5	3006	5613	150	160
	XS6	3006	5613	150	161
Torne River	XS1	3006	5613	150	26
	XS2	3006	5613	150	28
	XS3	3006	5613	150	28
	XS4	3006	5613	150	28
	XS5	3006	5613	150	28
	XS6	3006	5613	150	28
	XS7	3006	5613	150	28
	XS8	3006	5613	150	30
	XS9	3006	5613	150	32
	XS10	3006	5613	150	30
	XS11	3006	5613	150	
	XS12	3006	5613	150	37
	XS13	3006	5613	150	
	XS14	3006	5613	150	29
	XS15	3006	5613	150	
	XS16	3006	5613	150	37
	XS17	3006	5613	150	32
	XS19	3006	5613	150	30
	XS20	3006	5613	150	30
	XS21	3006	5613	150	32
	XS22	3006	5613	150	
	XS23	3006	5613	150	31
	XS24	3006	5613	150	33

Data Records

UAS bathymetric data and reference in situ datasets used for validation were collected, post-processed, and stored in the data repositories correspondingly organized by river and survey year⁵⁴⁻⁶¹. Within each survey-specific repository, the bathymetric data are stored in subfolders named according to the UAS platform and measurement payload used. For example, the folder

“Water_penetrating_radar_bathymetry_M300_ZondAeroLF” contains WPR bathymetric data collected using DJI M300 platform equipped with WPR Zond Aero LF.

Within each measurement folder, the data are further divided into raw and processed datasets. The raw data mainly include RINEX files containing observations from the base and rover GNSS receiver, SEG-Y files containing the complete radar or sonar echo records, and CSV log files containing time-stamped drone positions and corresponding trace numbers. The processed data are primarily stored in CSV format and include the x and y coordinates of each measurement point in the corresponding projected coordinate reference system, together with the riverbed elevation.

The processed bathymetric datasets also contain one column named “distance along reference line”, which describes the projected position of each measurement point within a cross-section specific reference coordinate system. Each cross-section was discretised into reference points at intervals decided according to its width and spatial scale. The lateral distance of each reference point from the river centreline was then calculated, with negative values assigned to the left bank and positive values to the right bank. The bathymetric measurement points were projected onto this relative cross-sectional coordinate system, enabling direct comparison among datasets collected at the same cross-section using different measurement methods. The CSV files also contain auxiliary variables required for processing the sonar and WPR measurements. The name, and description of individual variables are documented in the README file provided in each corresponding folder. The processed data folder also includes KML files defining the river chainage, which provides a relative longitudinal reference along the surveyed river reach, as well as cross-section reference line files used to define the local coordinate system of each cross-section (distance along reference line).

For Isar River (Krün)⁶¹, Rönne River⁶⁰, Torne River⁵⁸, Orco River and Po River 2024 survey⁵⁹, the file structure is slightly different, with three processing levels from Level 1 to Level 3. Level 1 contains the same content as raw data, whereas Level 3 corresponding to the processed data. Level 2 data are stored in CSV format and contain the same information as the processed data, except for the lateral distance of each reference point. To avoid redundancy, Level 2 was omitted from the datasets released subsequently.

In addition to the UAS derived datasets, the reference ground truth data used for validation are also stored in the corresponding repositories. The file structure is consistent with that of the UAS datasets: raw measurements obtained using different measurement methods, including RTK-GNSS and ADCP surveys, are stored in corresponding subfolders. The processed data folder containing the corresponding CSV files are also under the corresponding folder. The processed reference datasets include x, y coordinates and riverbed elevation in the same projected coordinate reference system as the UAS data. Distance along the reference line calculated using the same cross-sectional specific reference line as that applied to the UAS datasets are also included. Therefore, the reference and UAS bathymetric measurements can be directly compared for accuracy assessment and validation.

The file structures and columns of csv files are shown in Figure 5.

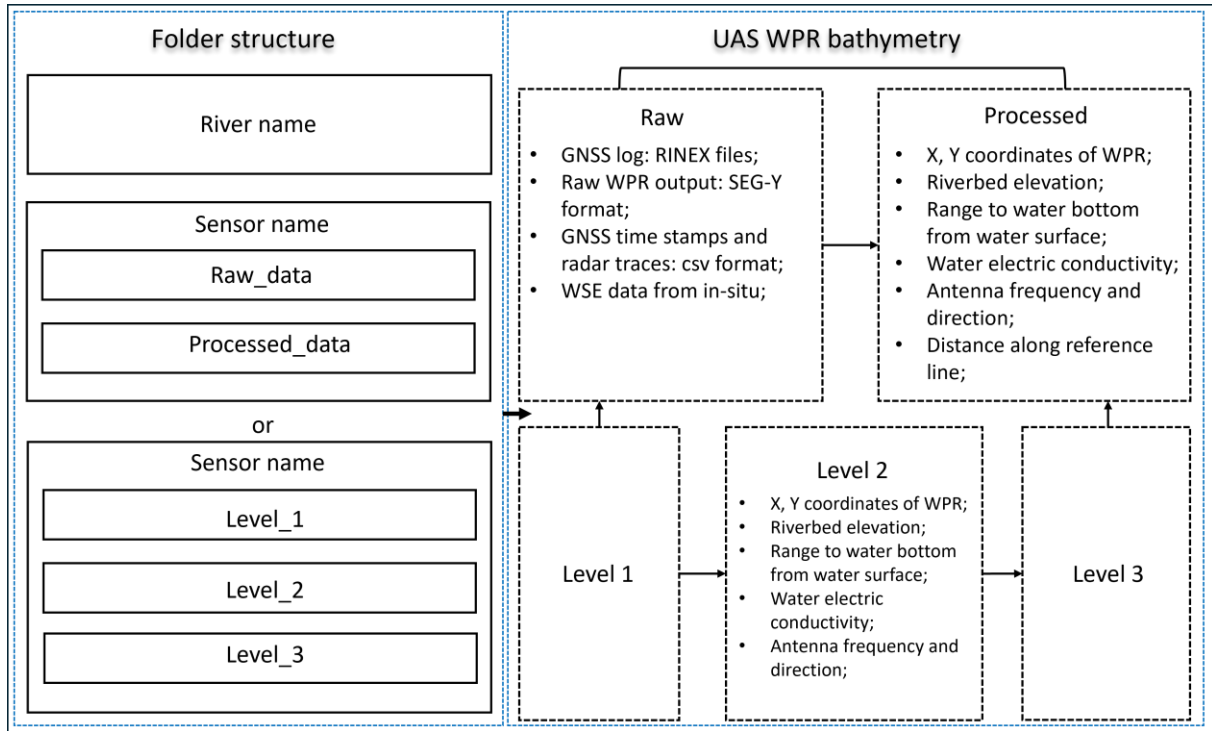


Figure 5. The folder structure and the columns of the generated csv files.

Technical Validation

The measured riverbed bathymetry was validated against ground-based in-situ reference data. Four statistical metrics were used to quantify measurement accuracy, the coefficient of determination (r^2), root mean square error (RMSE), mean absolute error (MAE) and bias. Since the in-situ measurement were available for only a subset of the surveyed cross-sections due to the realistic condition constraint, the validation was restricted to these cross-sections where in-situ references are available (Table 2). The number of cross-sections included in each assessment is reported as validation profiles as presented in Table 3 and Table 4.

The accuracy of measured riverbed bathymetry was evaluated using both point-to-point (Table 3) and interpolation-based (Table 4) comparisons³. For the point-to-point analysis, all UAS derived measurement points located within a radius of 0.1m^{62} around each ground reference point were used and averaged for the comparison. The analysis was conducted for profiles with RTK-GNSS bathymetry measurements. Table 3 summarizes the first quartile, median and third quartile of the resulting accuracy metrics across all validation profiles.

Interpolation-based comparisons were conducted primarily for cross-sections with available ADCP measurements. The UAS-derived and ADCP measurements were projected onto the same reference cross-section coordinate system and interpolated onto a common grid of 0.1m spacing. Locally Weighted Scatterplot Smoothing (LOWESS)⁶³ was used for the interpolation to capture the overall trend while avoiding overfitting to the measurement noise. The comparison was then conducted on the resulting profiles at corresponding grid locations. The interpolated-based comparison represents the accuracy of the reconstructed profiles which are commonly used as geometric inputs in hydraulic modelling. The results are reported in Table 4. The point-to-point comparison avoids the interpolation errors associated with profile reconstruction but assumes that measurements within the search radius represent the same local

bed surface, which could introduce errors from real changes of the elevation within the distance. In contrast, the interpolation-based comparison evaluates the accuracy of the final reconstructed cross-sectional geometry profiles but incorporates errors associated with spatial resolution, interpolation method, and data smoothing⁶².

From the point-to-point validation, the WPR Zond Aero LF achieved a median RMSE of 0.12 m, a median MAE of 0.09 m, and a median bias of 0.01 m. The interpolation-based errors were generally comparable to the point-level errors, with a median RMSE of 0.14 m, median MAE of 0.11 m, and median bias of 0.01 m. For the ECT400S sonar, the point-to-point RMSE, MAE, and bias were 0.24 m, 0.19 m, and 0.14 m, respectively, while the corresponding interpolation-based errors were 0.23 m, 0.19 m, and 0.13 m. Overall, the Zond Aero LF WPR demonstrated broad applicability as a fully contactless method for river bathymetric surveying. Compared with sonar, it can remain operational under high-speed flow conditions and in reaches with dense submerged vegetation, while achieving an overall accuracy of 0.10 m. Sonar can therefore serve as a complementary method in situations where WPR measurements are not feasible.

Figure 6 additionally presents representative cross-sections of the primary UAS-borne Zond Aero LF WPR bathymetry results, together with in-situ measurements and combined LiDAR-derived land elevations for comparison. Overall, good agreement is observed among the different datasets. Figure 7 provides a 3D illustration of the reconstructed river surface terrain along Isar River (Bad Tölz), covering CS1 to CS5, to demonstrate the potential of this dataset for continuous terrain reconstruction and hydraulic modelling applications. Appendix A further presents the full cross-sectional geometries for all surveyed cross-sections where WPR Zond Aero LF bathymetry is available. The full geometry is constructed by combining the WPR-derived bathymetry with LiDAR DEM. Corresponding reference measurements are also shown for cross-sections where such data are available.

Table 3. Point-to-point accuracy of measured riverbed bathymetry

Sensor	WPR Zond Aero LF	WPR Gekko80	Sonar ECT400	Sonar ECT400S	Sonar Deeper CHIRPplus
Validation profiles	26	5	6	10	6
First quartile r^2	0.59	0.52	0.38	0.38	0.60
Median r^2	0.84	0.60	0.70	0.72	0.91
Third quartile r^2	0.95	0.69	0.86	0.87	0.95
First quartile <i>RMSE (m)</i>	0.08	0.21	0.23	0.18	0.10
Median <i>RMSE (m)</i>	0.12	0.29	0.34	0.24	0.14
Third quartile <i>RMSE (m)</i>	0.15	0.43	0.41	0.30	0.18
First quartile <i>MAE (m)</i>	0.07	0.17	0.16	0.13	0.08
Median <i>MAE (m)</i>	0.09	0.22	0.29	0.19	0.10
Third quartile <i>MAE (m)</i>	0.13	0.28	0.34	0.22	0.11
First quartile <i>bias (m)</i>	-0.06	-0.10	0.15	0.06	0.00
Median <i>bias (m)</i>	0.01	0.05	0.28	0.14	0.05
Third quartile <i>bias (m)</i>	0.05	0.15	0.31	0.20	0.09

Table 4. Interpolation-based accuracy of measured riverbed bathymetry

Sensor	WPR Zond Aero LF	WPR Gekko80	Sonar ECT400	Sonar ECT400S	Sonar Deeper CHIRPplus
Validation profiles	12	5	6	9	6
First quartile r^2	0.80	0.43	0.38	0.43	0.66
Median r^2	0.92	0.69	0.66	0.89	0.88
Third quartile r^2	0.97	0.82	0.86	0.97	0.96
First quartile $RMSE$ (m)	0.11	0.20	0.25	0.18	0.13
Median $RMSE$ (m)	0.14	0.21	0.34	0.23	0.17
Third quartile $RMSE$ (m)	0.25	0.31	0.41	0.30	0.19
First quartile MAE (m)	0.08	0.13	0.20	0.14	0.11
Median MAE (m)	0.11	0.16	0.28	0.19	0.15
Third quartile MAE (m)	0.21	0.23	0.37	0.25	0.17
First quartile $bias$ (m)	-0.06	-0.15	0.20	-0.05	-0.02
Median $bias$ (m)	0.01	-0.08	0.28	0.13	0.13
Third quartile $bias$ (m)	0.09	0.09	0.37	0.21	0.14

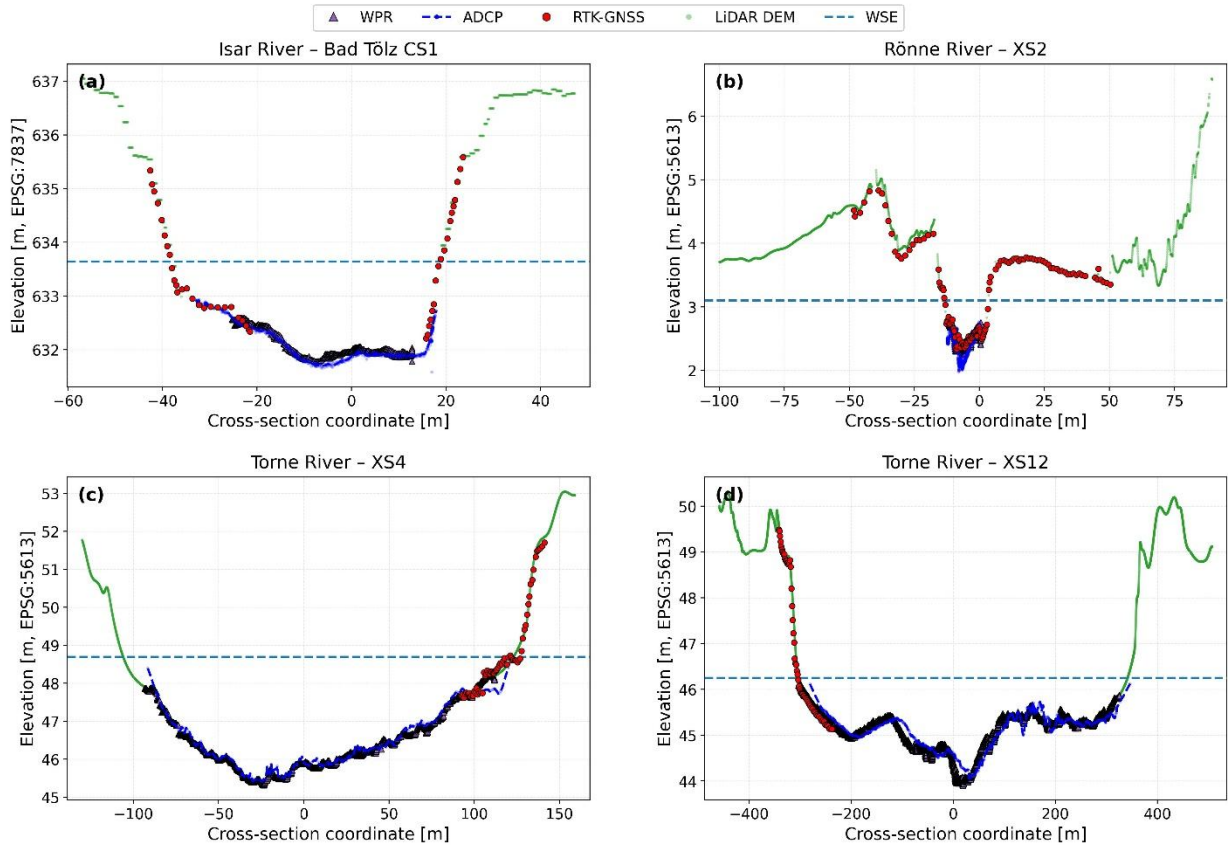


Figure 6. Comparison of bathymetry results between WPR Zond Aero LF, ADCP and RTK-GNSS.

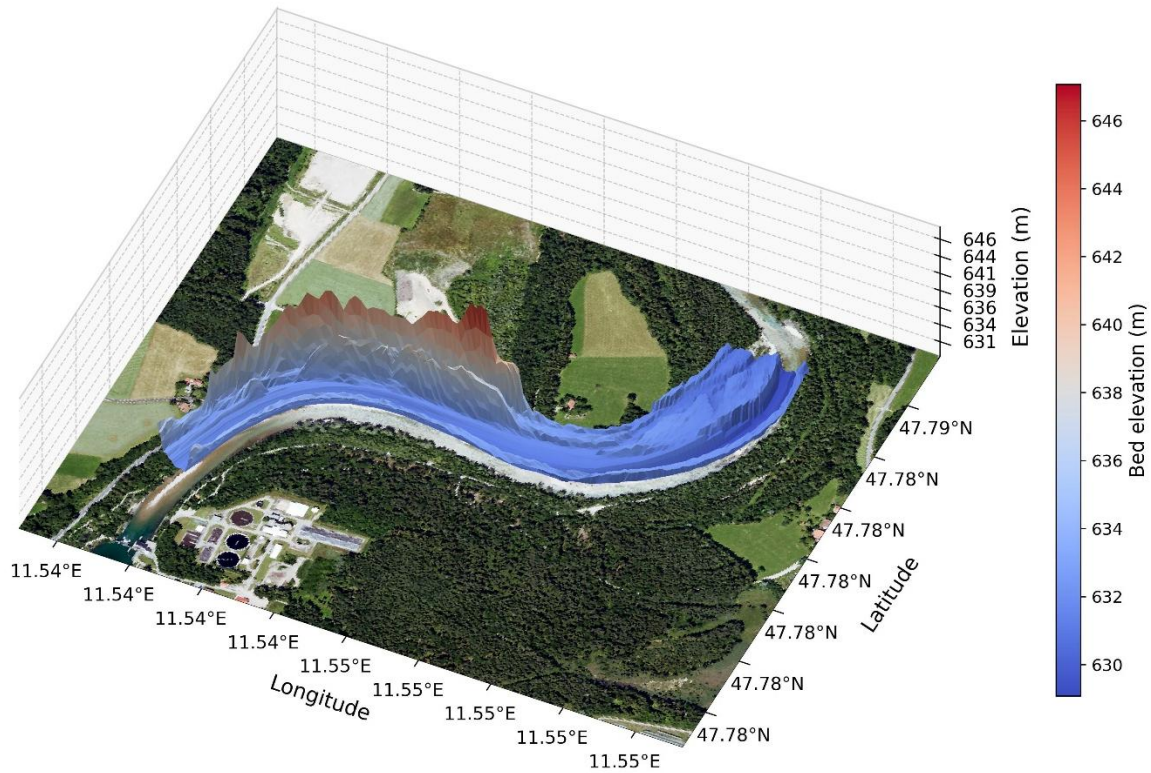


Figure 7. 3D plot of reconstructed river terrain at Isar River (Bad Tölz), CS1-CS5.

Usage Notes

Specialized software is required to process most of the raw data, whereas the processed data are provided as standard comma-separated value (CSV) files.

Data availability

The data presented in this work are available in publicly repositories and structured as follows:

- Isar River (Krün)⁶¹
- Isar River (Bad Tölz)⁵⁶
- Ogun River⁵⁴
- Orco River and Po River 2024 survey⁵⁹
- Orco River and Po River 2025 survey⁵⁷
- Torne River⁵⁸
- Ouémé River⁵⁵
- Rönne River⁴⁸

Code availability

The codes for UAS bathymetric data processing can be downloaded from the public data repository⁶⁴.

Author contributions

X.H. fieldwork, collected the data, code in Python and wrote the manuscript; Z.Z. code in Python and curated the data; F.M., M.D., E.C., S.B., D.G., A.T., V.F.J., M.A.P., S.N., D.W., V.F.,

D.G., A.D., N.O., T.G. and L.D. fieldwork and collected data; P.B. conceptualization, code in Python, curated the data, repository (meta) data management, and project administration. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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Appendix A

Appendix Figures A1–A78 present individual plots of the full cross-sectional geometry for all surveyed cross-sections.

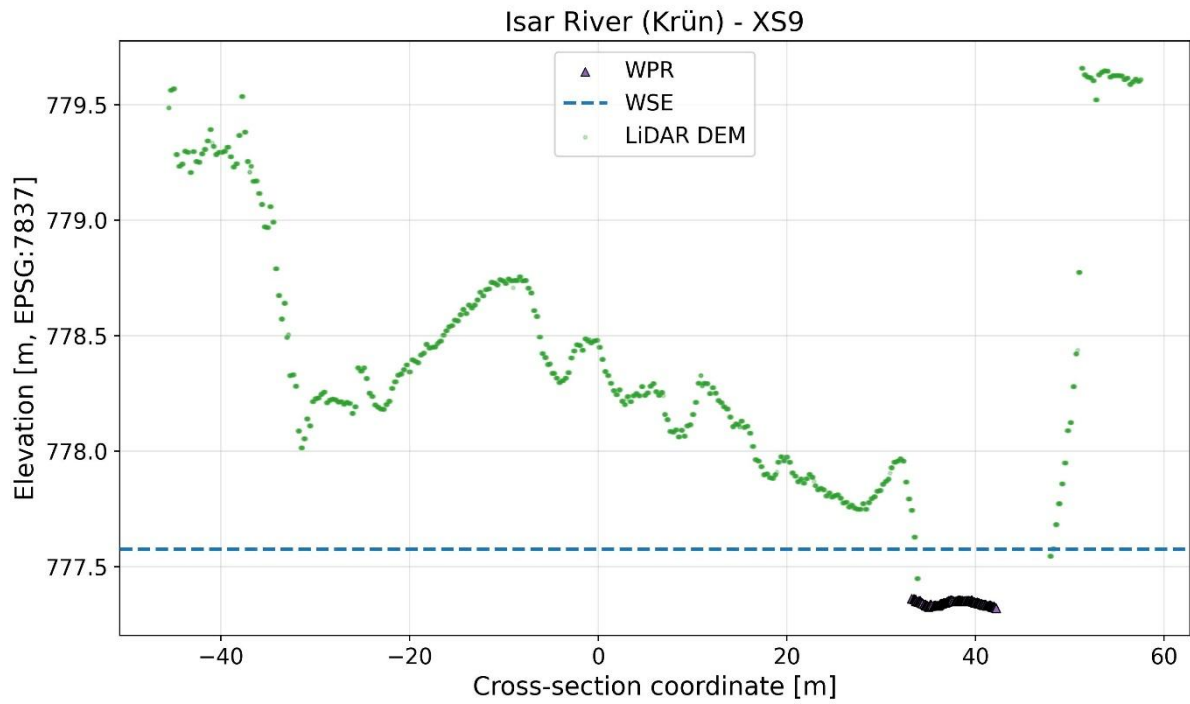


Figure A1. Cross-section XS9 at Isar River (Krün)

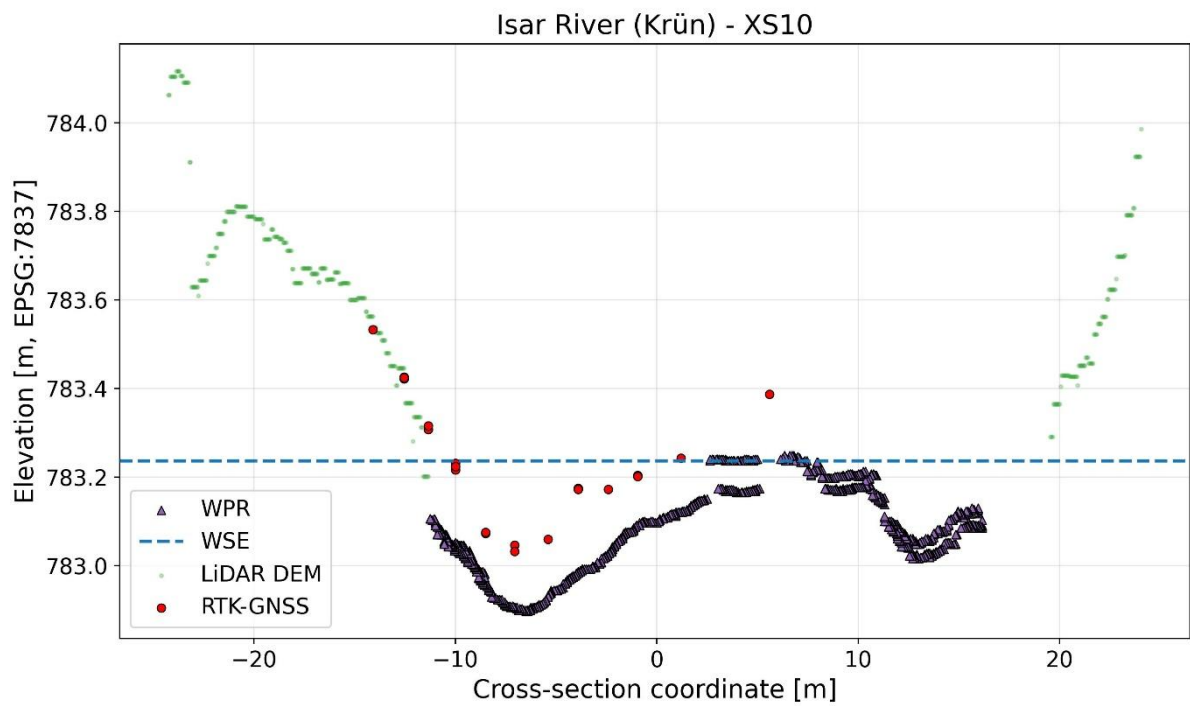


Figure A2. Cross-section XS10 at Isar River (Krün)

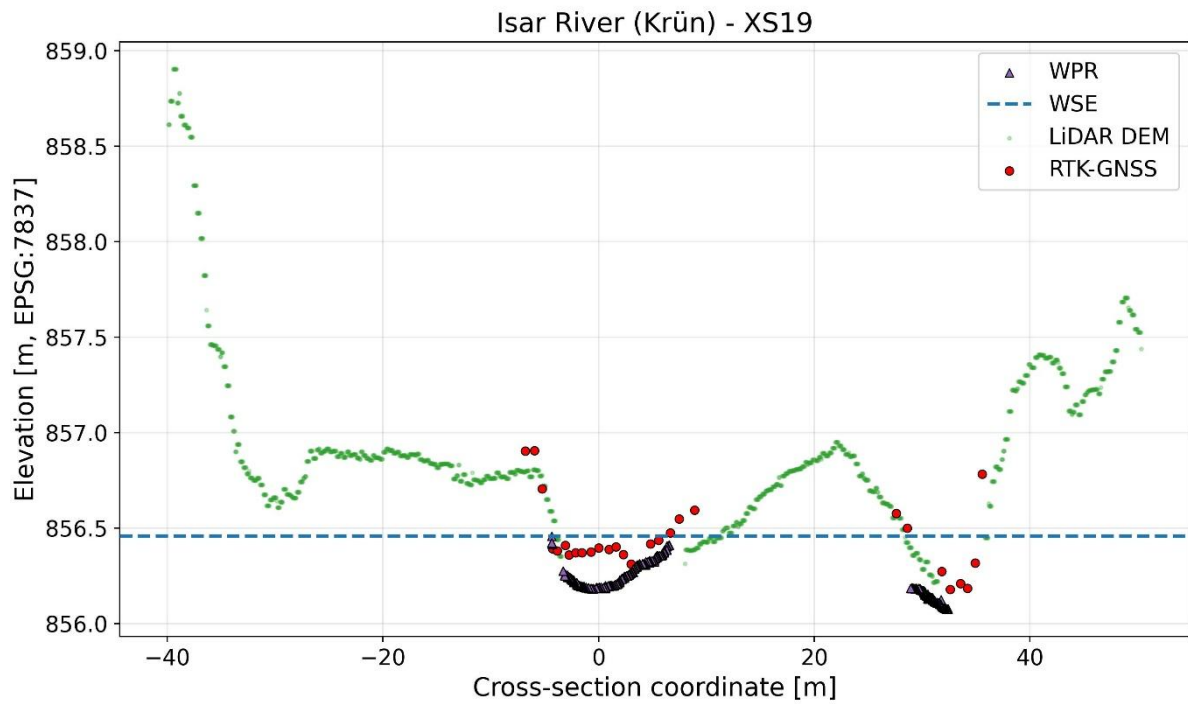


Figure A3. Cross-section XS19 at Isar River (Krün)

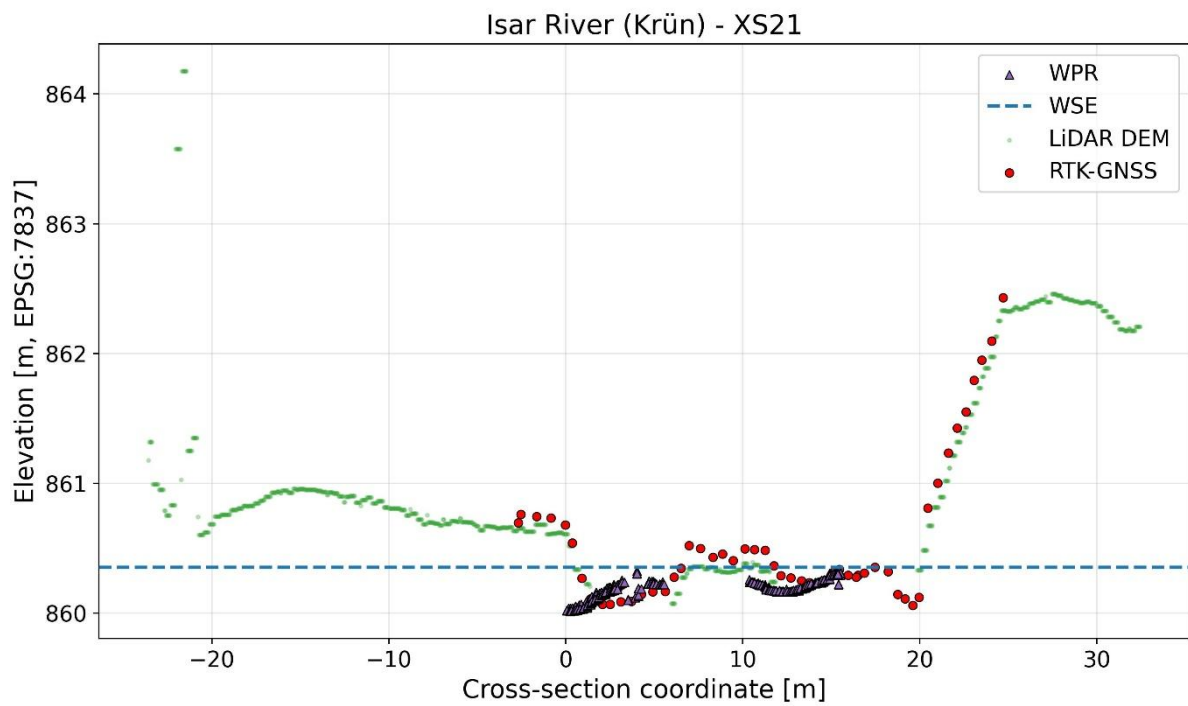


Figure A4. Cross-section XS21 at Isar River (Krün)

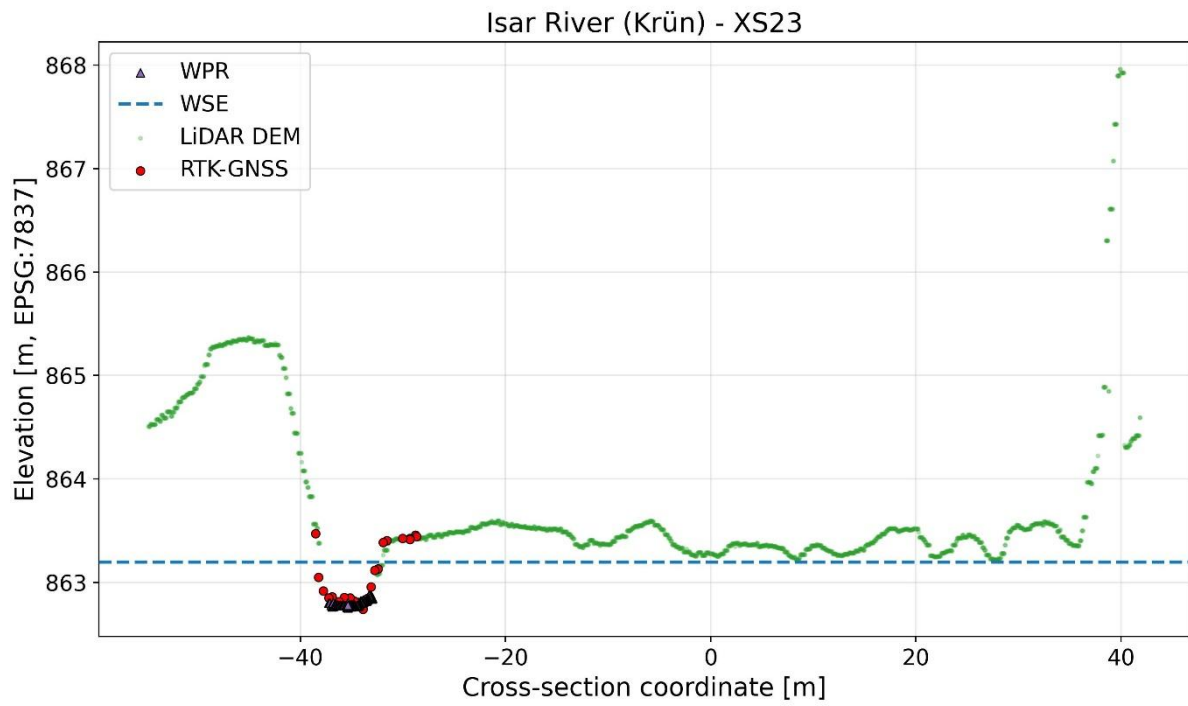


Figure A5. Cross-section XS23 at Isar River (Krün)

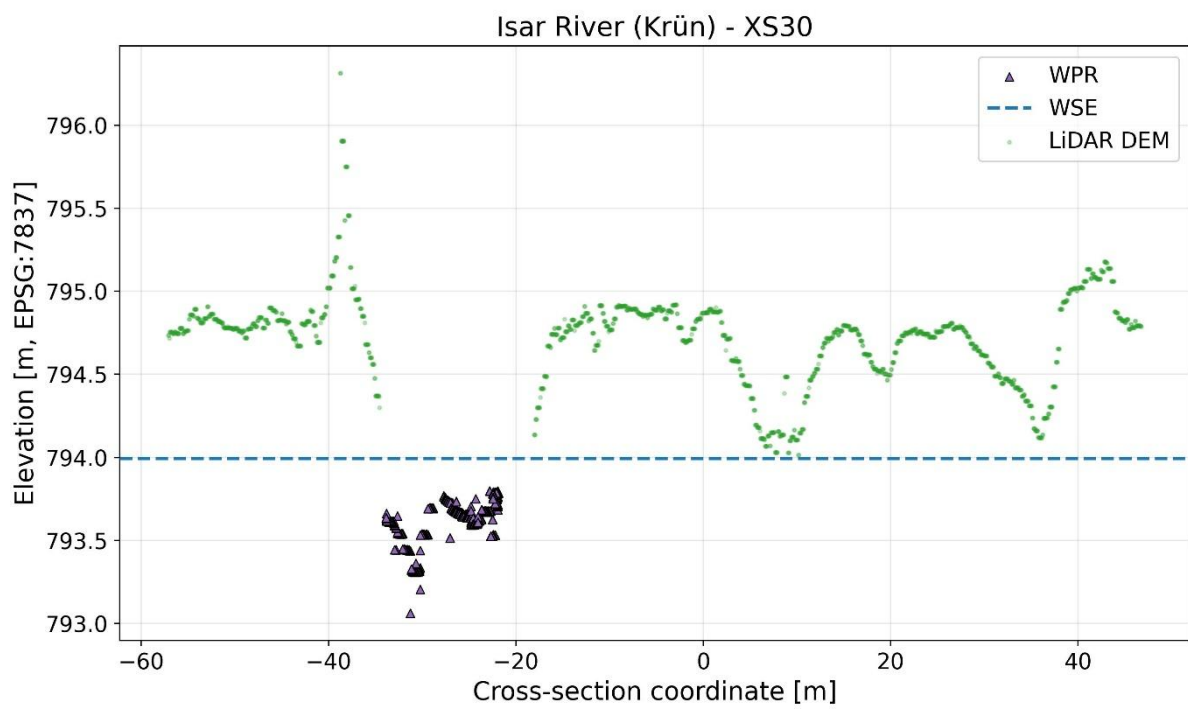


Figure A6. Cross-section XS30 at Isar River (Krün)

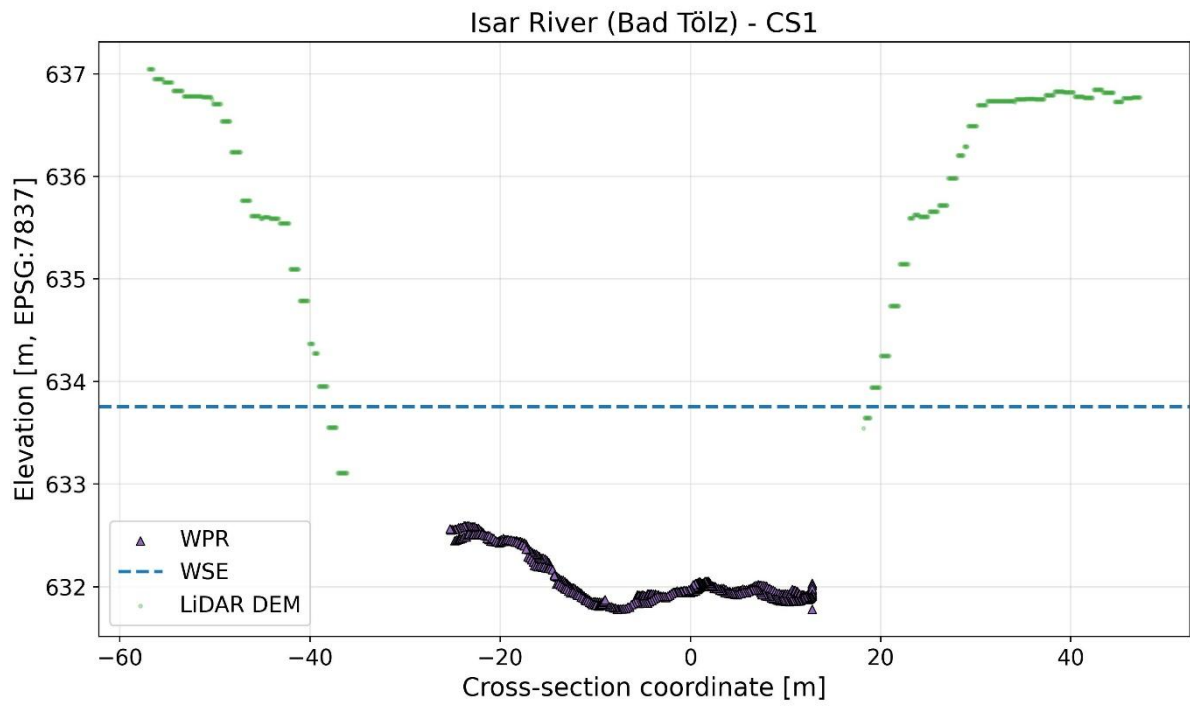


Figure A7. Cross-section CS1 at Isar River (Bad Tölz)

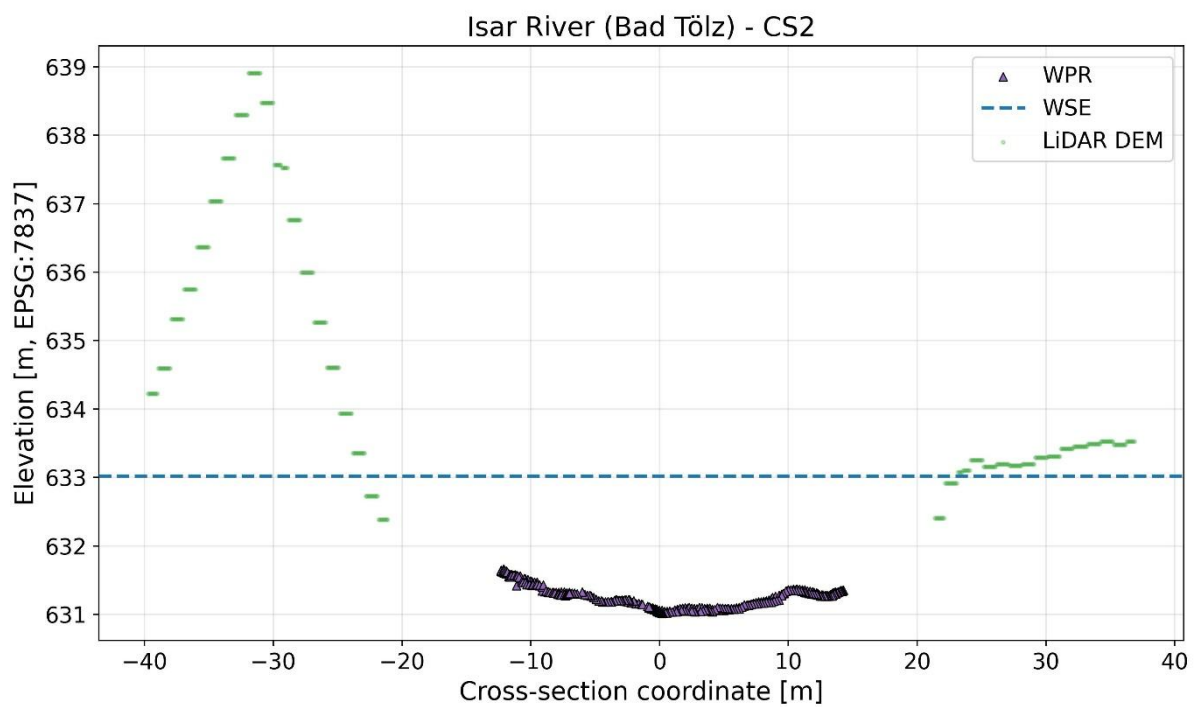


Figure A8. Cross-section CS2 at Isar River (Bad Tölz)

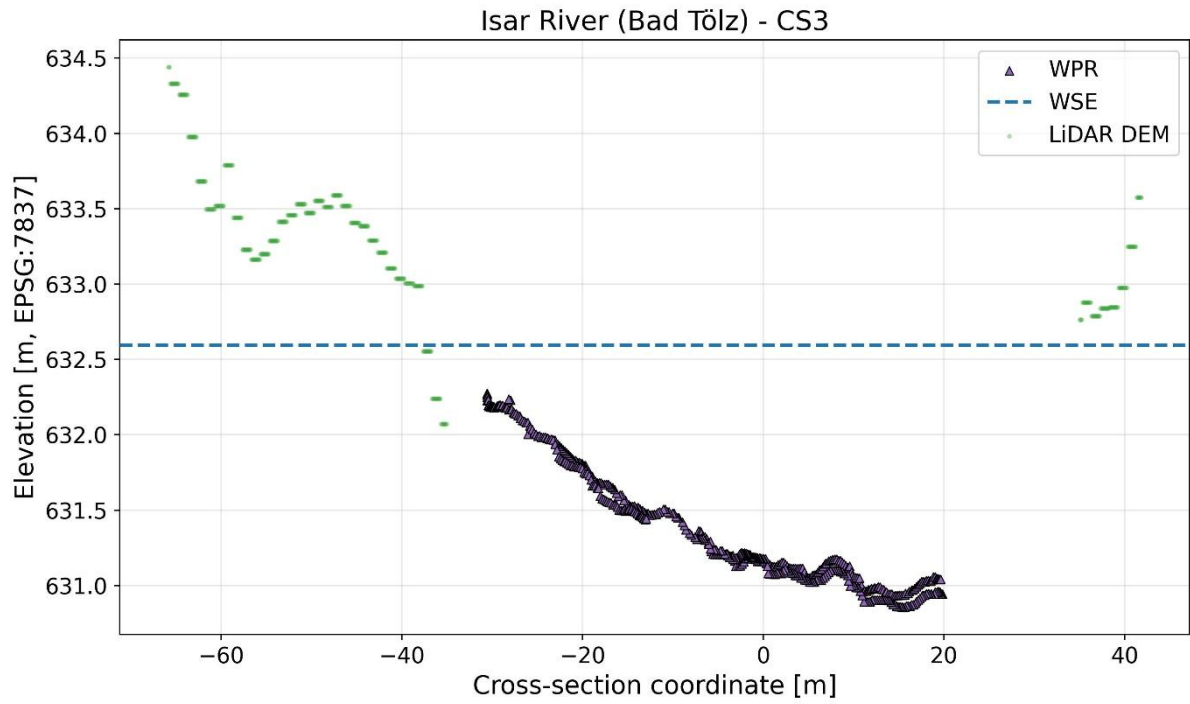


Figure A9. Cross-section CS3 at Isar River (Bad Tölz)

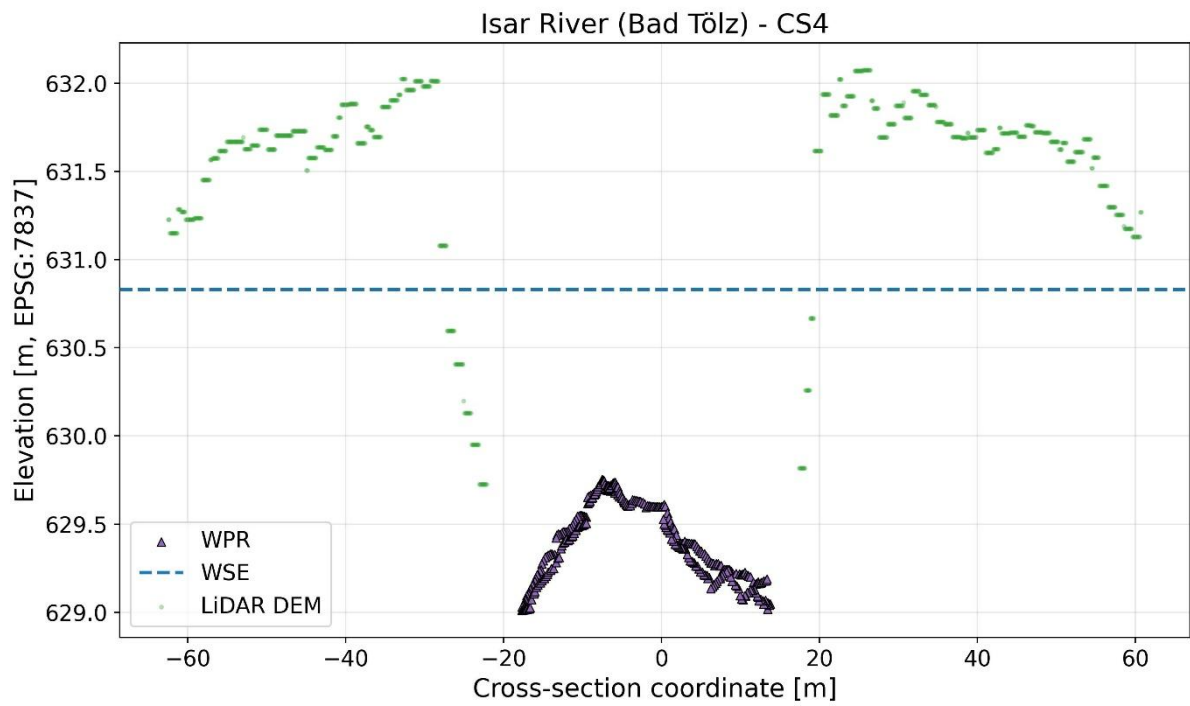


Figure A10. Cross-section CS4 at Isar River (Bad Tölz)

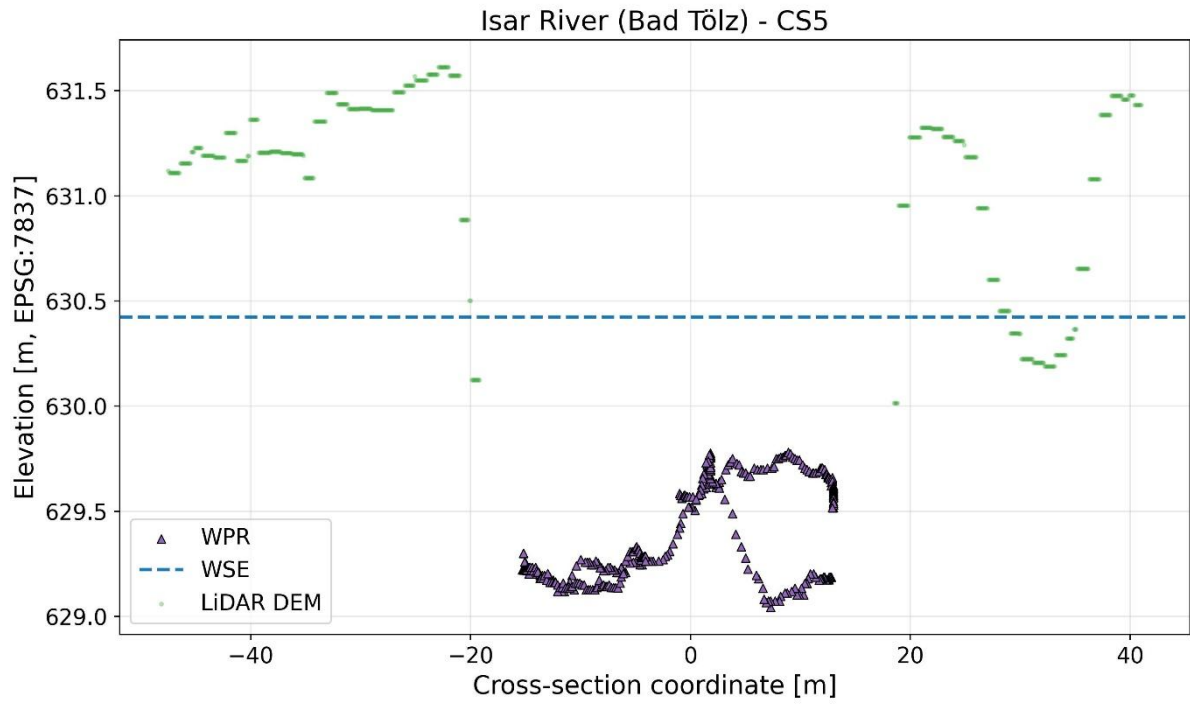


Figure A11. Cross-section CS5 at Isar River (Bad Tölz)

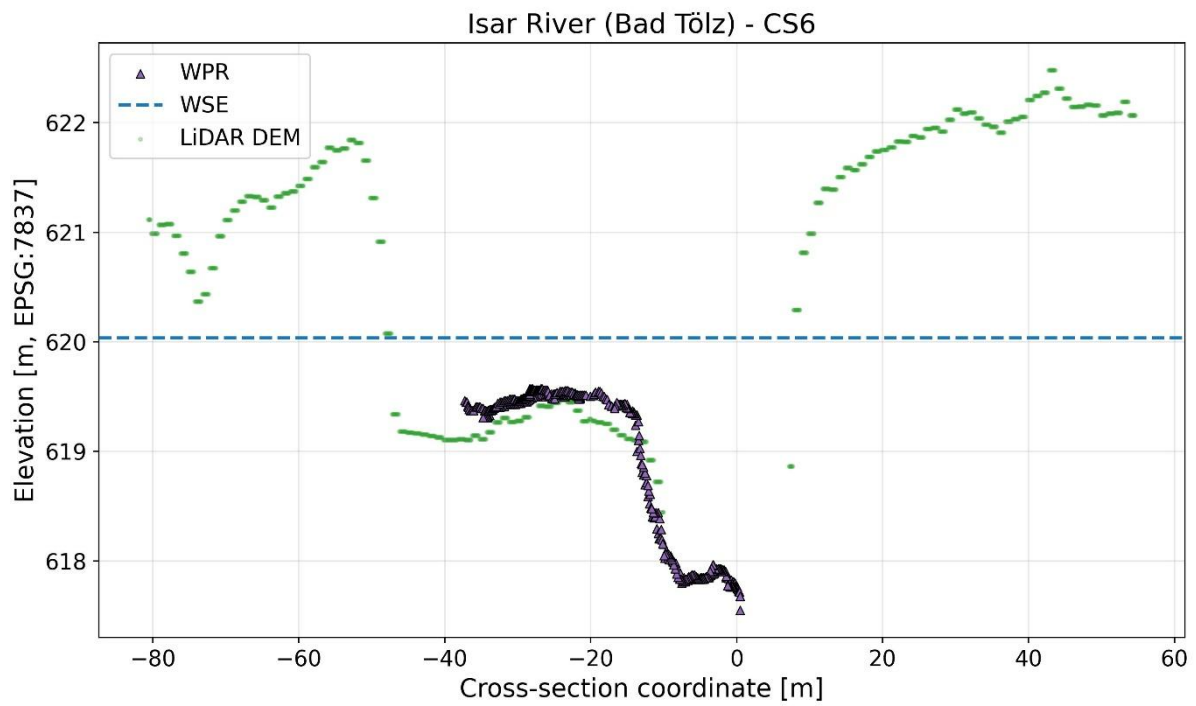


Figure A12. Cross-section CS6 at Isar River (Bad Tölz)

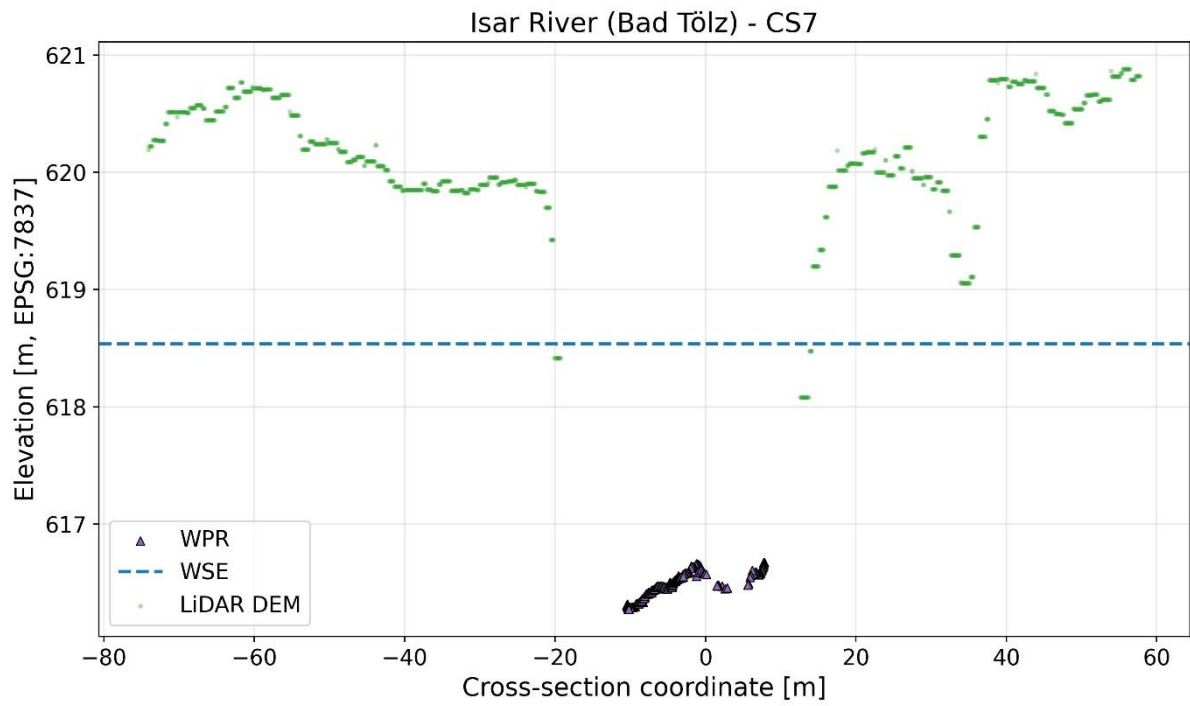


Figure A13. Cross-section CS7 at Isar River (Bad Tölz)

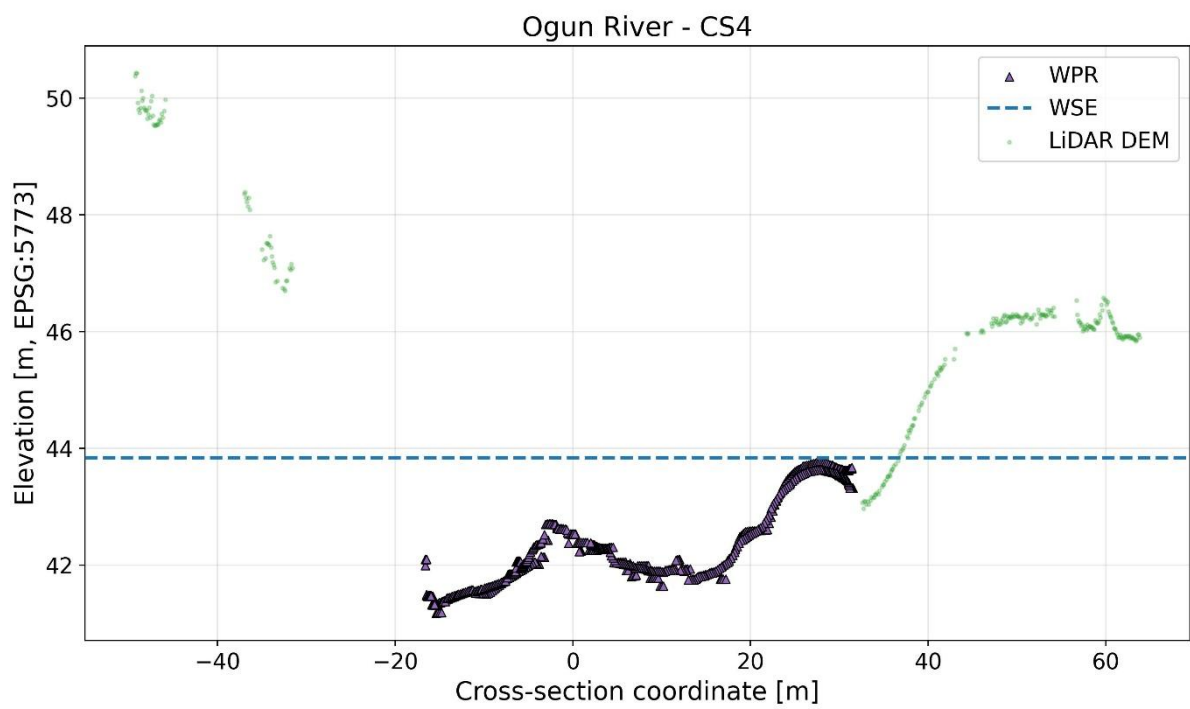


Figure A14. Cross-section CS4 at Ogun River

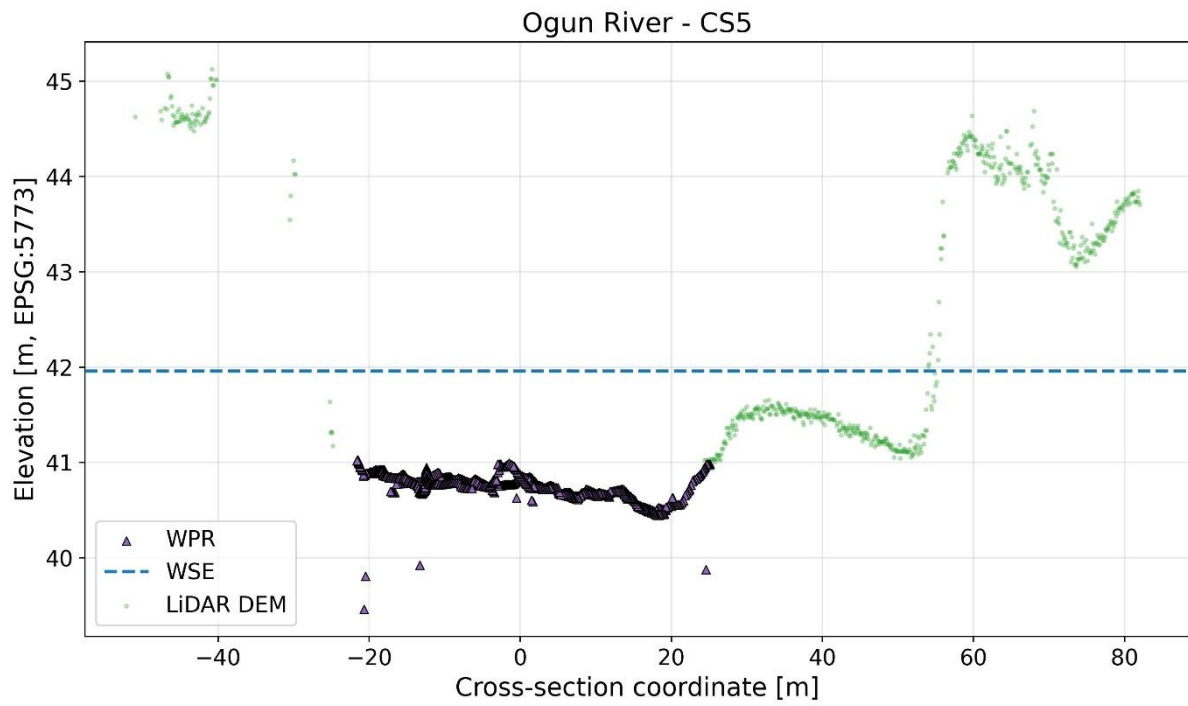


Figure A15. Cross-section CS5 at Ogun River

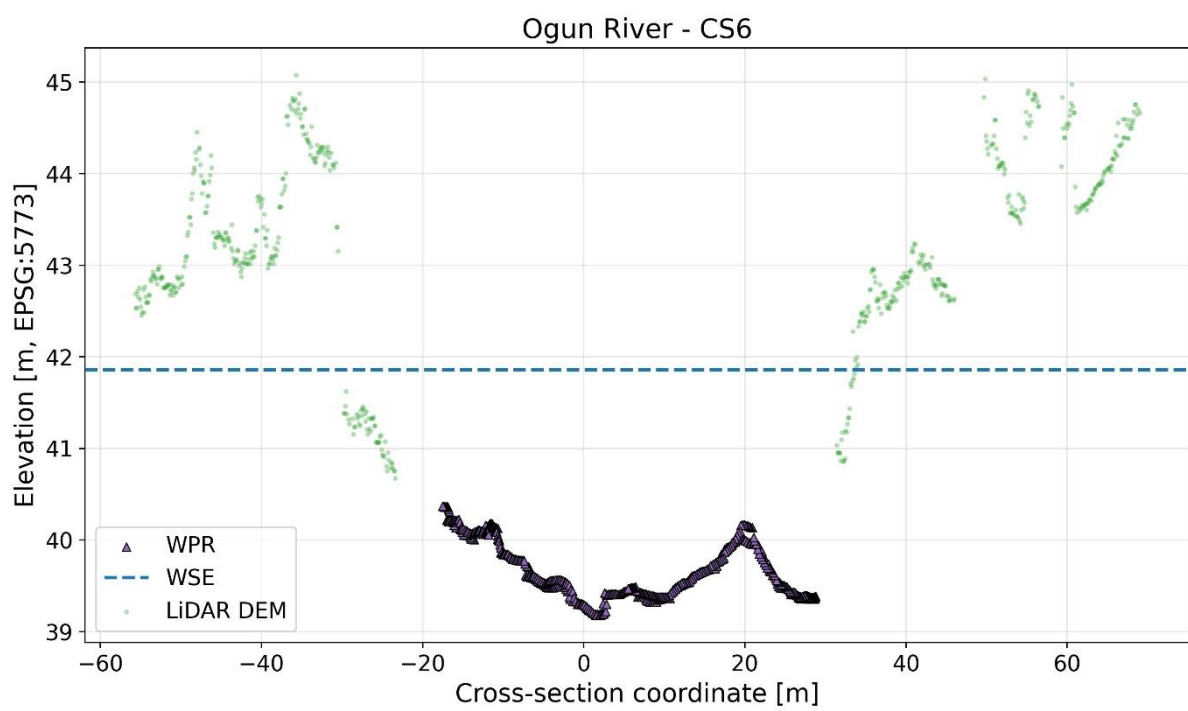


Figure A16. Cross-section CS6 at Ogun River

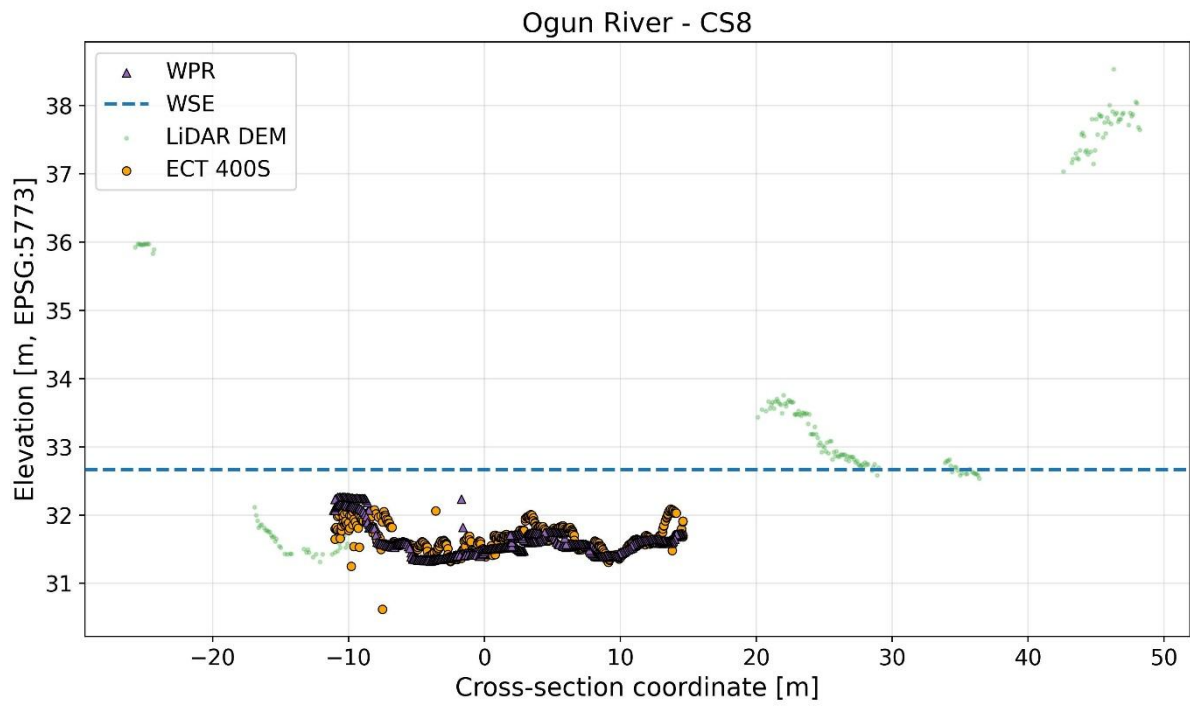


Figure A17. Cross-section CS8 at Ogun River

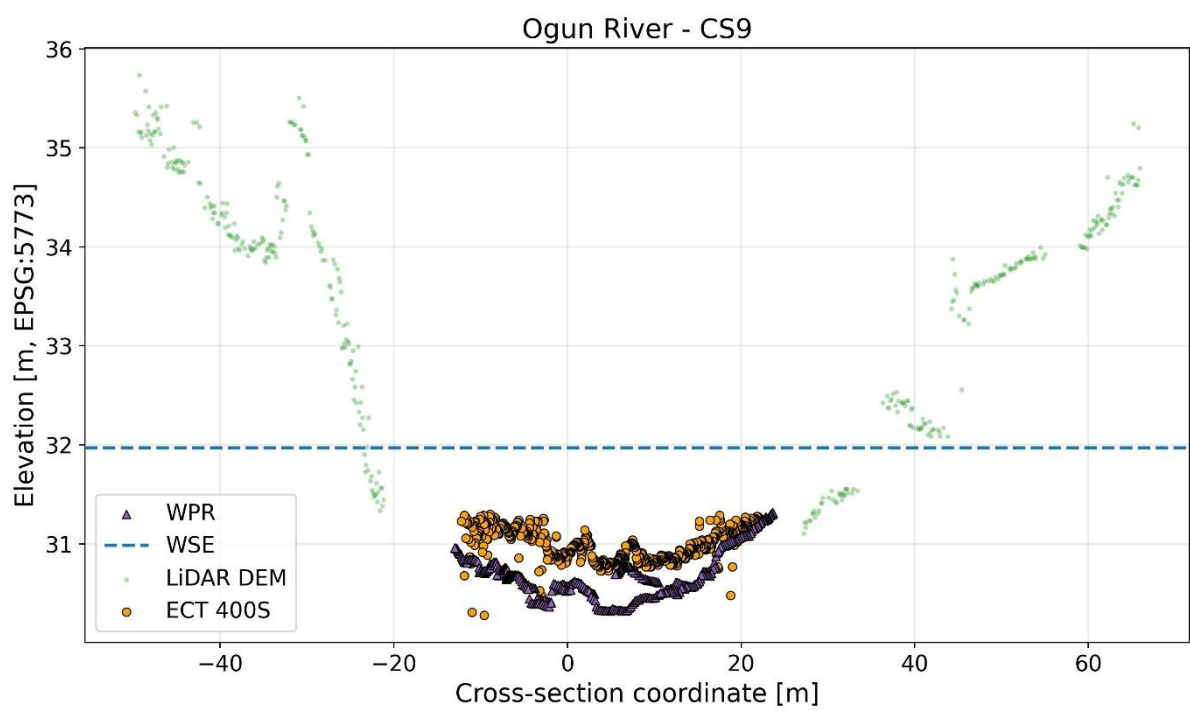


Figure A18. Cross-section CS9 at Ogun River

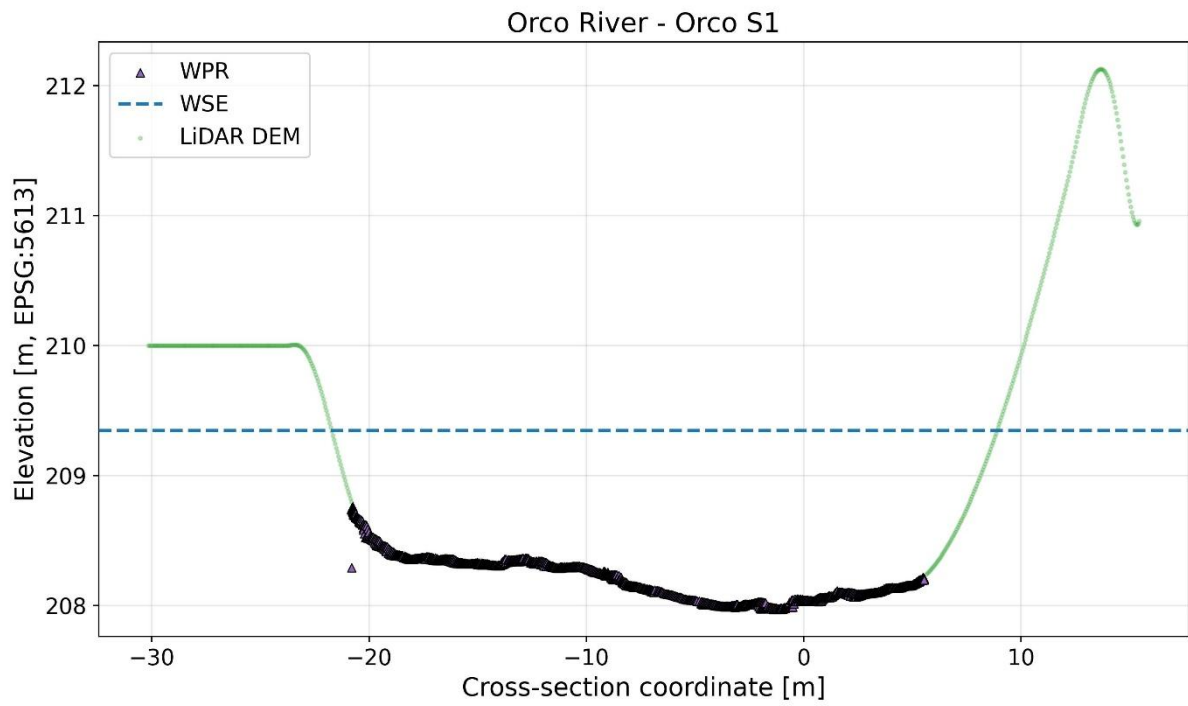


Figure A19. Cross-section Orco S1 at Orco River

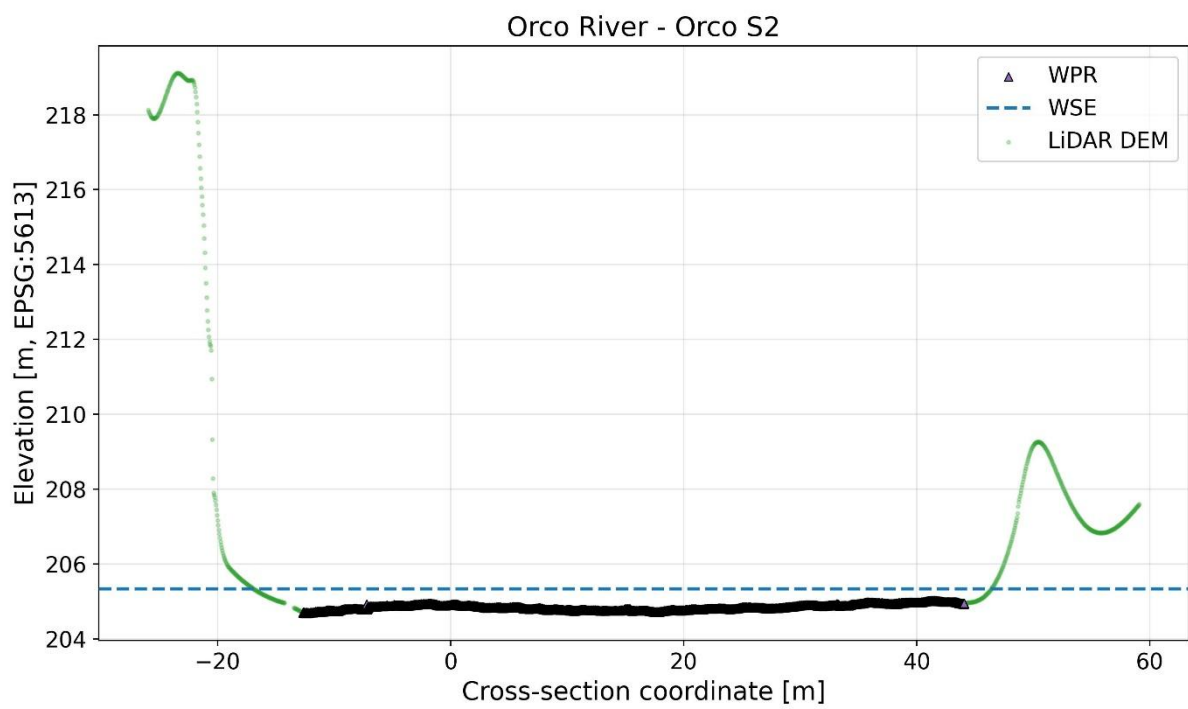


Figure A20. Cross-section Orco S2 at Orco River

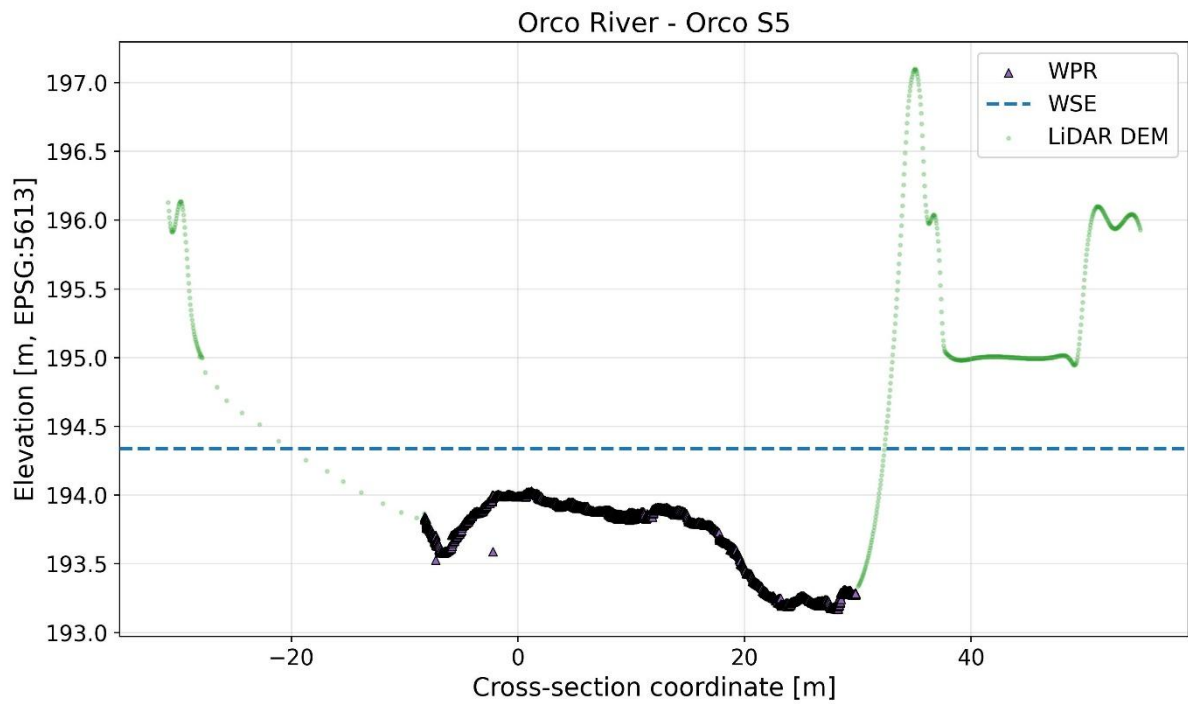


Figure A21. Cross-section Orco S5 at Orco River

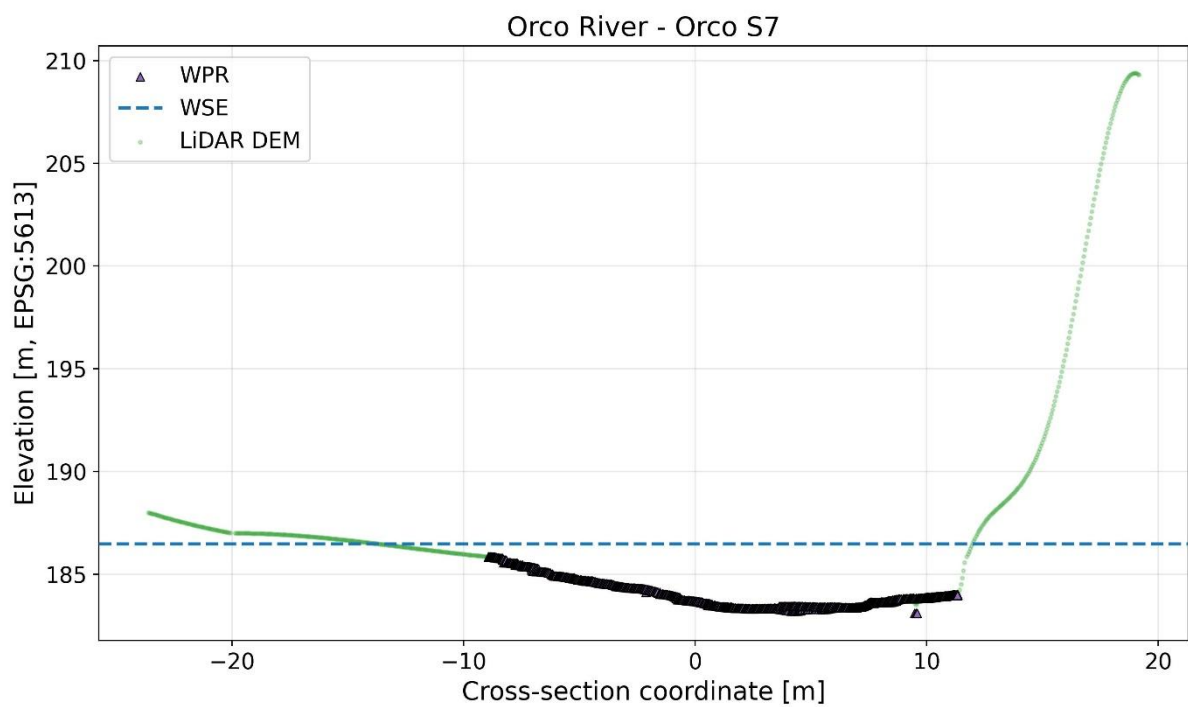


Figure A22. Cross-section Orco S7 at Orco River

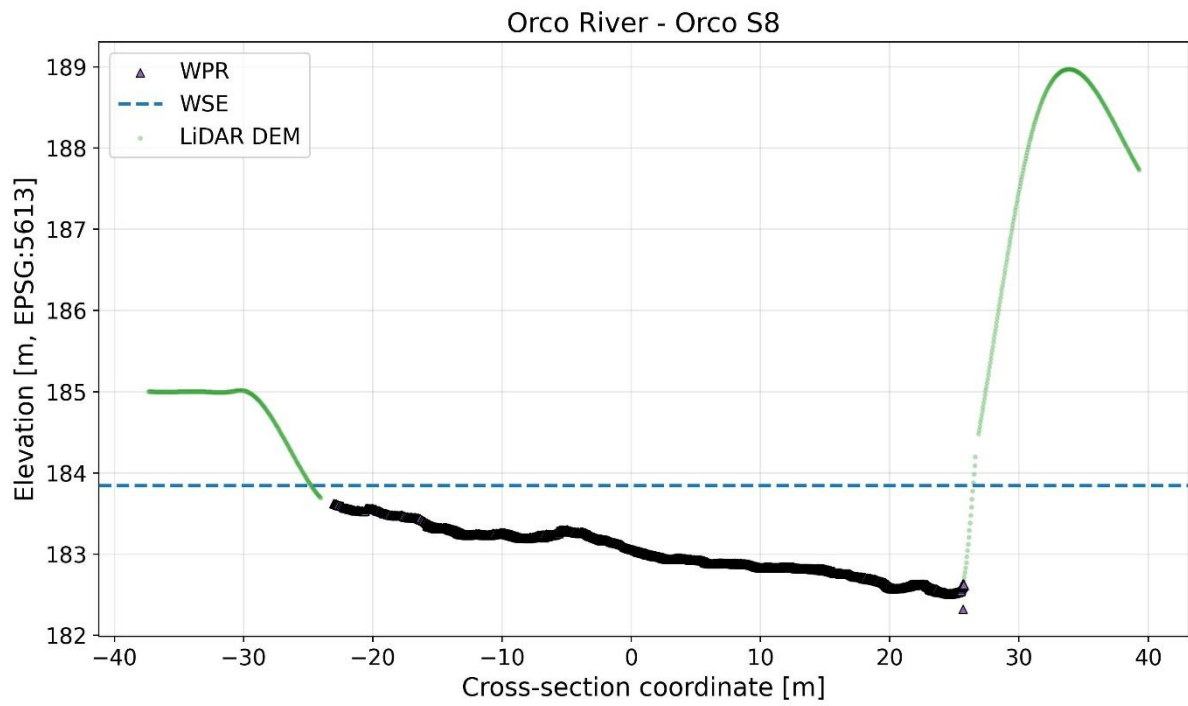


Figure A23. Cross-section Orco S8 at Orco River

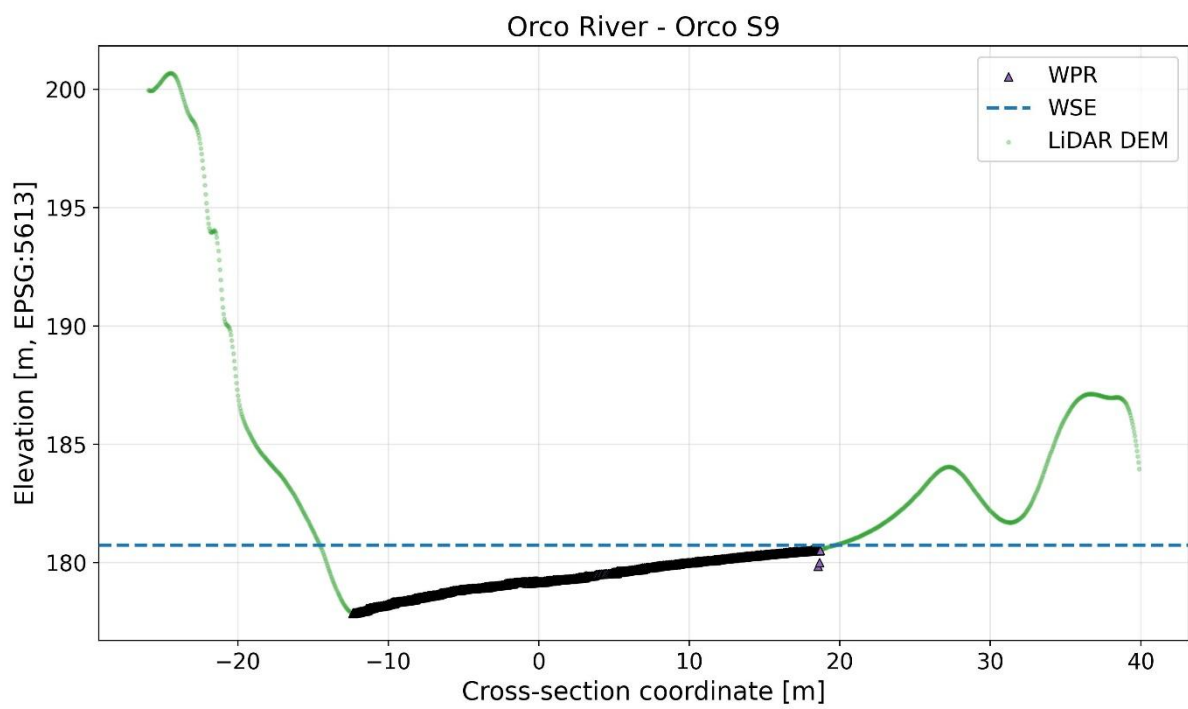


Figure A24. Cross-section Orco S9 at Orco River

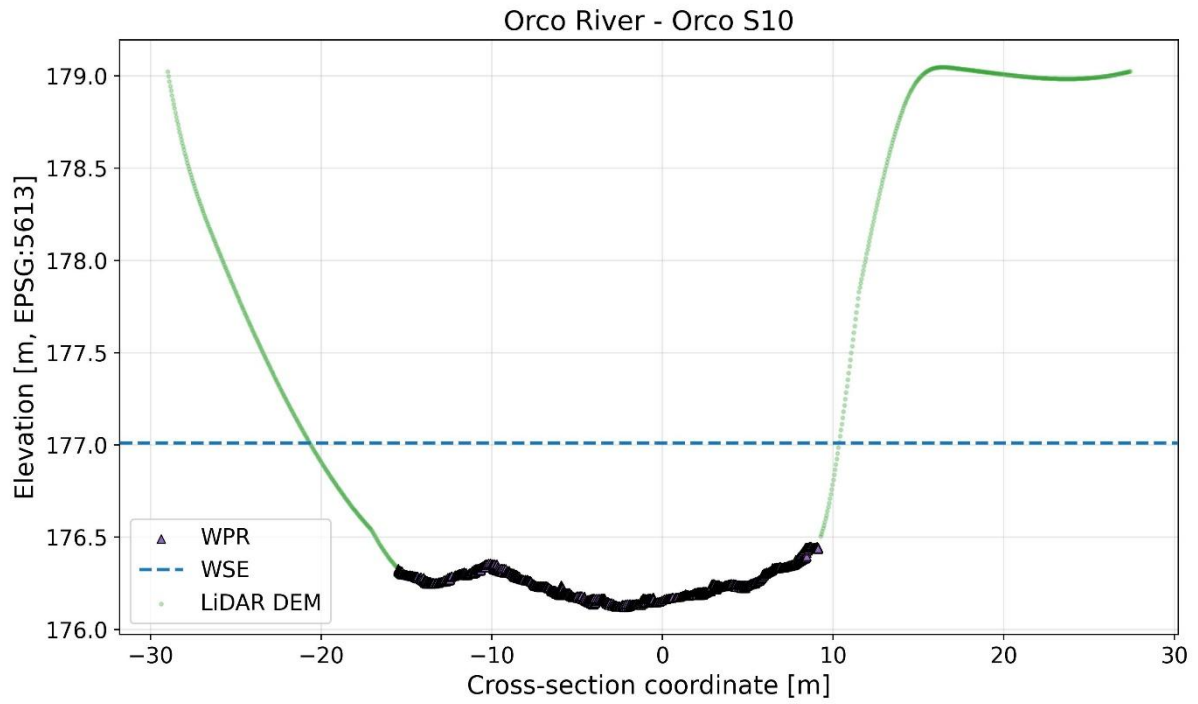


Figure A25. Cross-section Orco S10 at Orco River

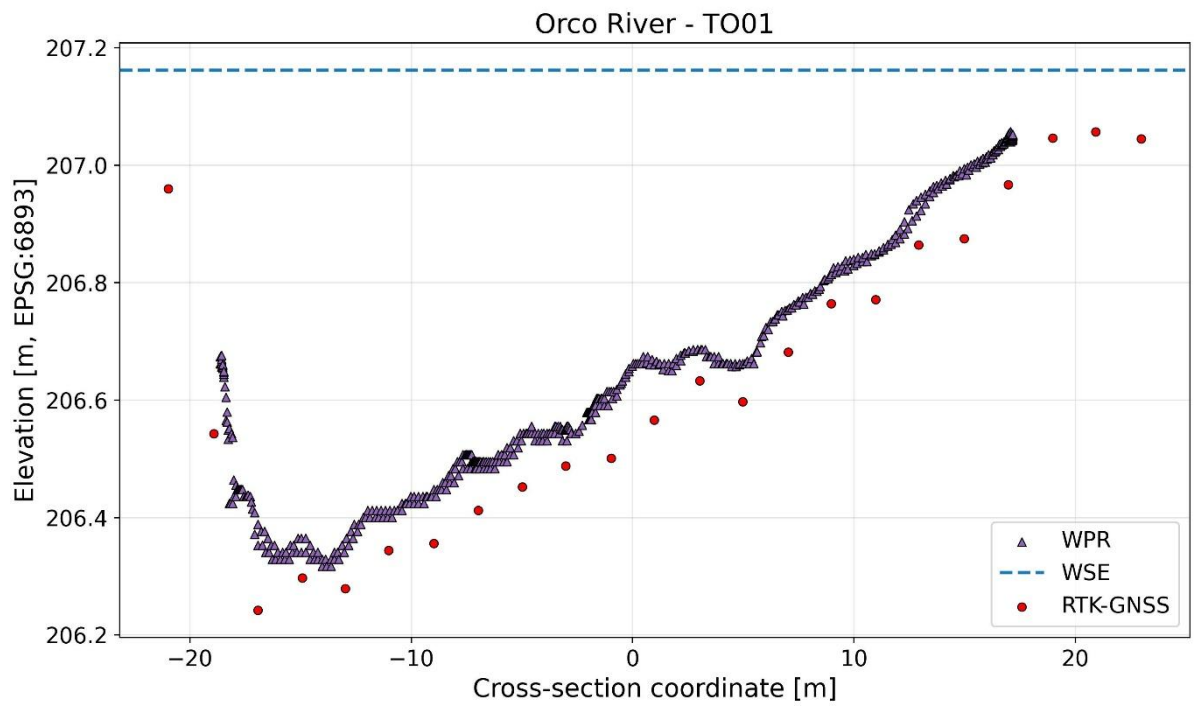


Figure A26. Cross-section TO01 at Orco River

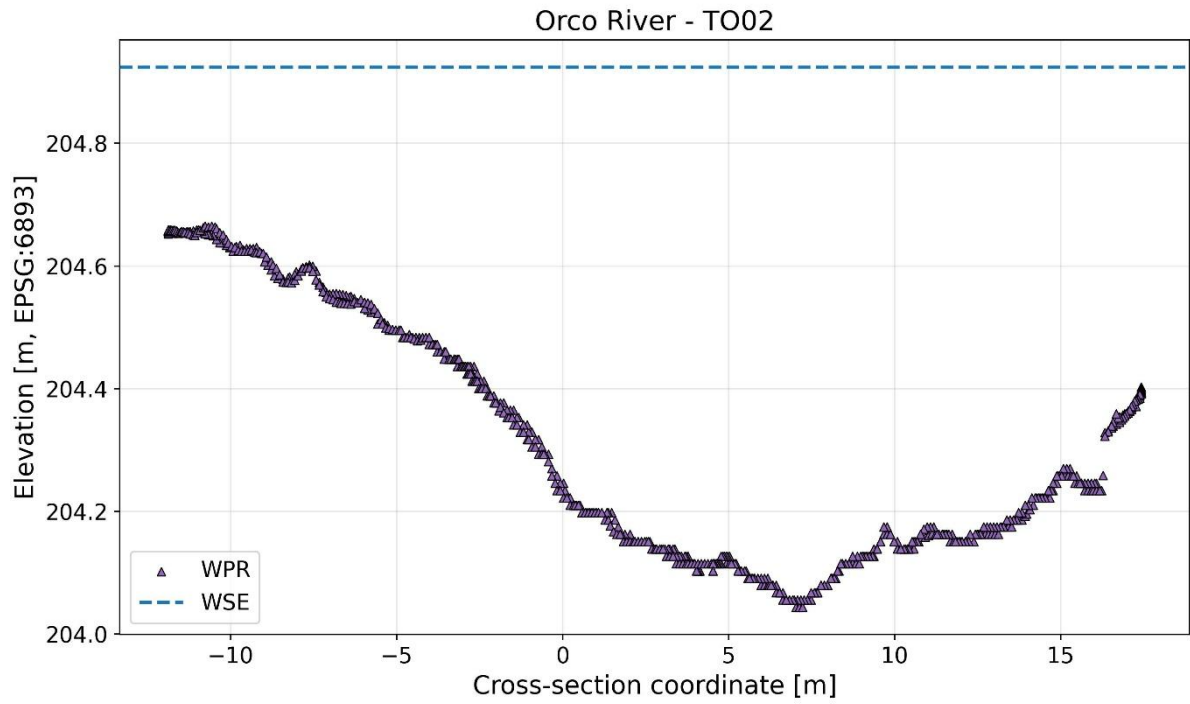


Figure A27. Cross-section TO02 at Orco River

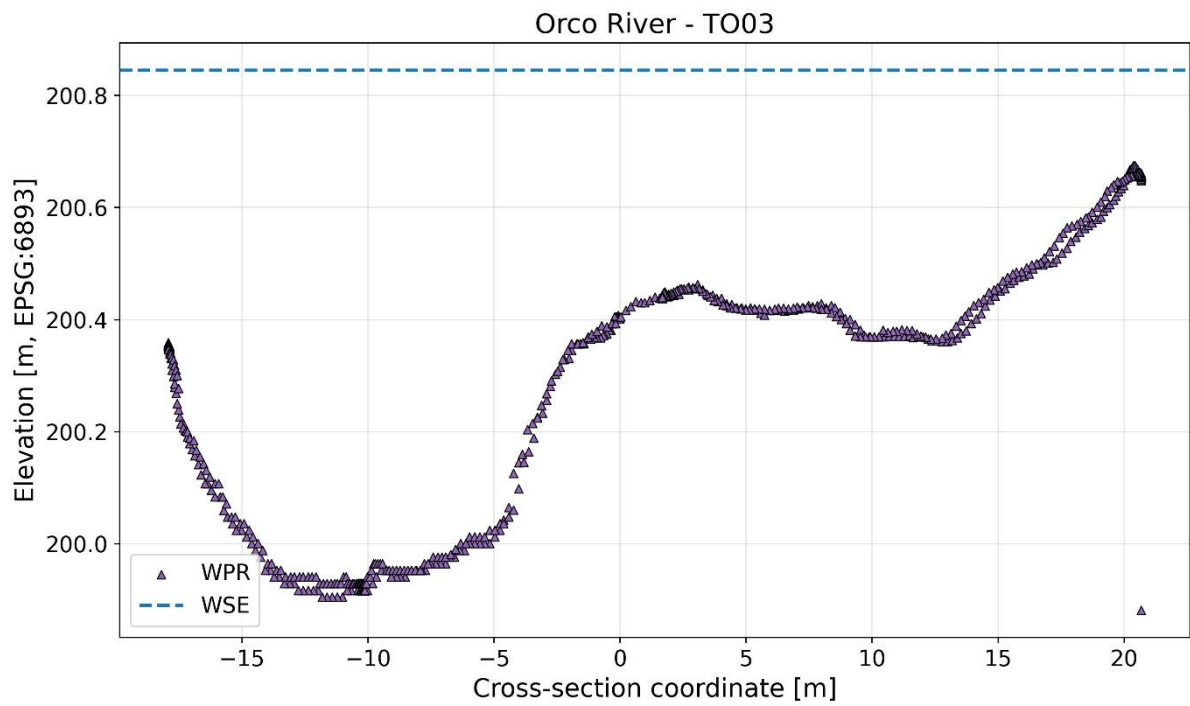


Figure A28. Cross-section TO03 at Orco River

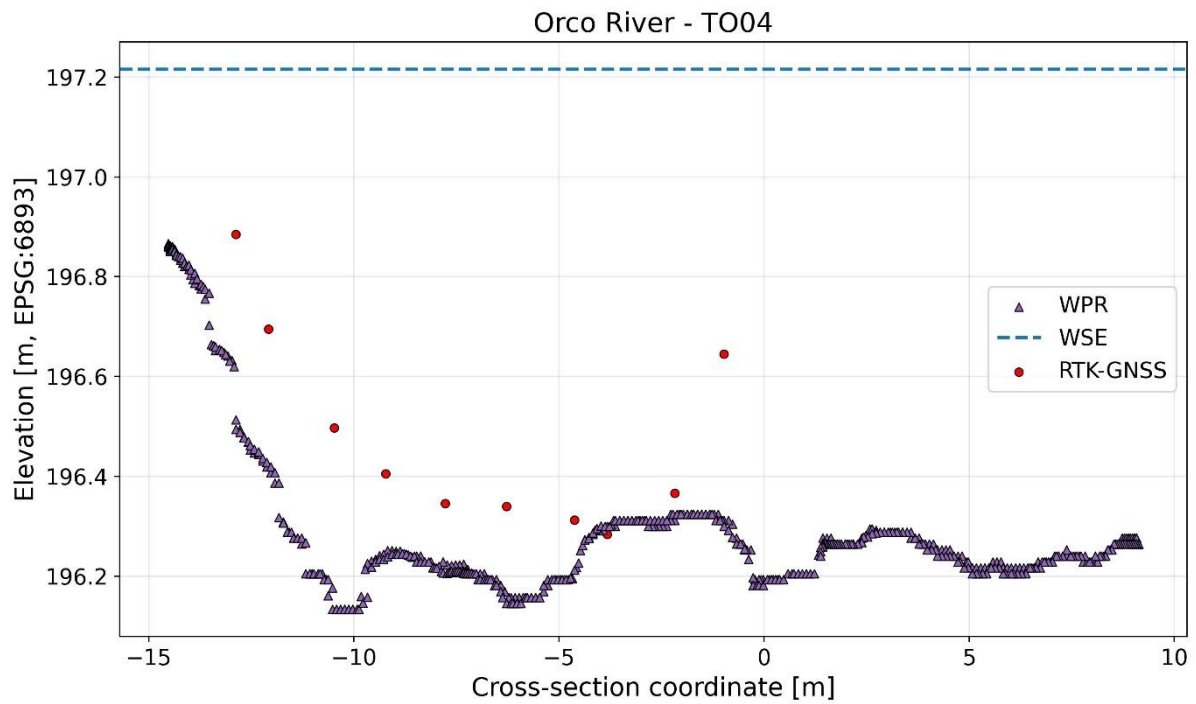


Figure A29. Cross-section TO04 at Orco River

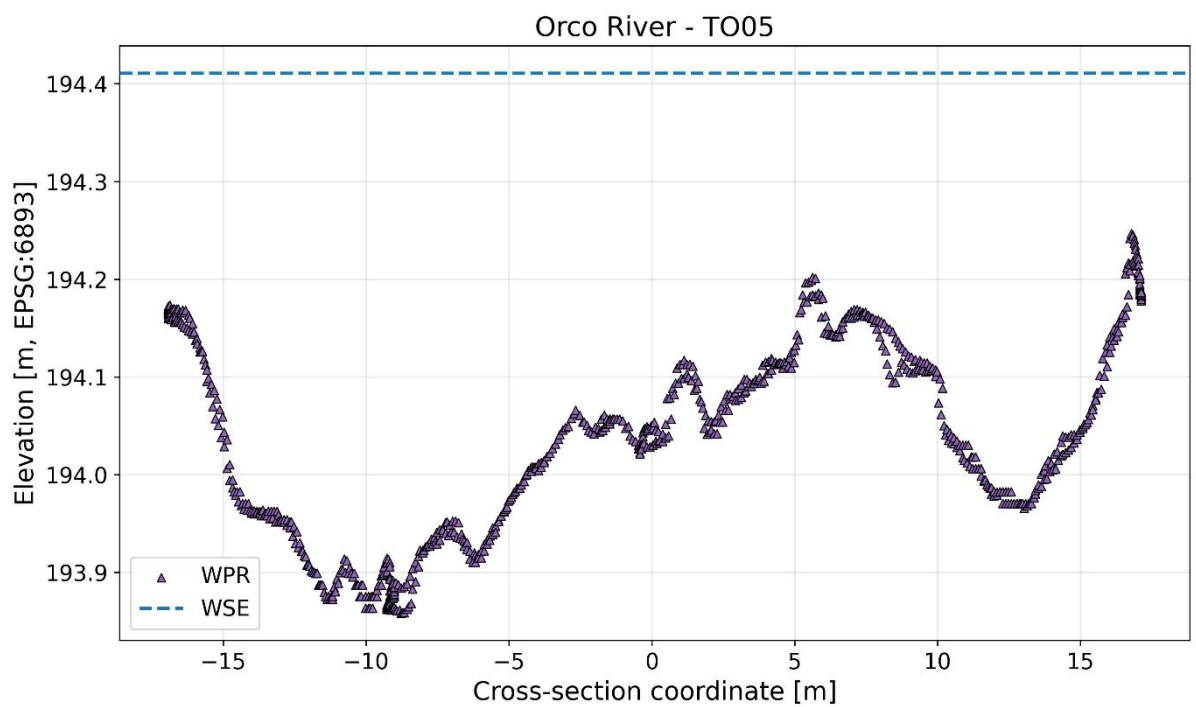


Figure A30. Cross-section TO05 at Orco River

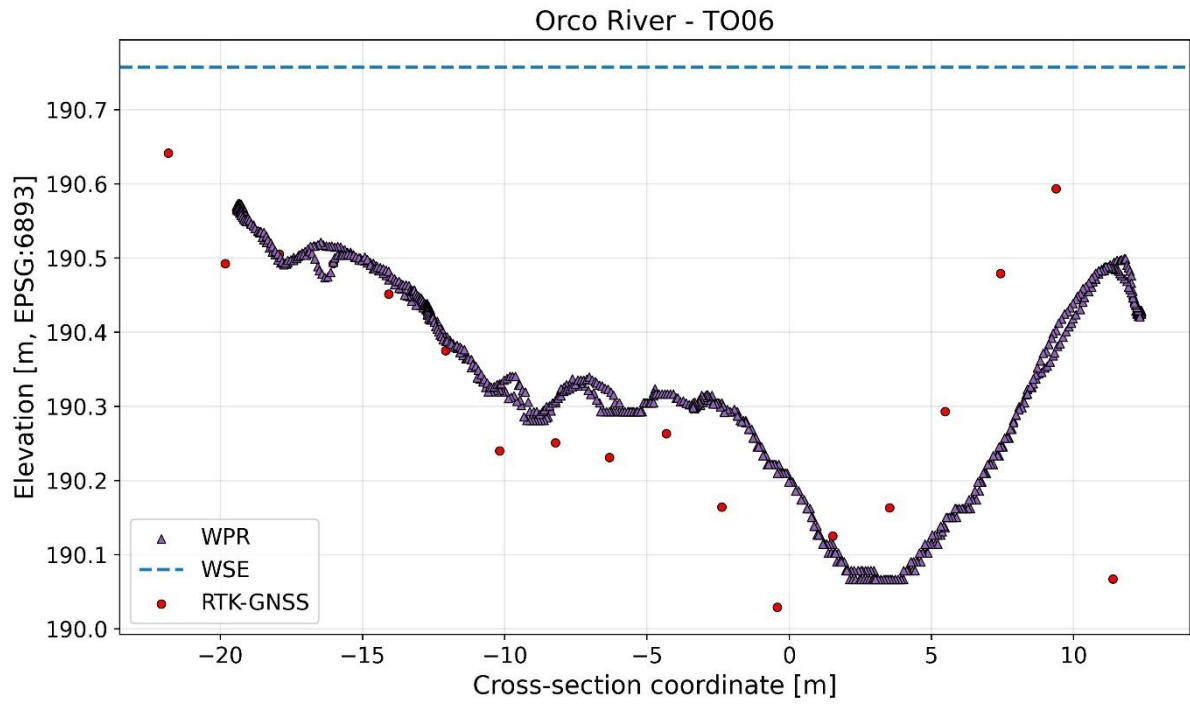


Figure A31. Cross-section TO06 at Orco River

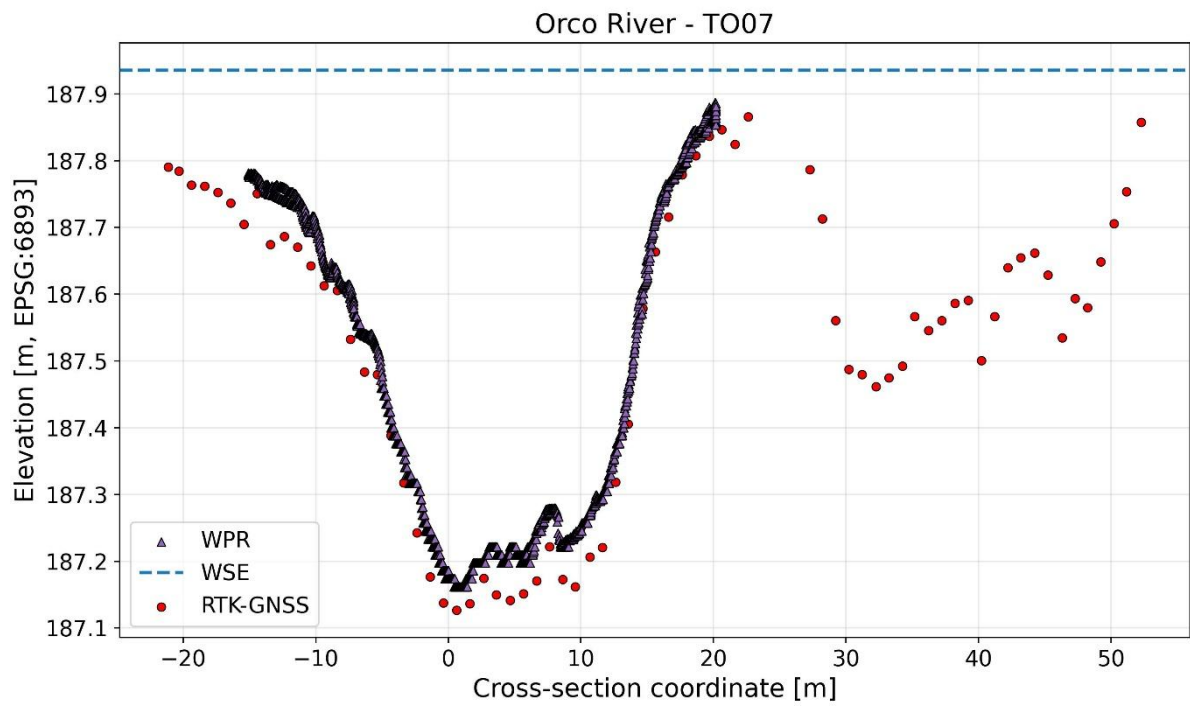


Figure A32. Cross-section TO07 at Orco River

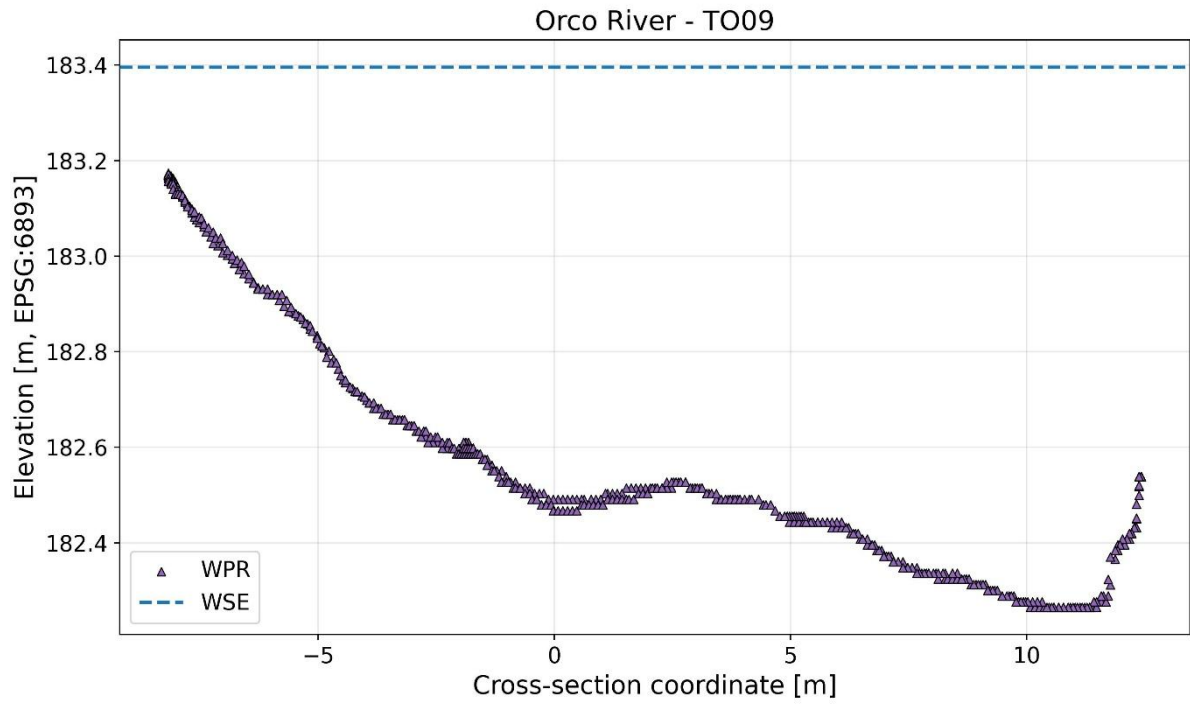


Figure A33. Cross-section TO09 at Orco River

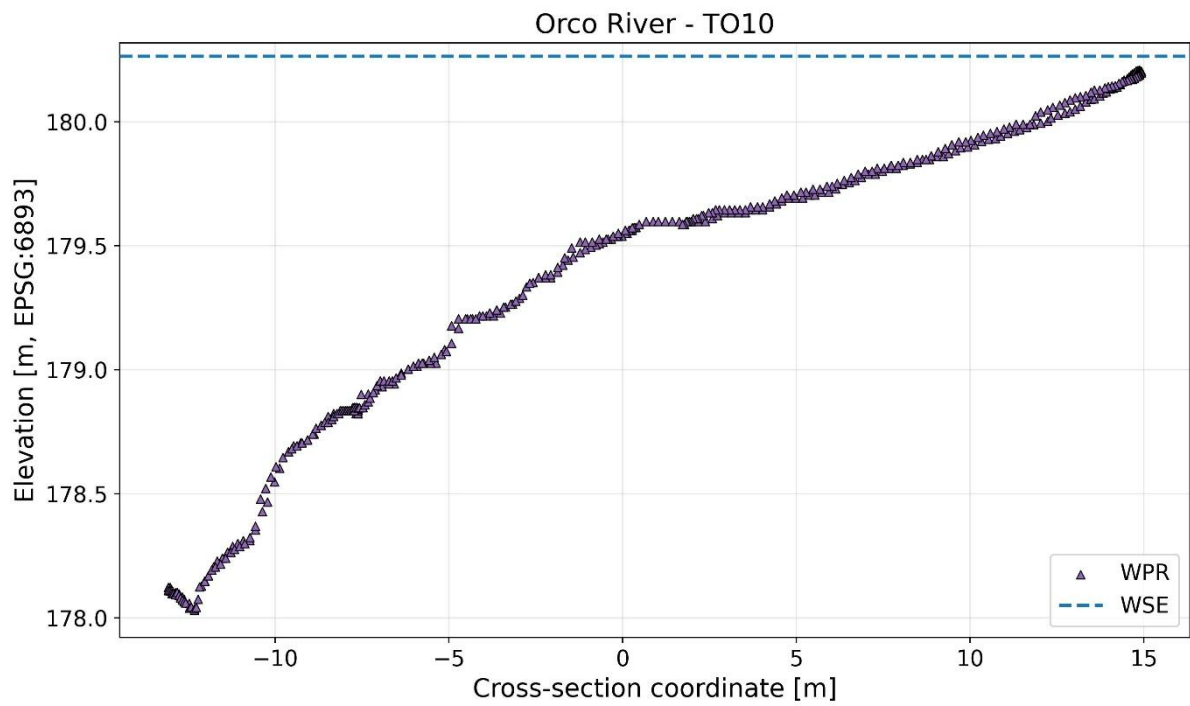


Figure A34. Cross-section TO10 at Orco River

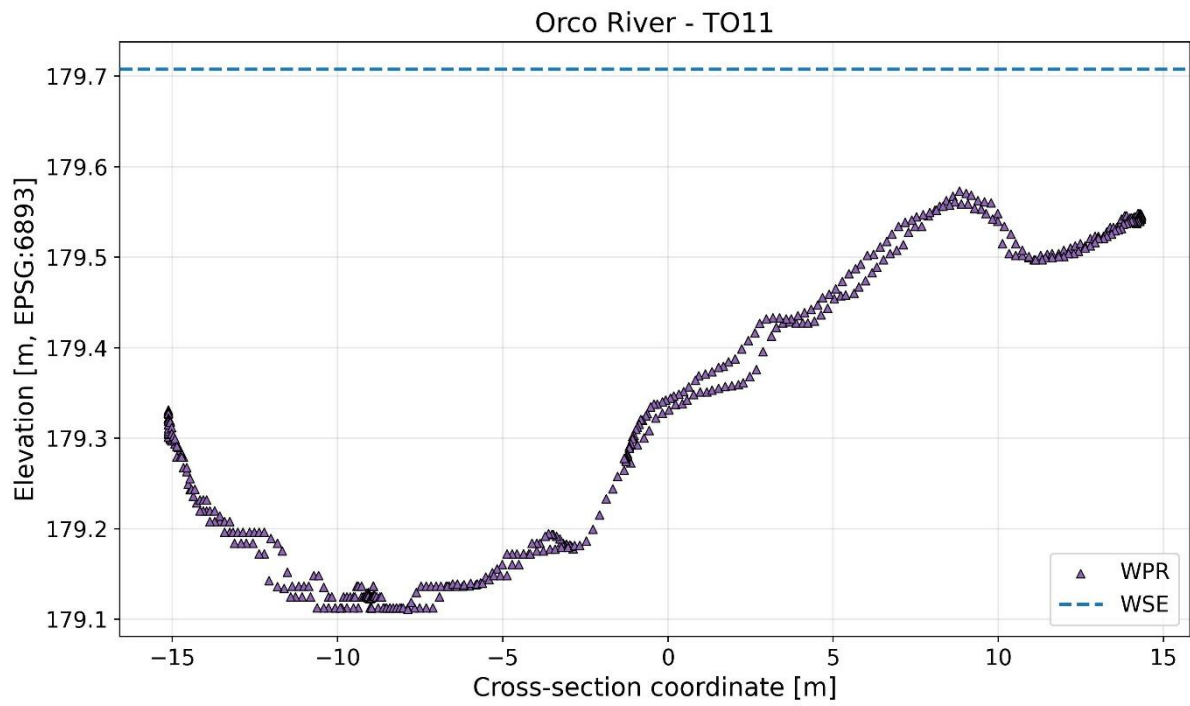


Figure A35. Cross-section TO11 at Orco River

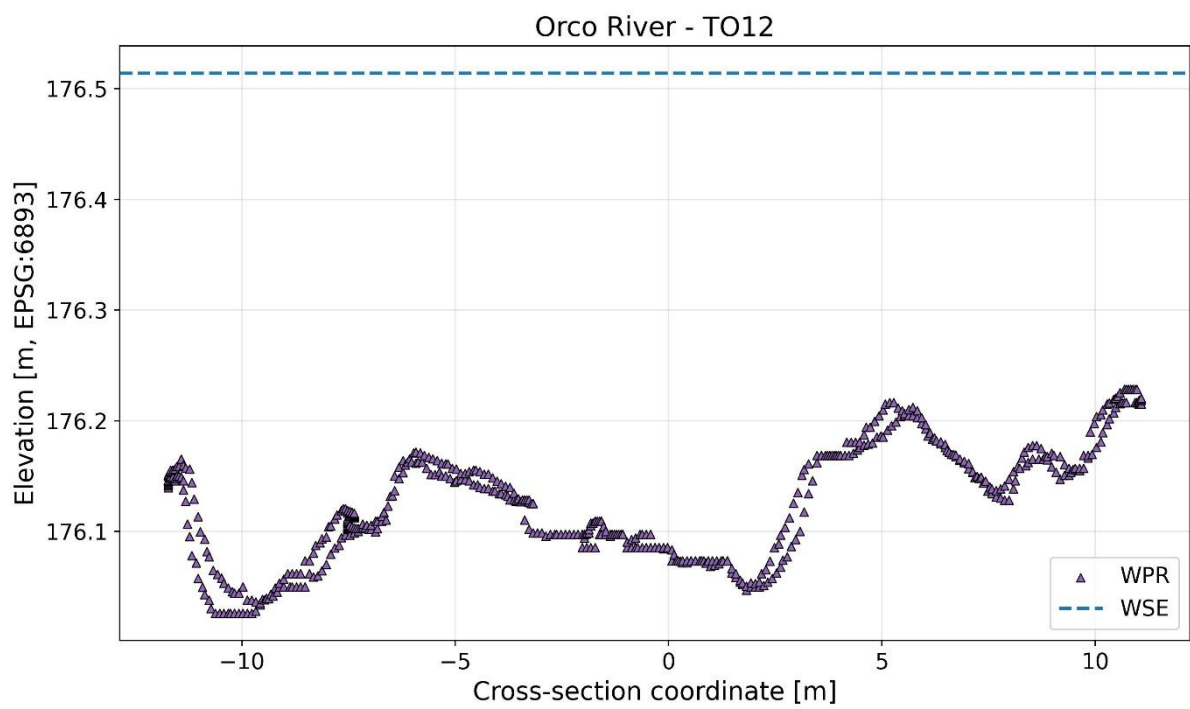


Figure A36. Cross-section TO12 at Orco River

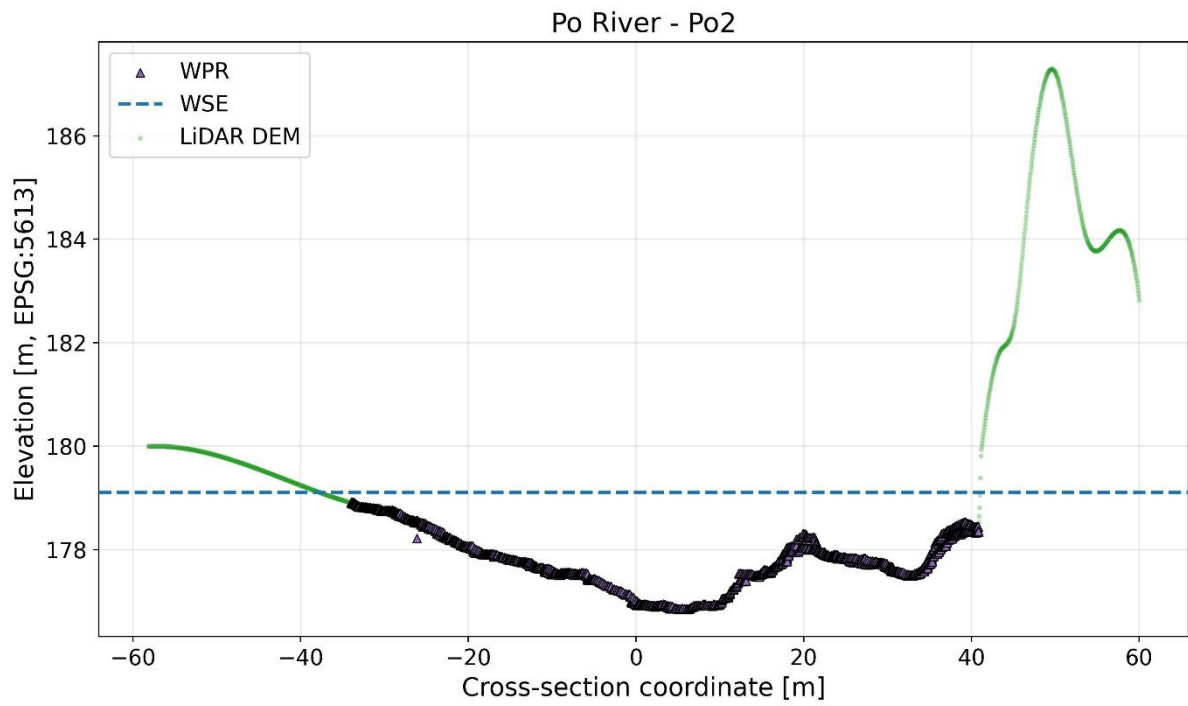


Figure A37. Cross-section Po 2 at Po River

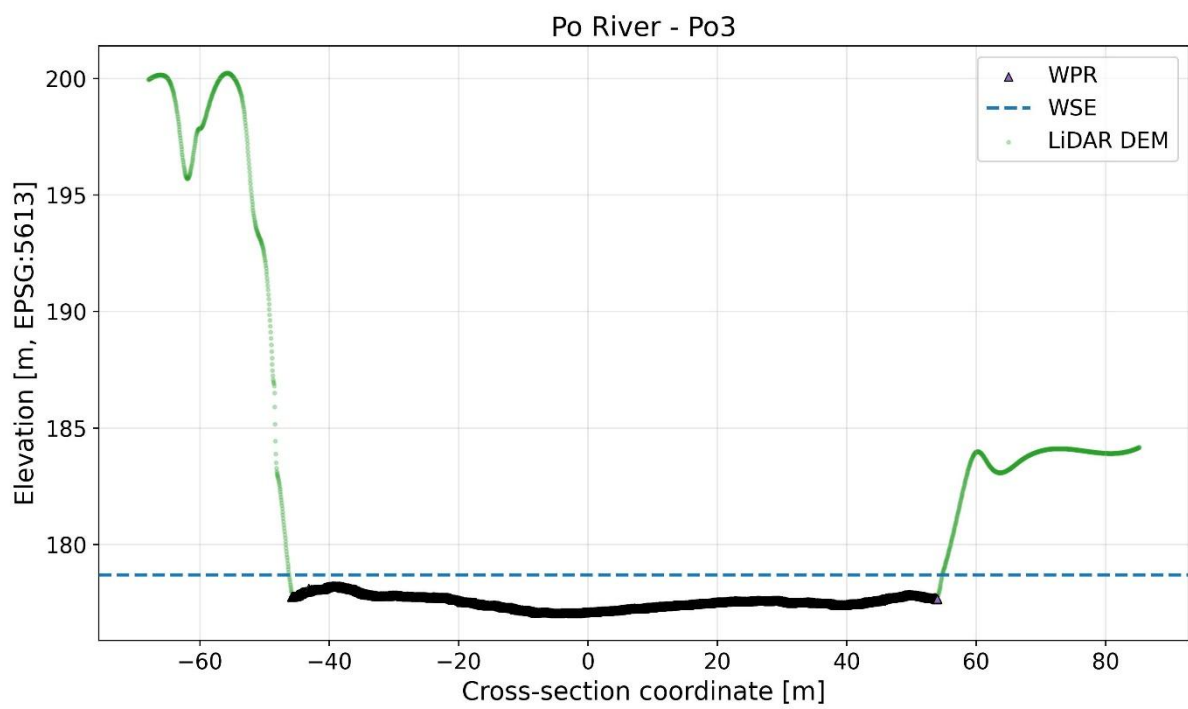


Figure A38. Cross-section Po 3 at Po River

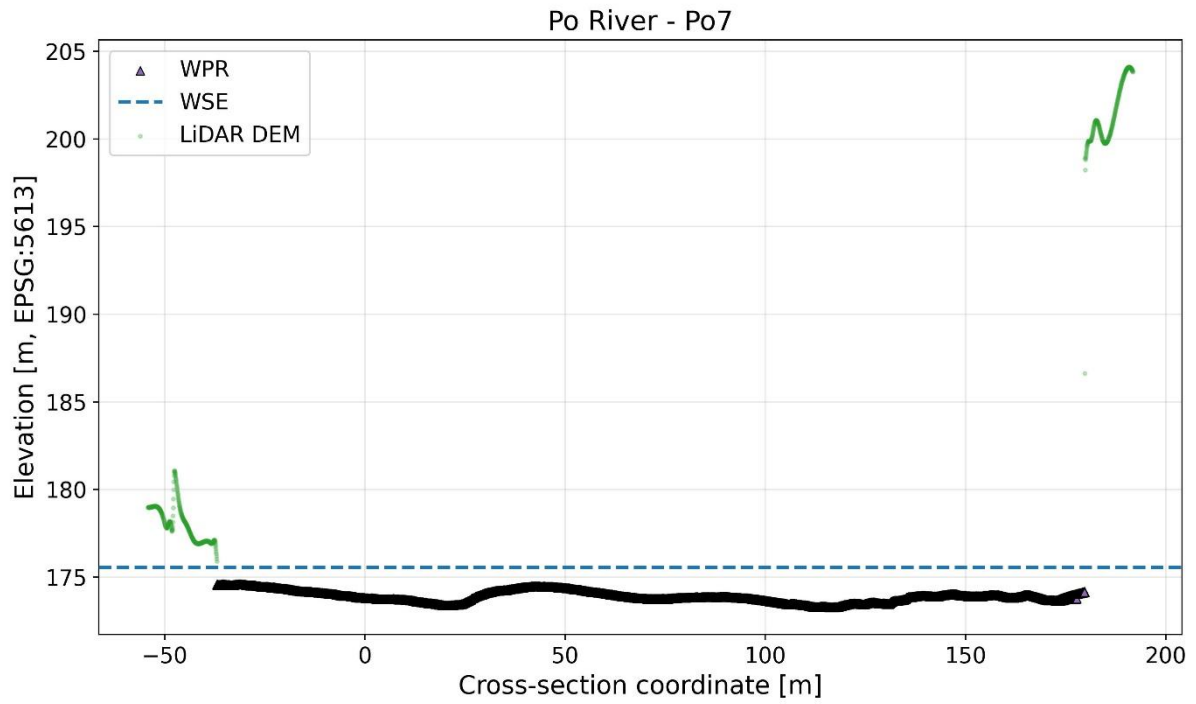


Figure A39. Cross-section Po 7 at Po River

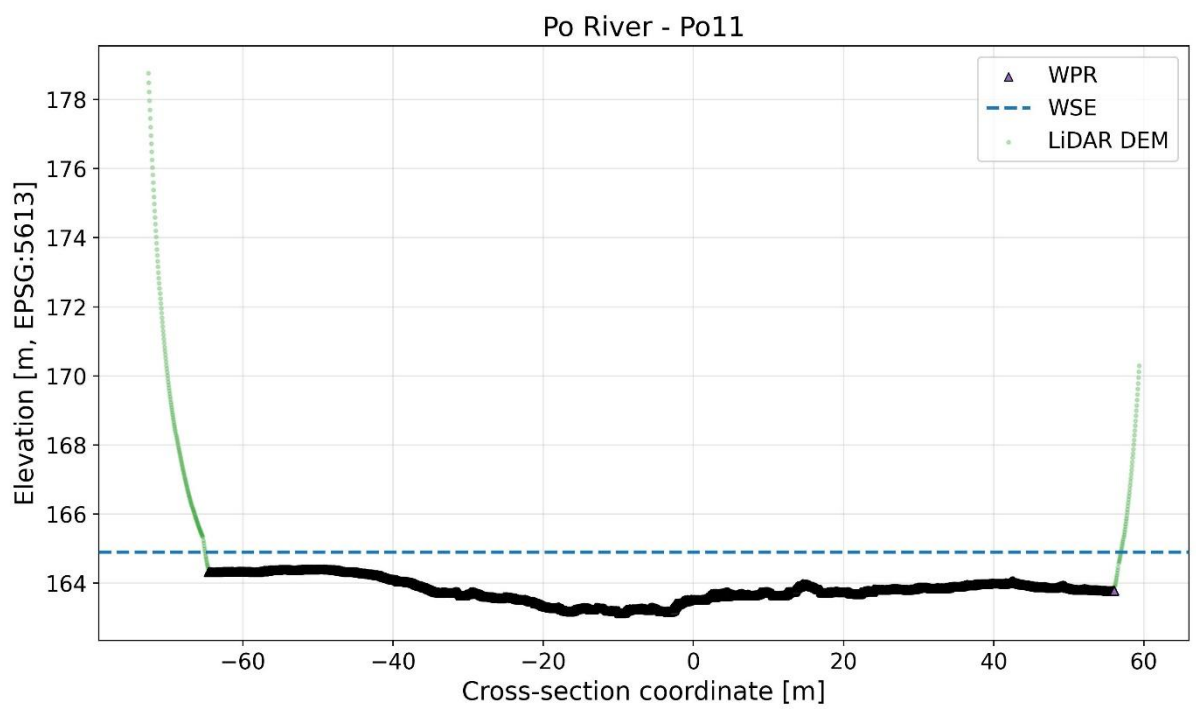


Figure A40. Cross-section Po 11 at Po River

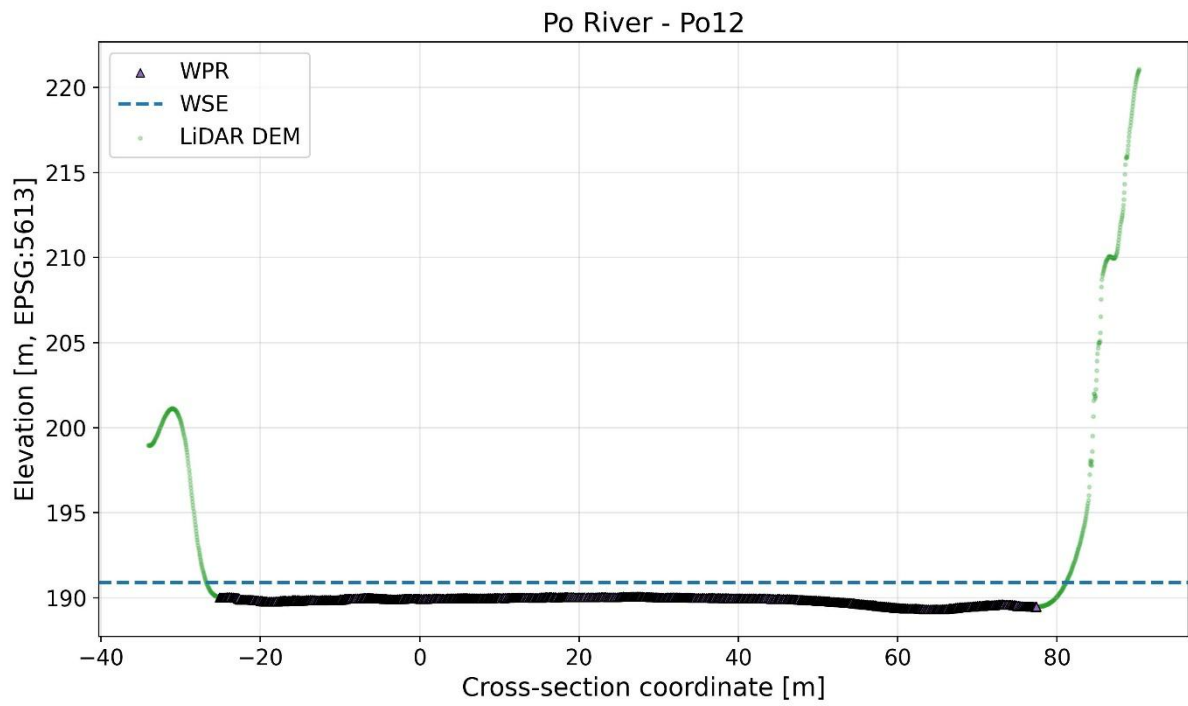


Figure A41. Cross-section Po 12 at Po River

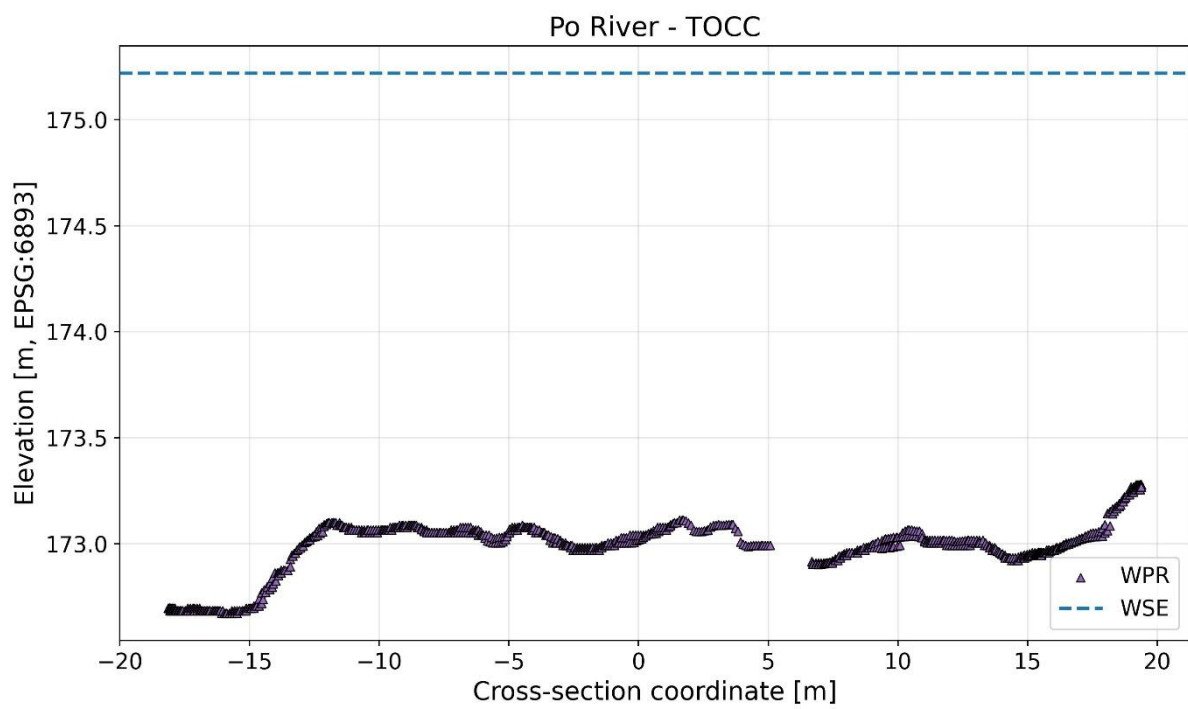


Figure A42. Cross-section TOCC at Po River

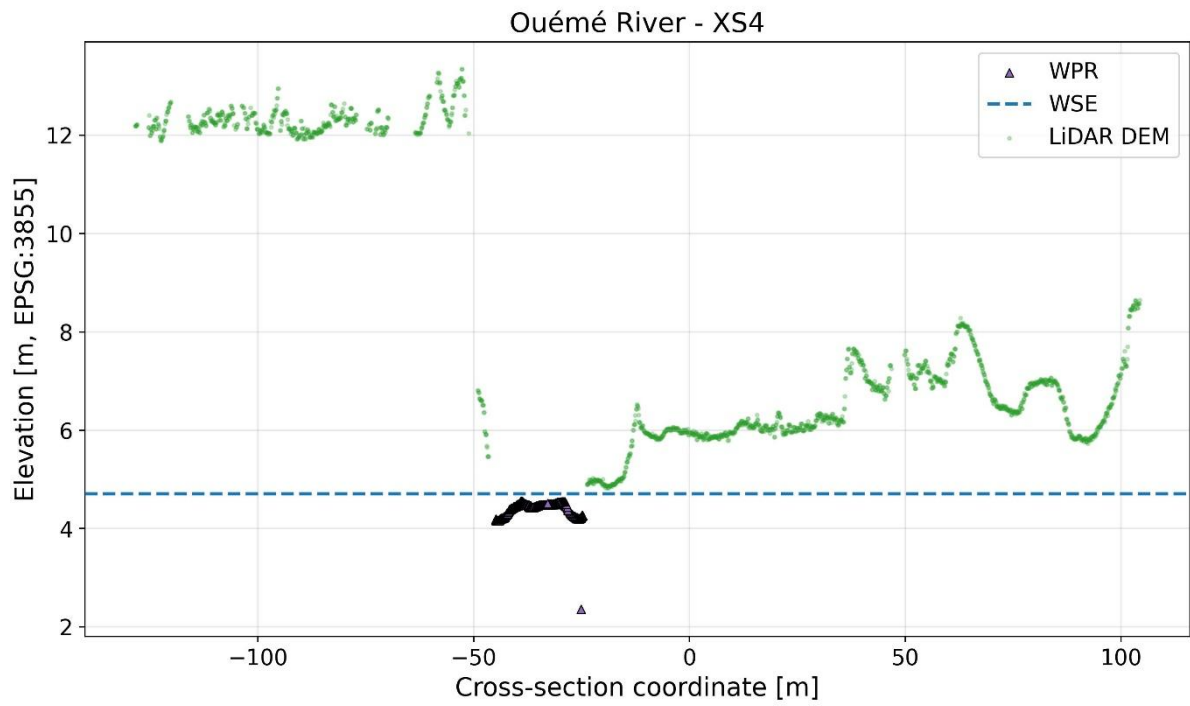


Figure A43. Cross-section XS4 at Ouémé River

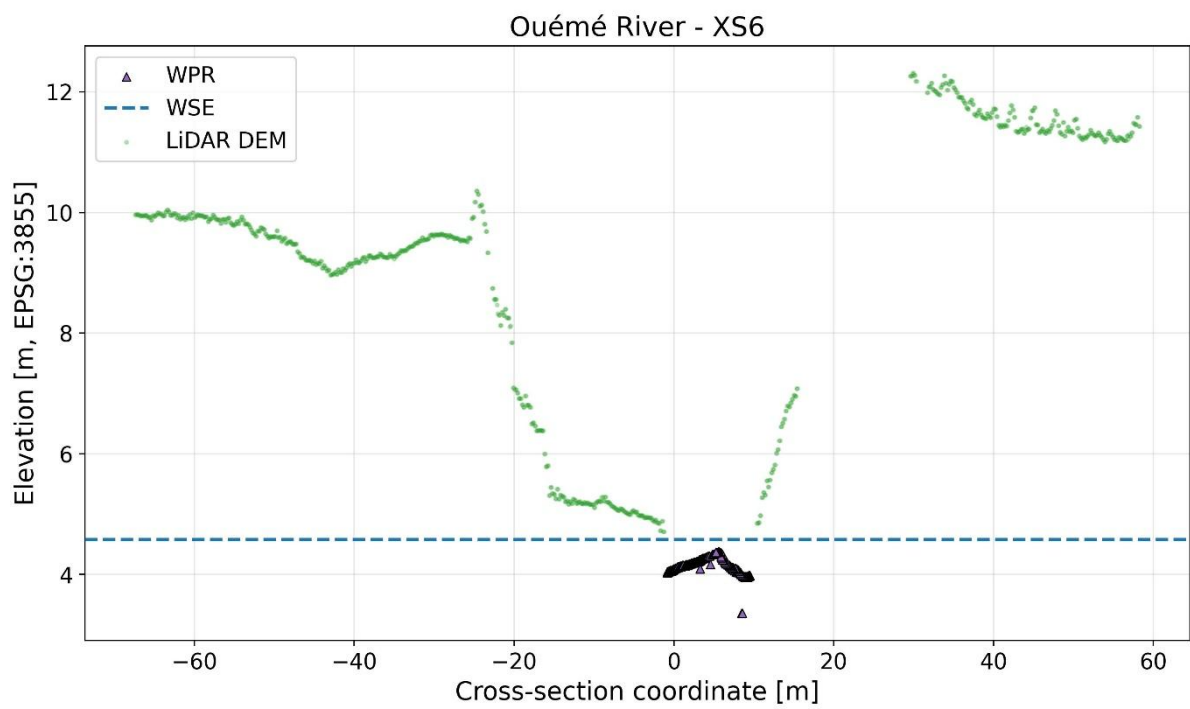


Figure A44. Cross-section XS6 at Ouémé River

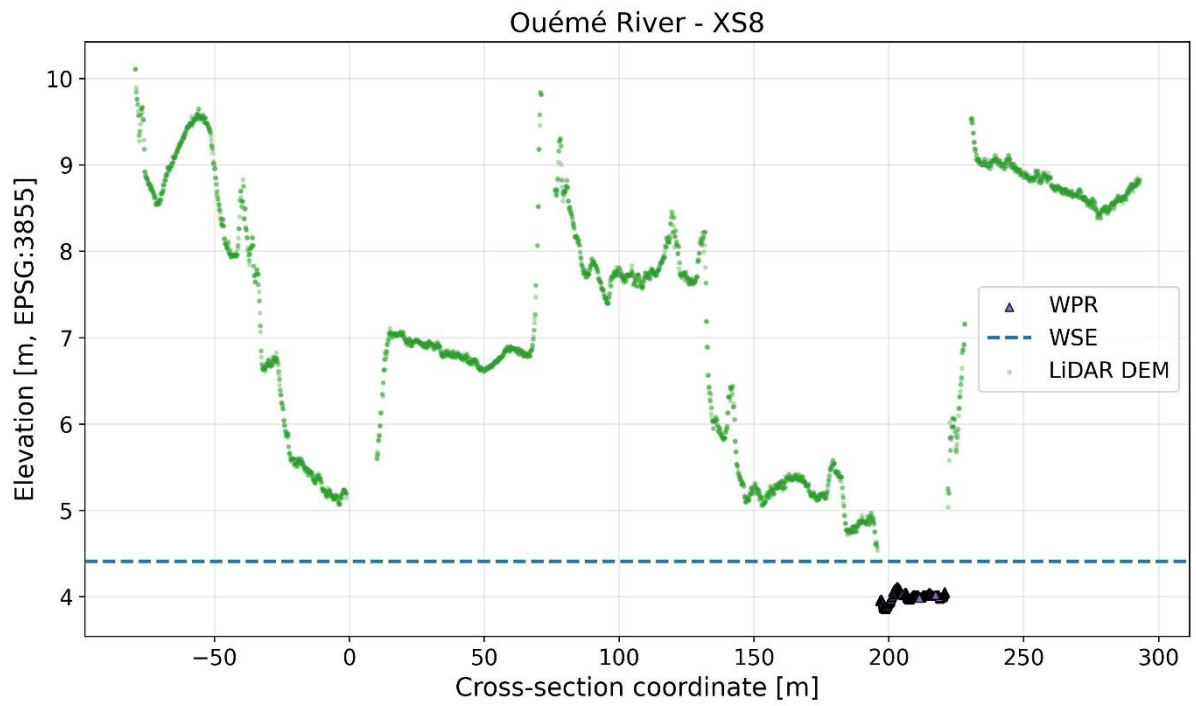


Figure A45. Cross-section XS8 at Ouémé River

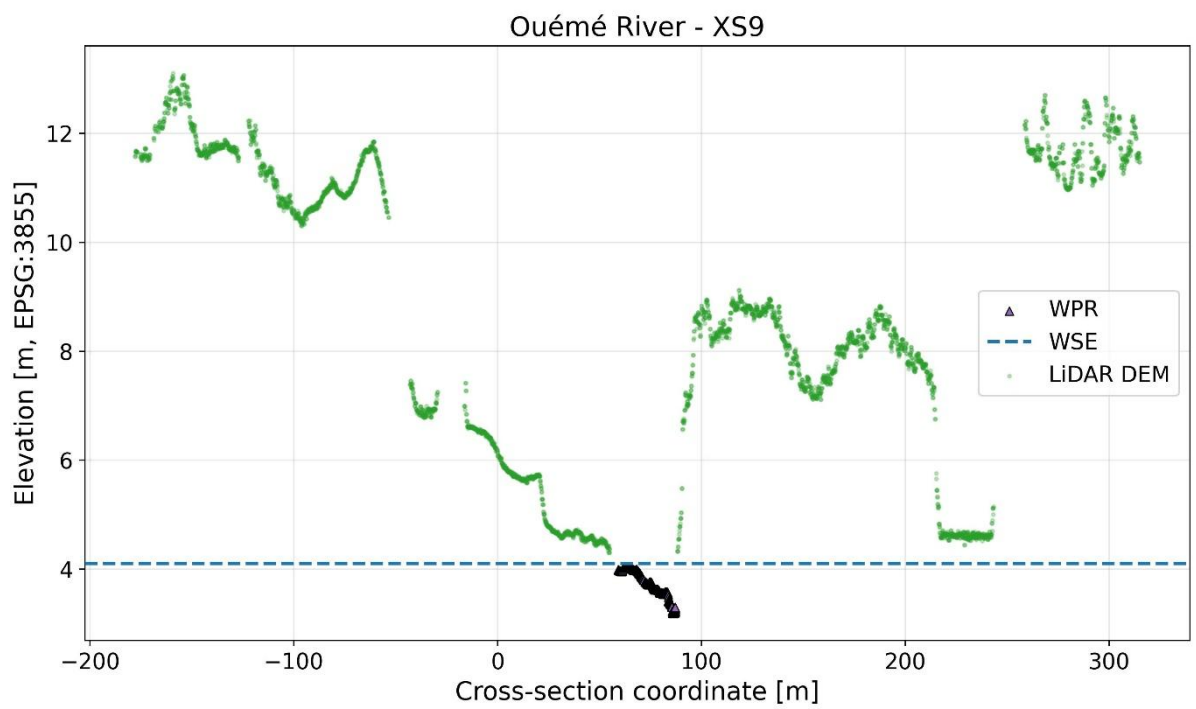


Figure A46. Cross-section XS9 at Ouémé River

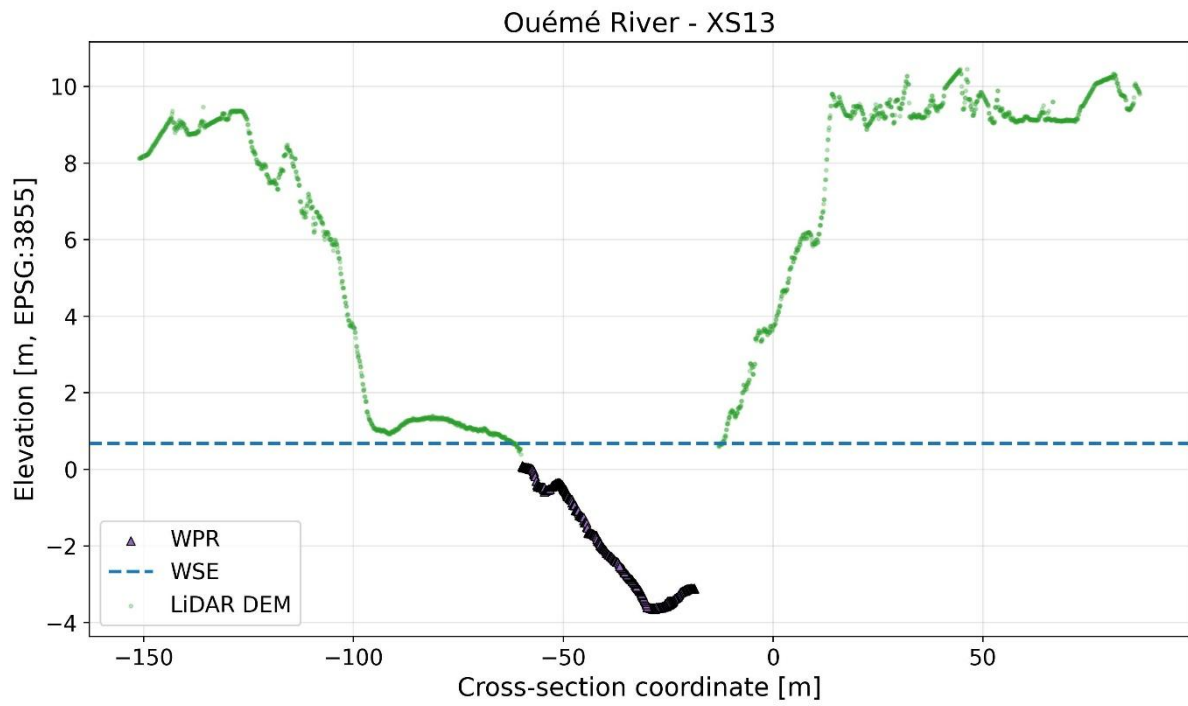


Figure A47. Cross-section XS13 at Ouémé River

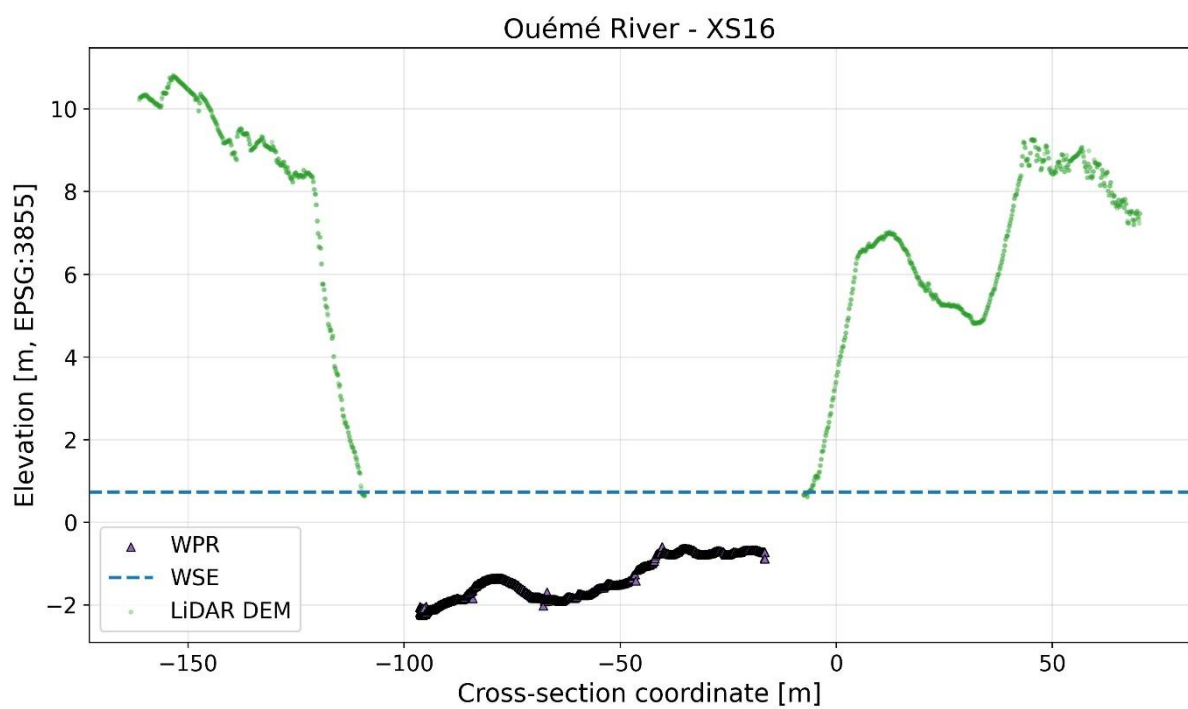


Figure A48. Cross-section XS16 at Ouémé River



Figure A49. Cross-section XS17 at Ouémé River

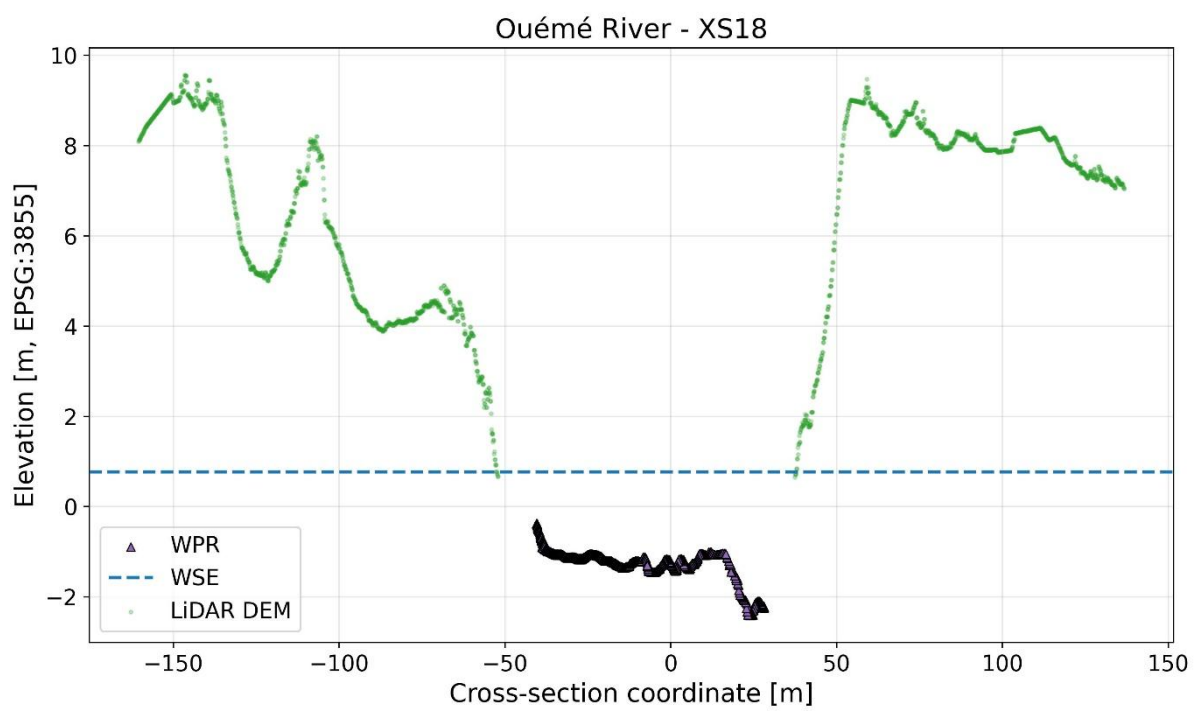


Figure A50. Cross-section XS18 at Ouémé River

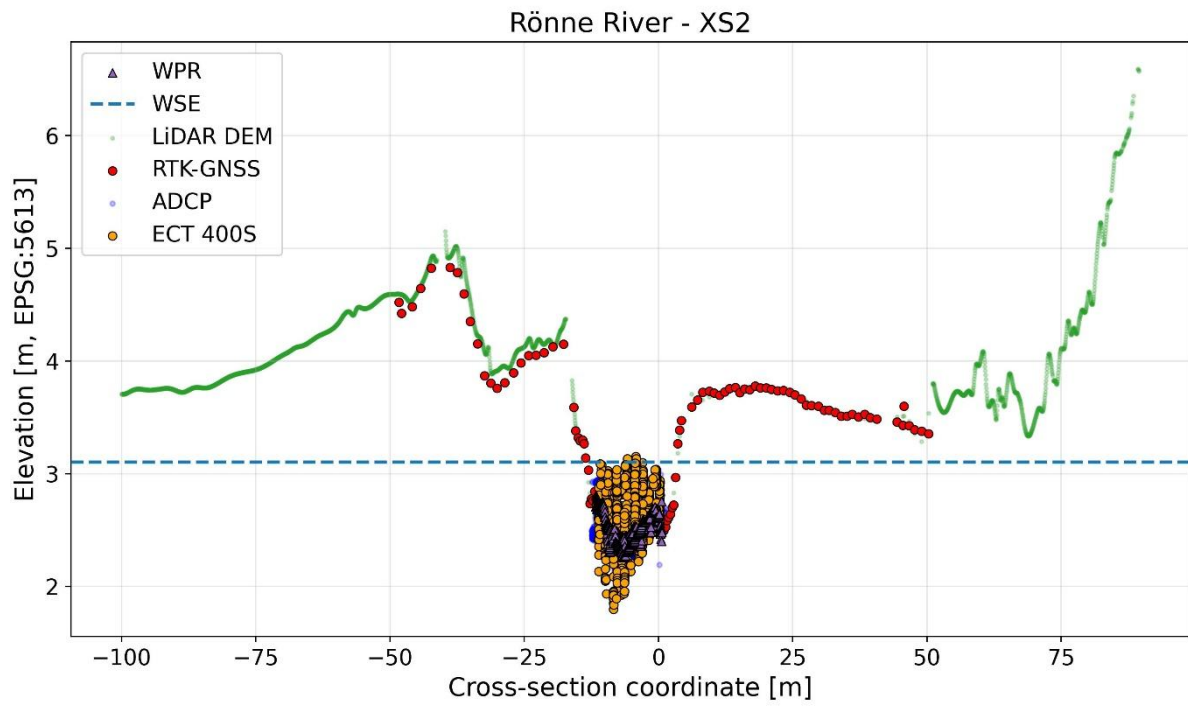


Figure A51. Cross-section XS2 at Rönne River

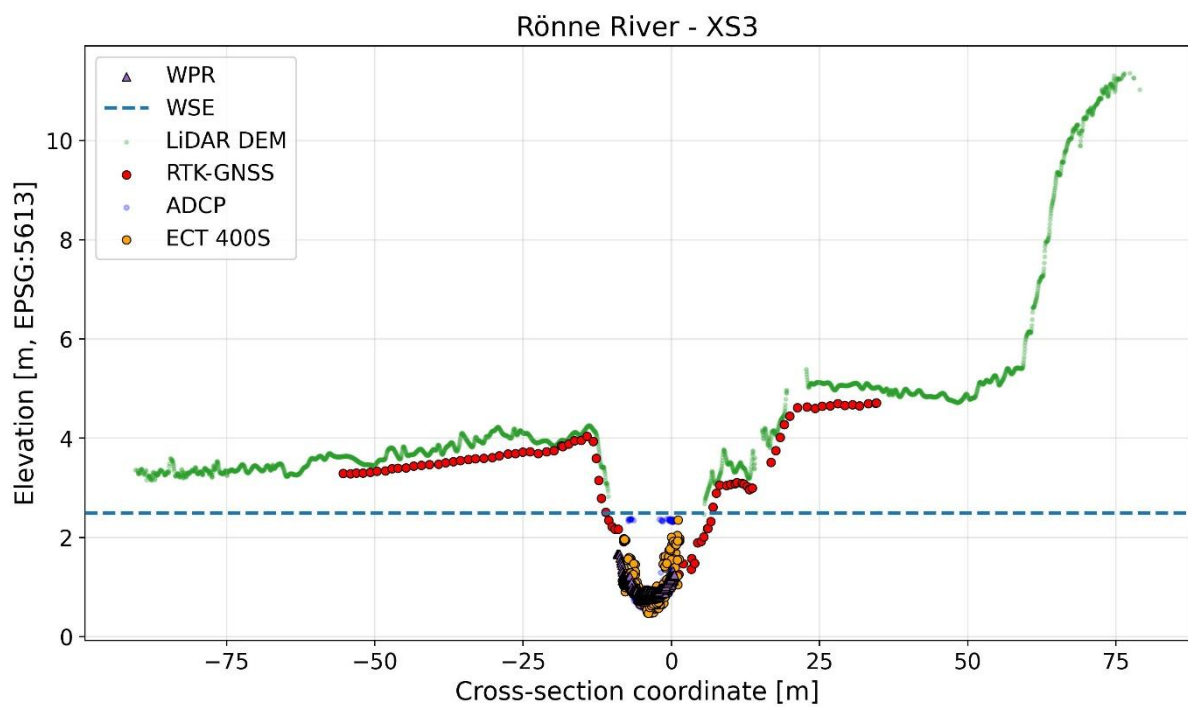


Figure A52. Cross-section XS3 at Rönne River

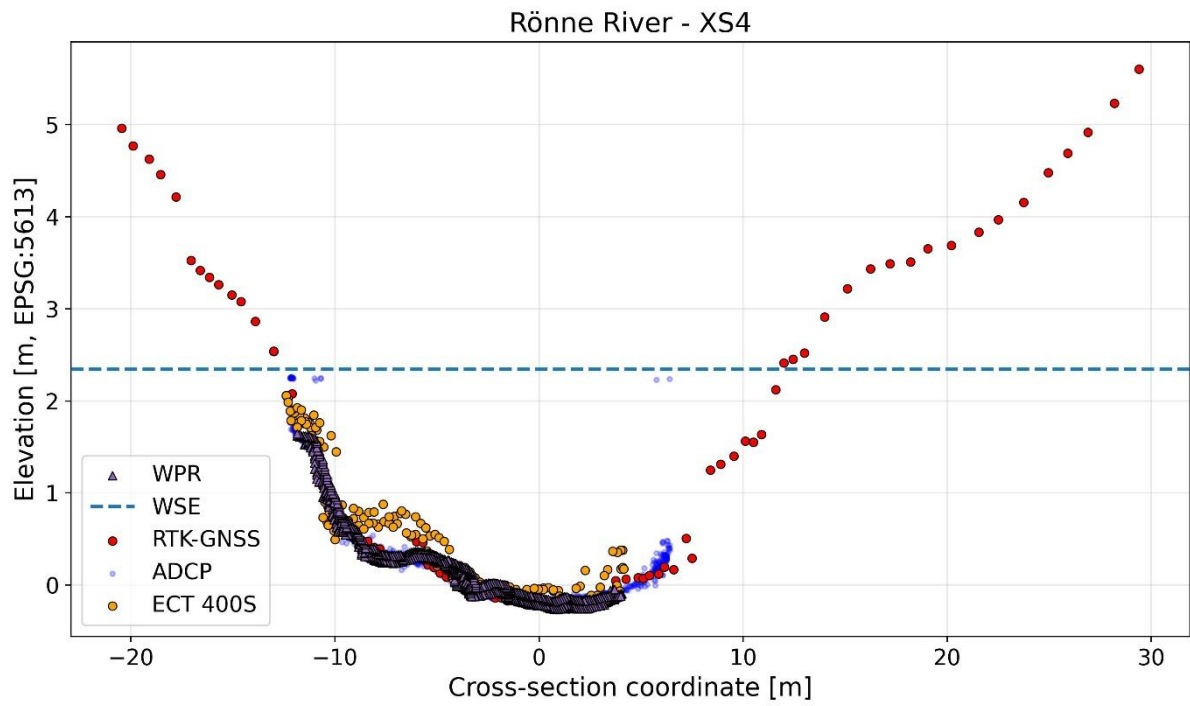


Figure A53. Cross-section XS4 at Rönne River

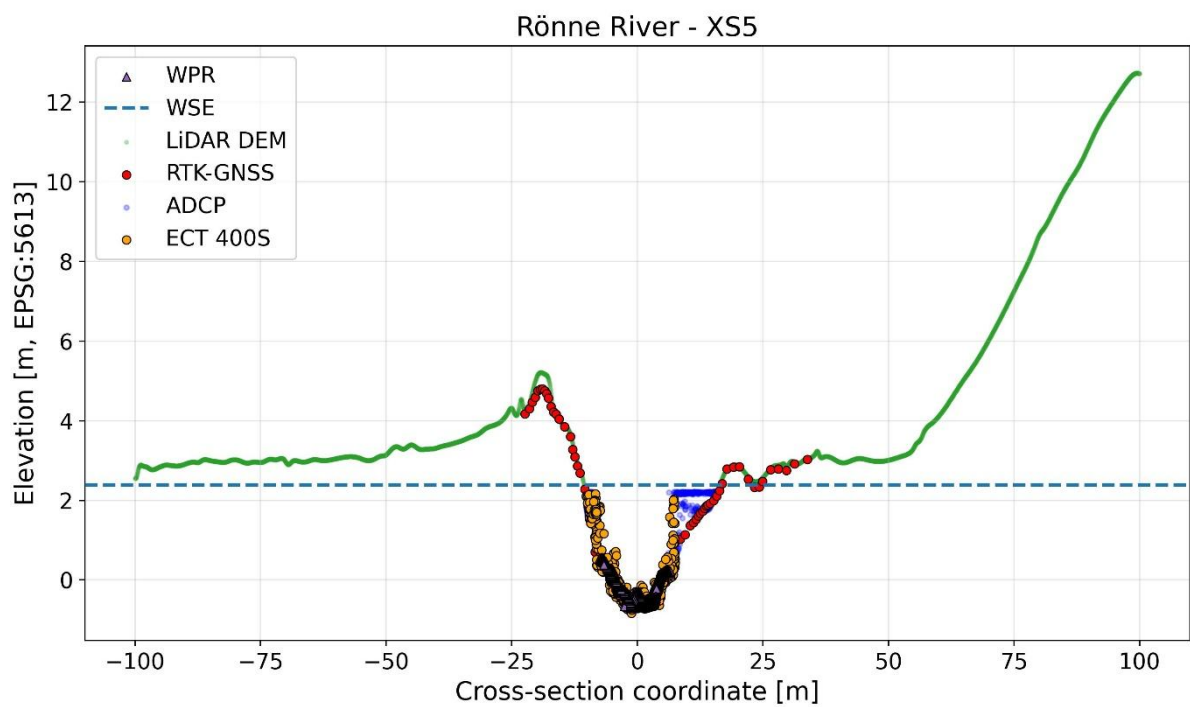


Figure A54. Cross-section XS5 at Rönne River

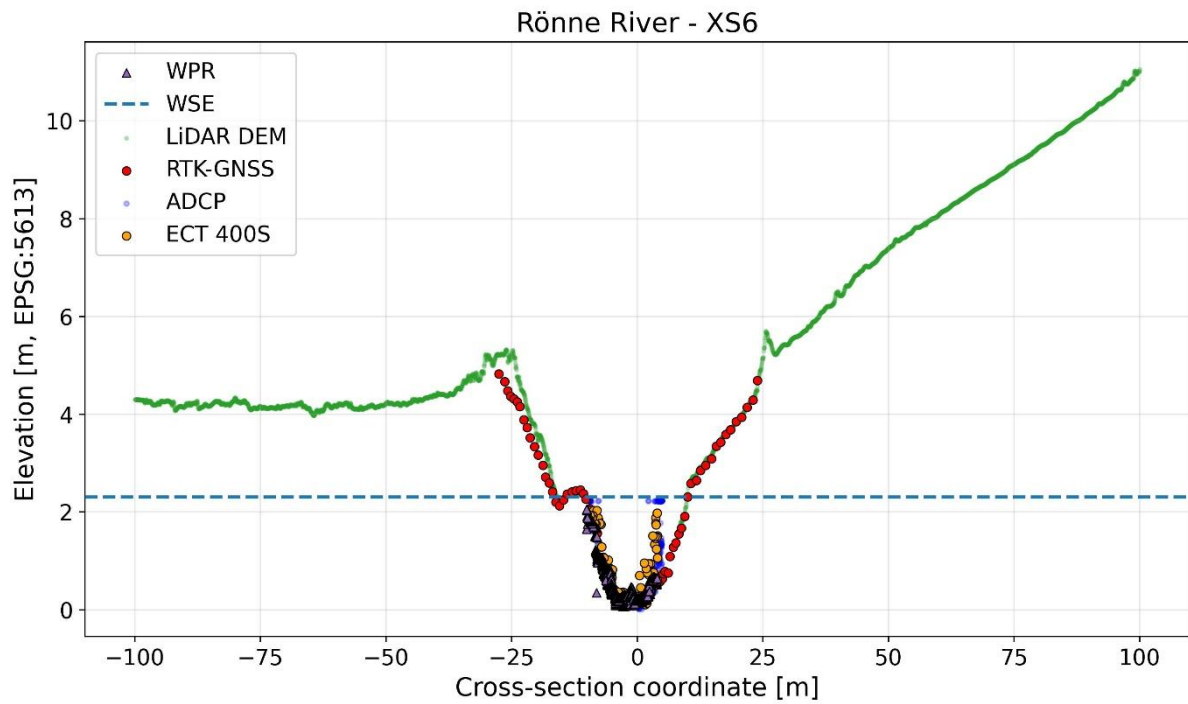


Figure A55. Cross-section XS6 at Rönne River

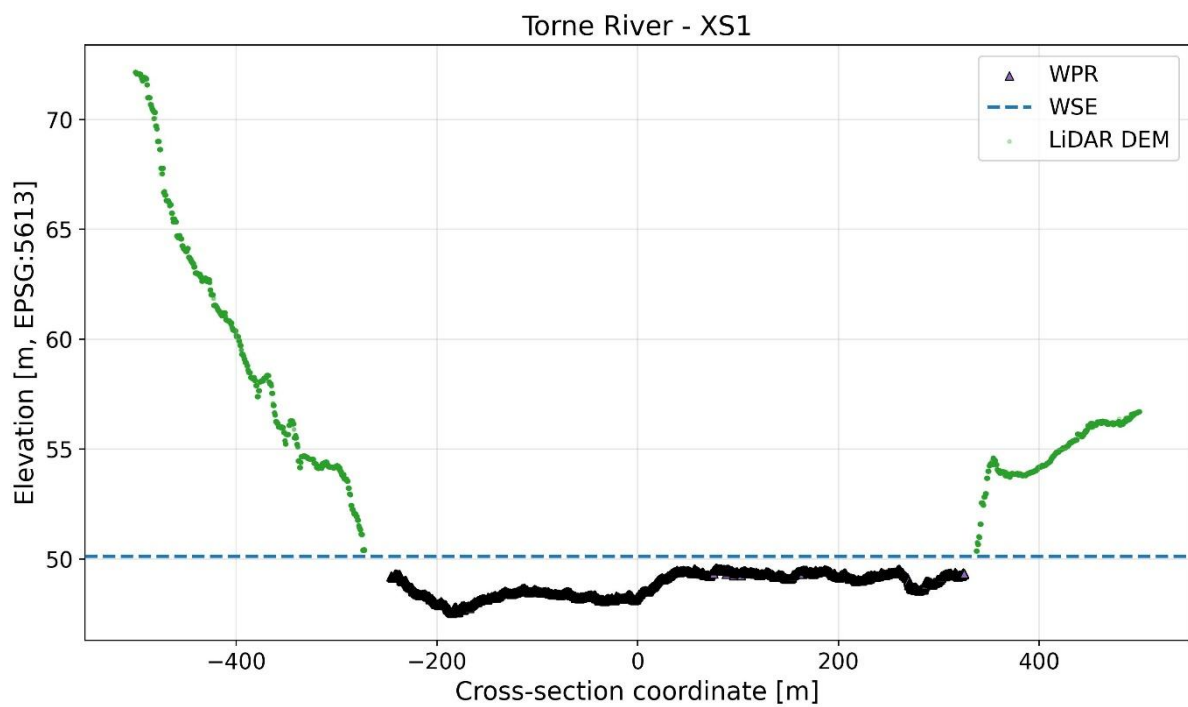


Figure A56. Cross-section XS1 at Torne River

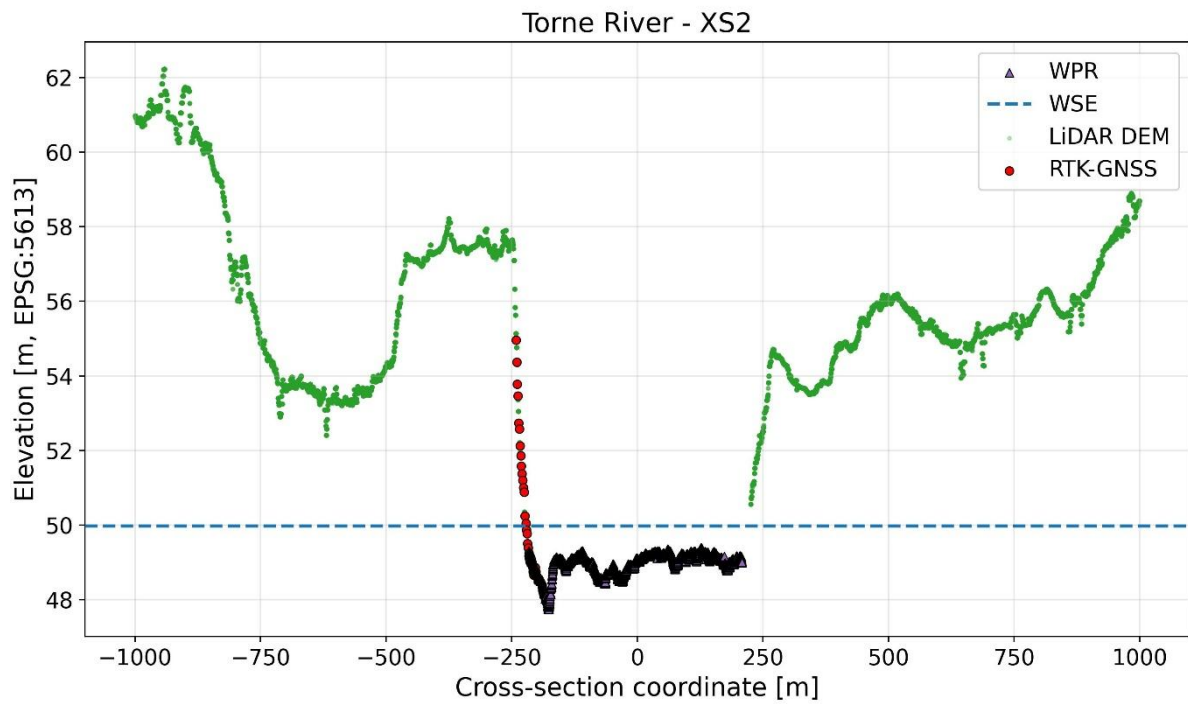


Figure A57. Cross-section XS2 at Torne River

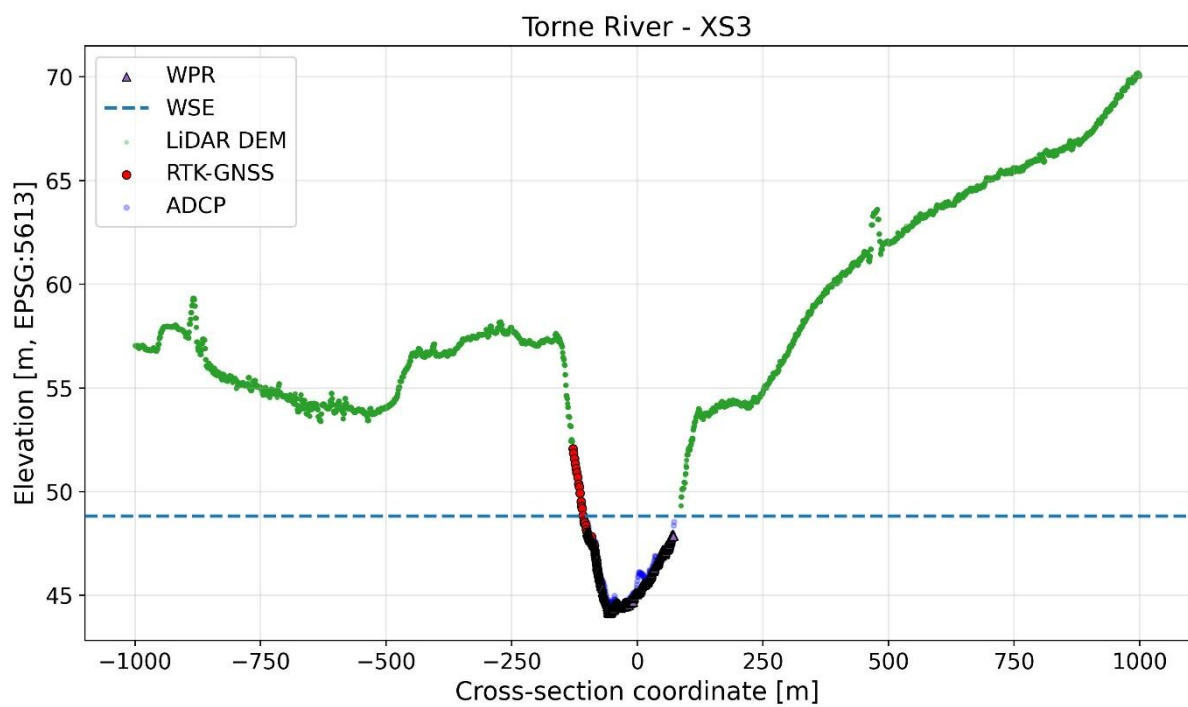


Figure A58. Cross-section XS3 at Torne River

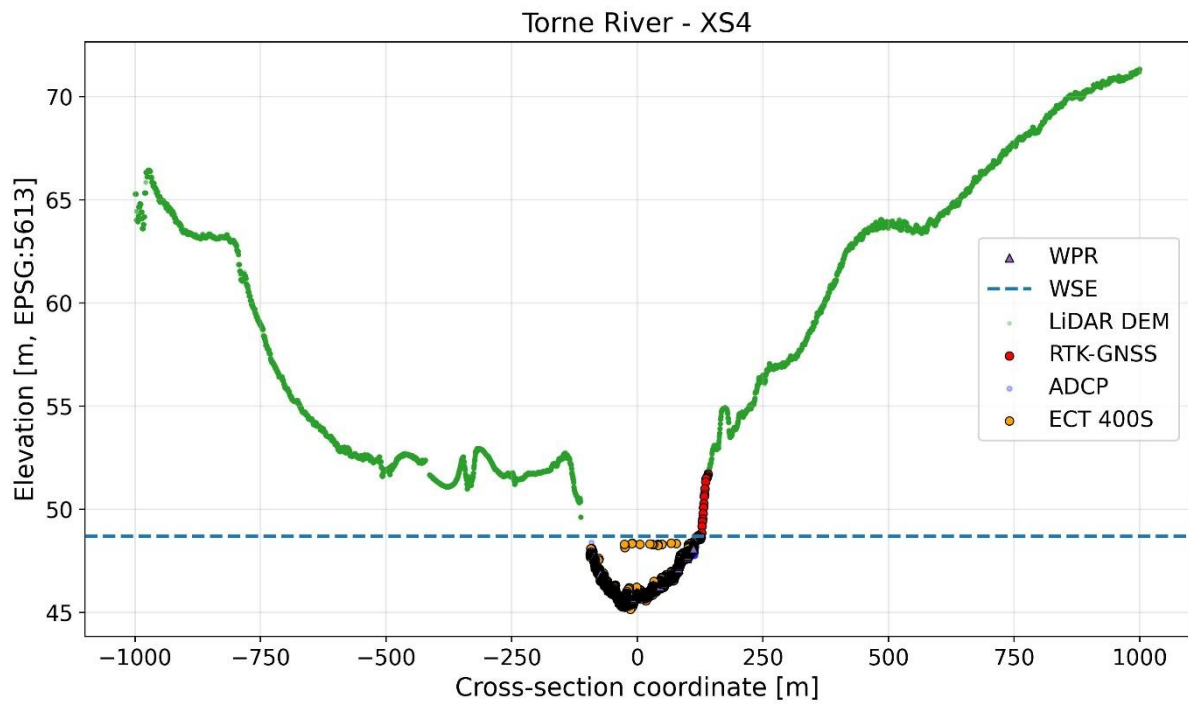


Figure A59. Cross-section XS4 at Torne River

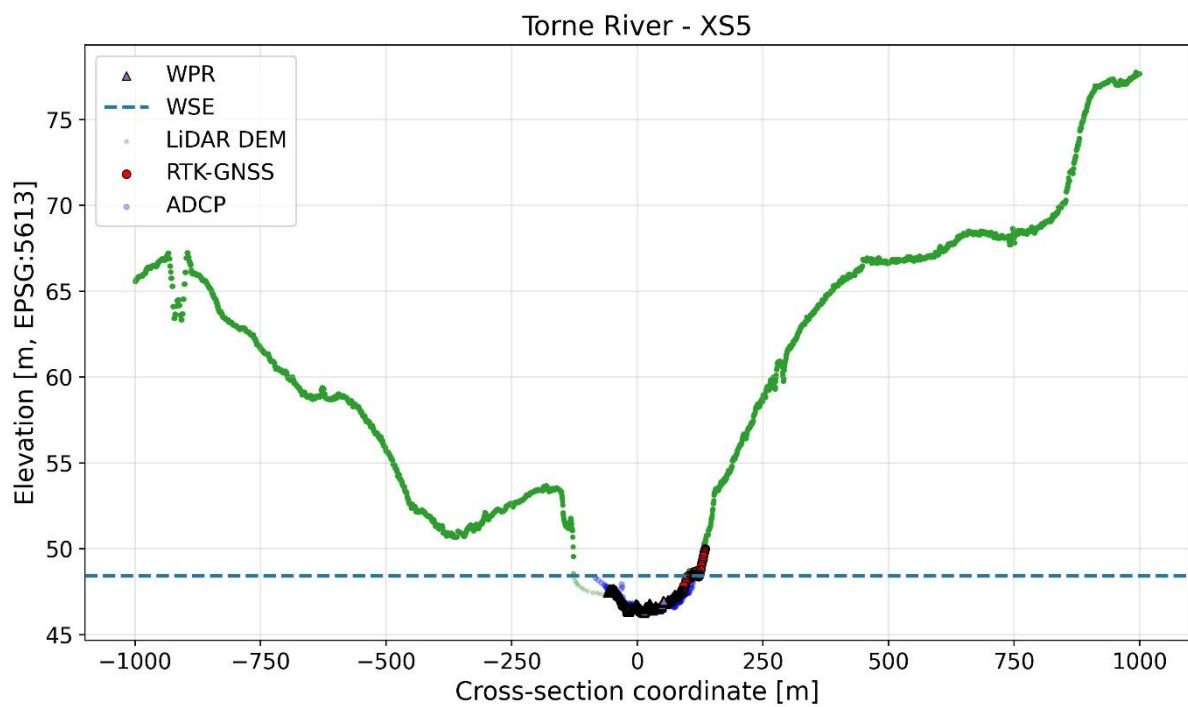


Figure A60. Cross-section XS5 at Torne River

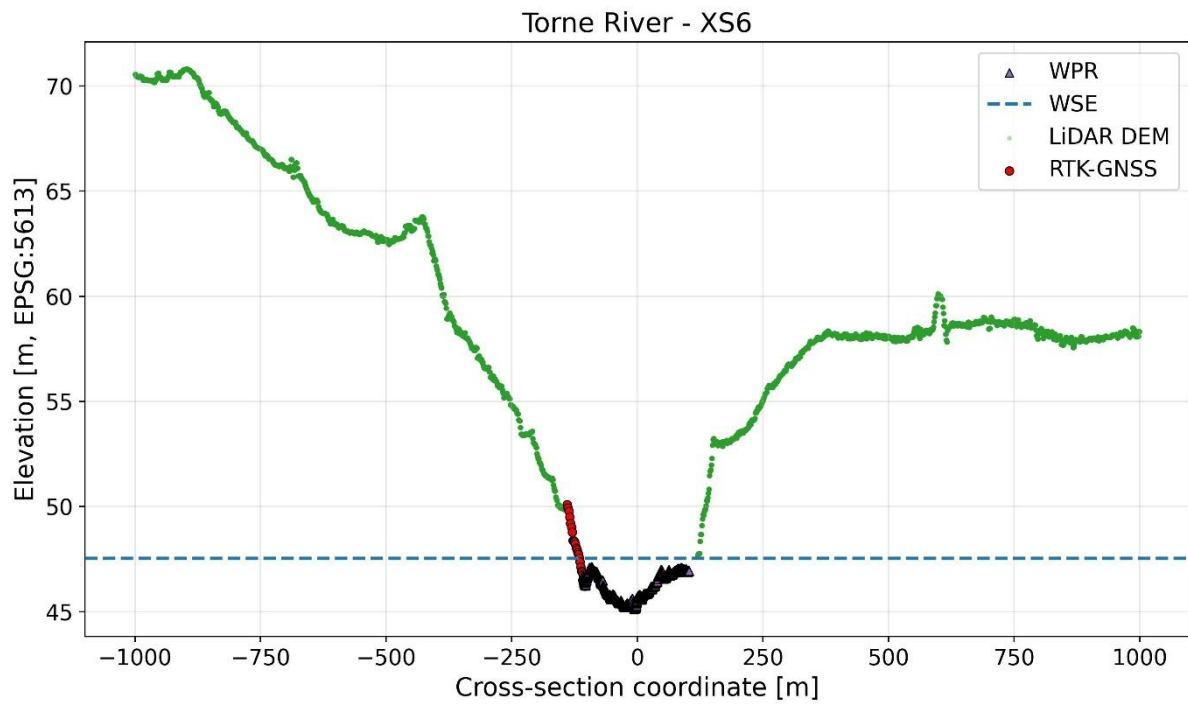


Figure A61. Cross-section XS6 at Torne River

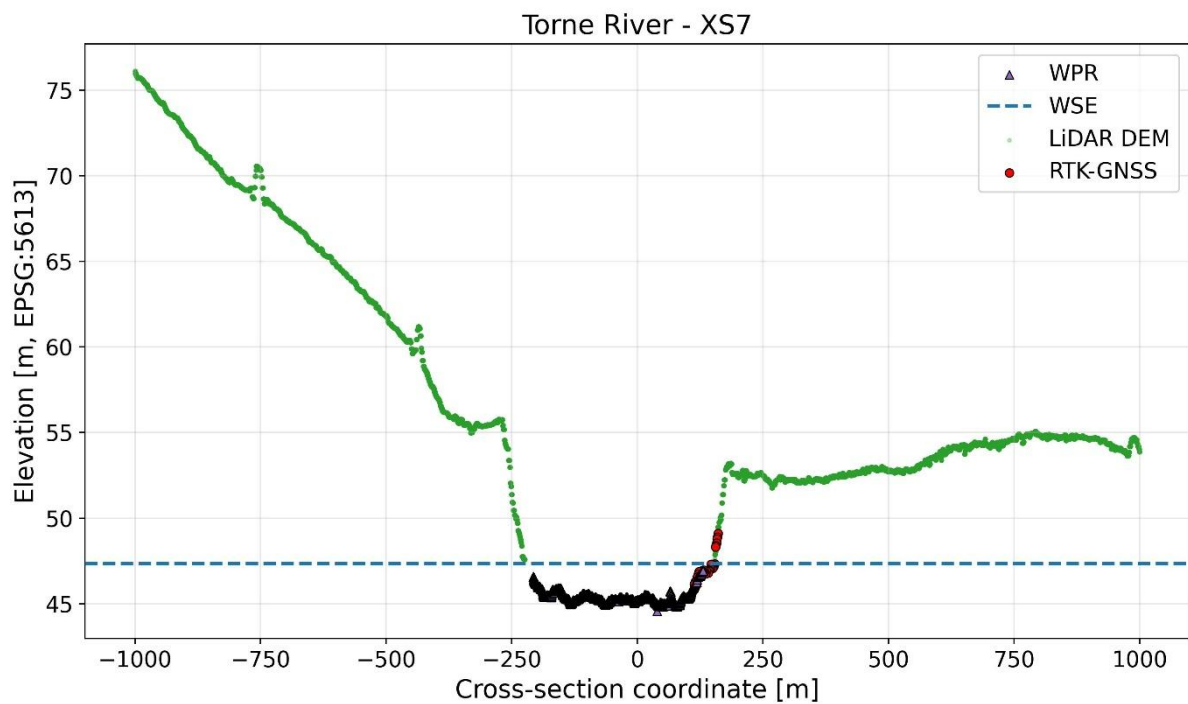


Figure A62. Cross-section XS7 at Torne River

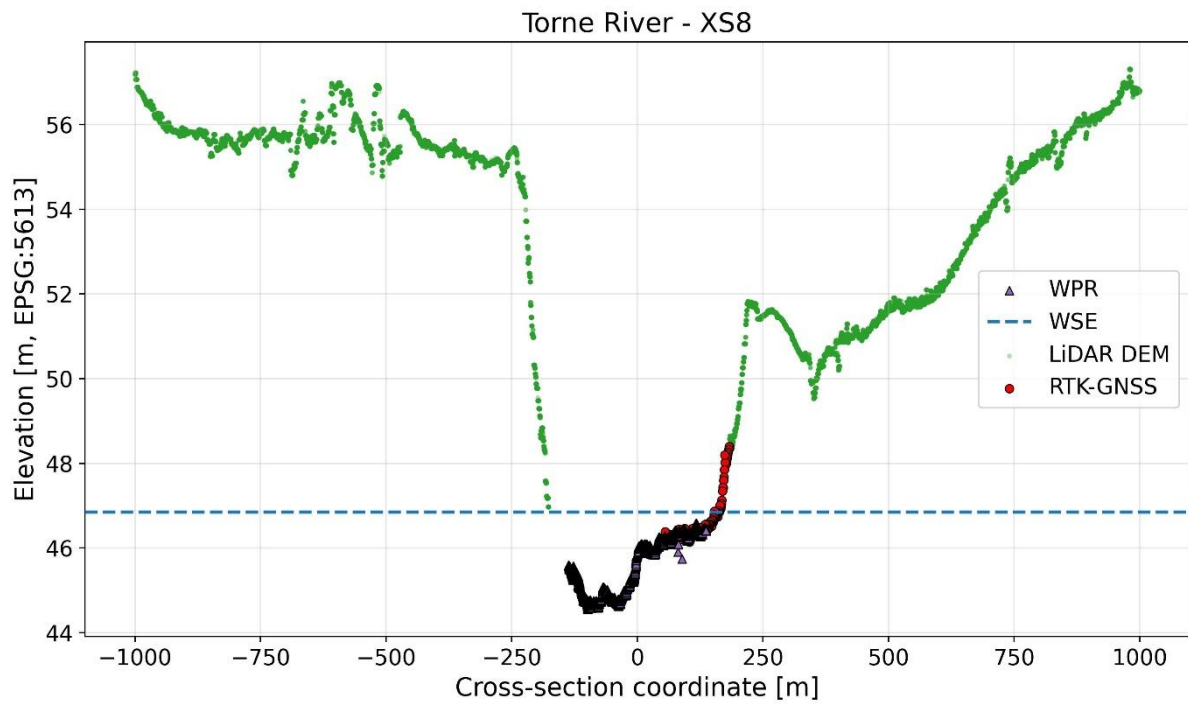


Figure A63. Cross-section XS8 at Torne River

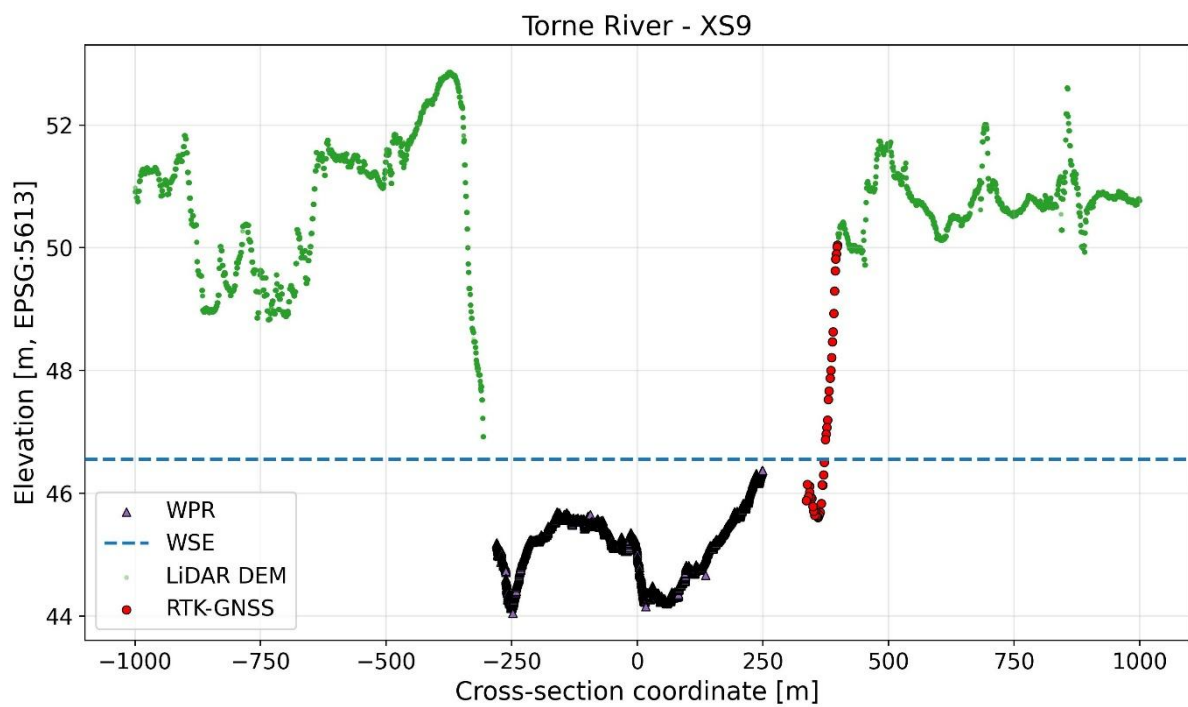


Figure A64. Cross-section XS9 at Torne River

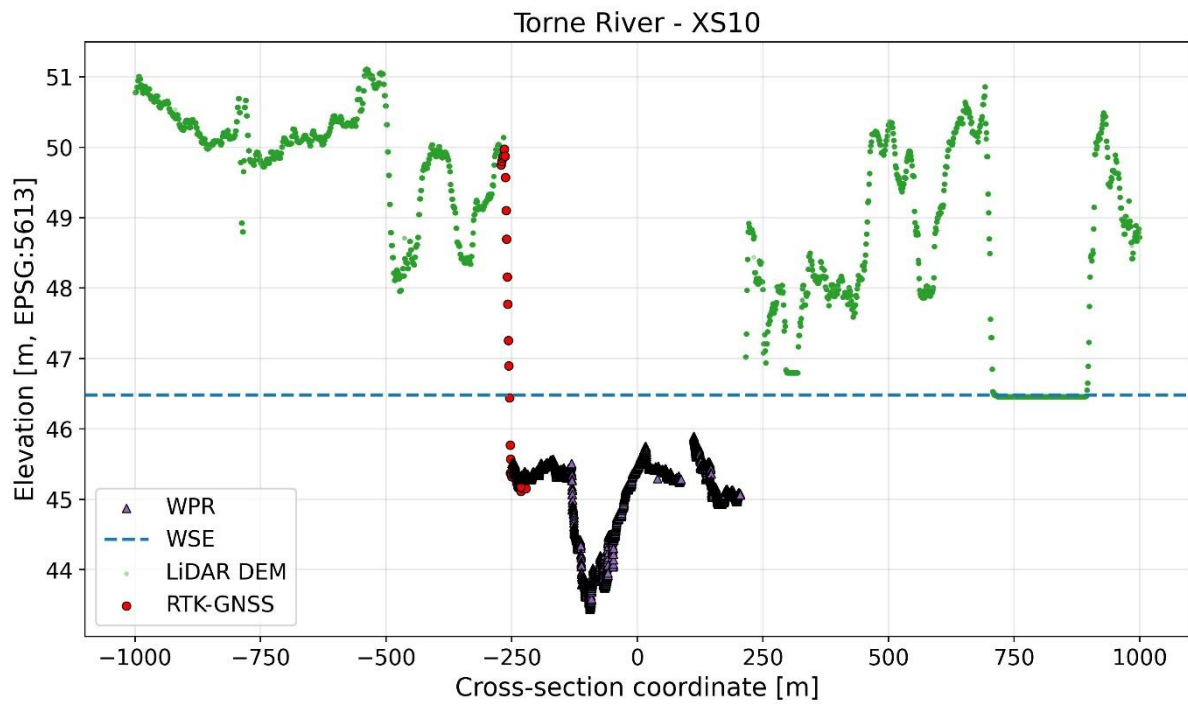


Figure A65. Cross-section XS10 at Torne River

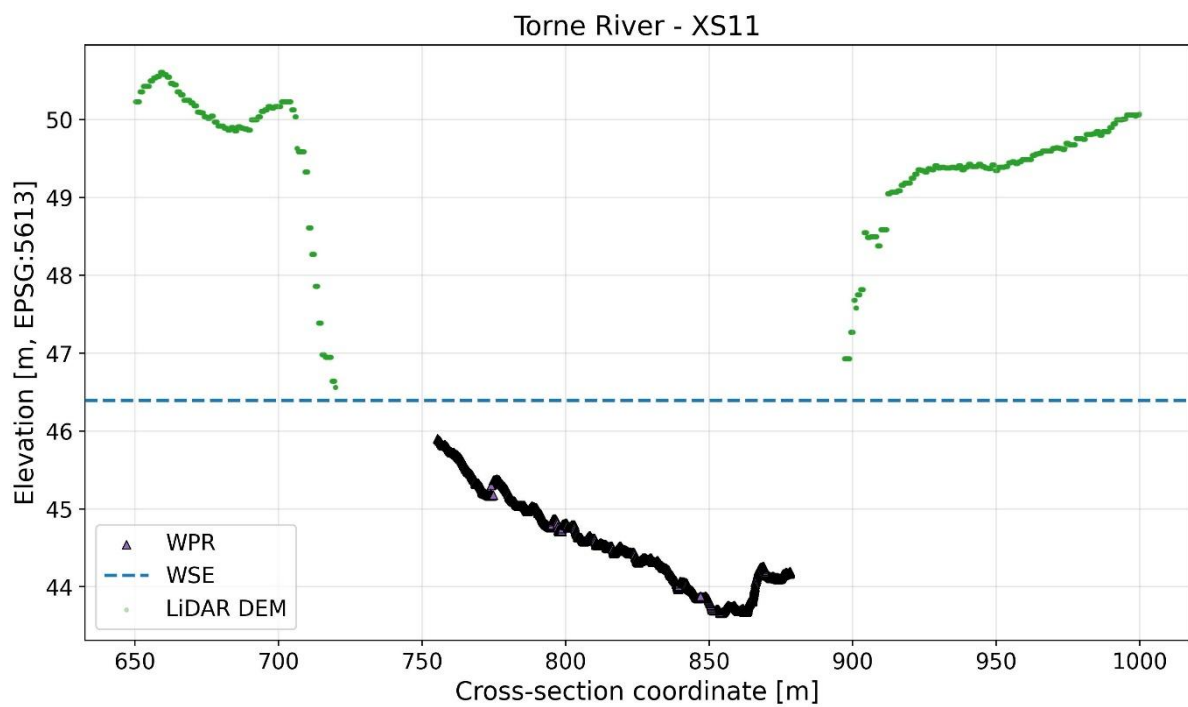


Figure A66. Cross-section XS11 at Torne River

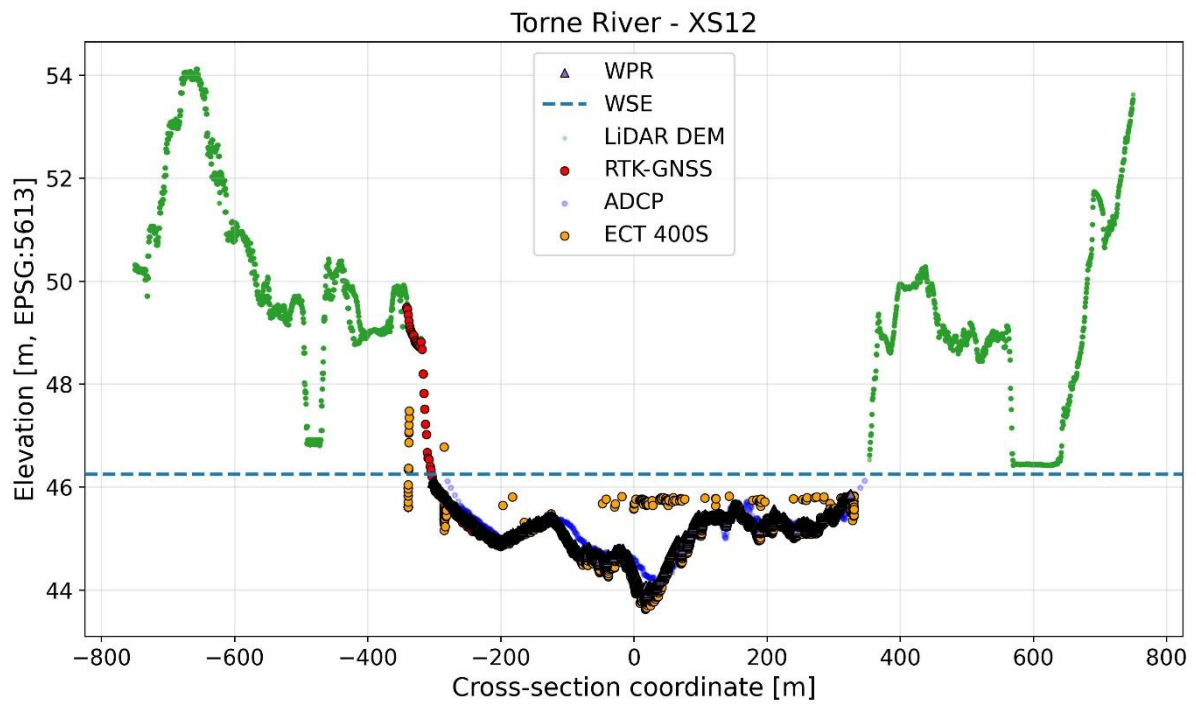


Figure A67. Cross-section XS12 at Torne River

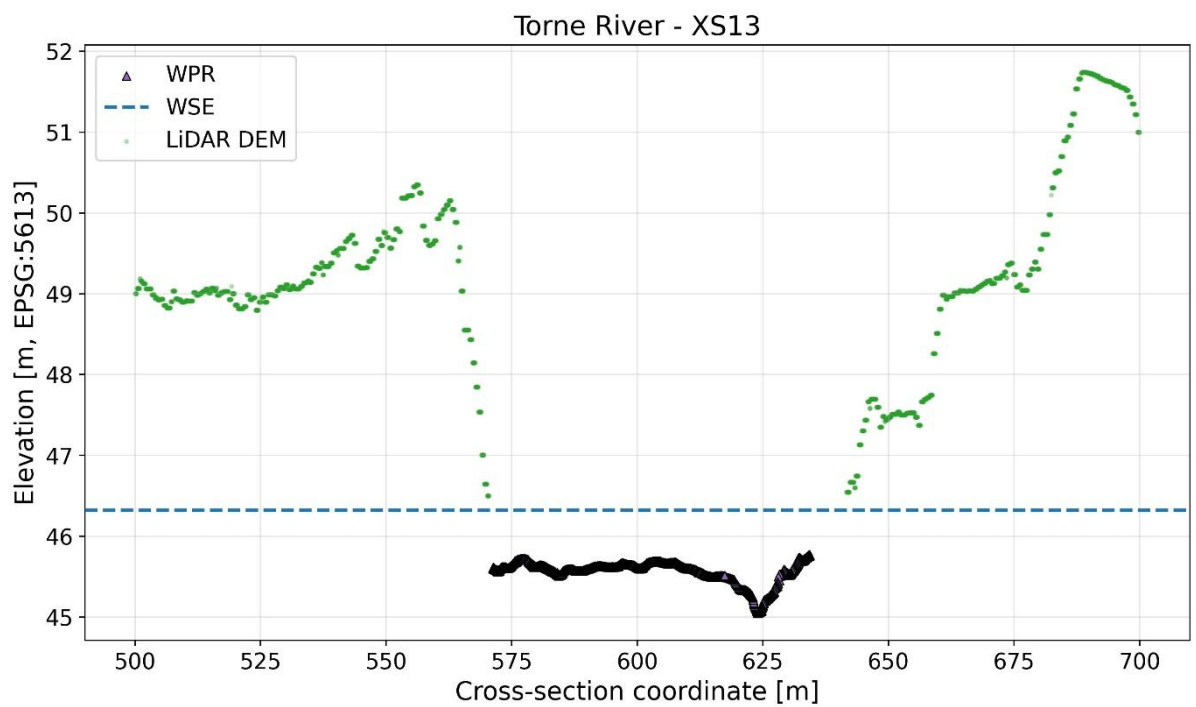


Figure A68. Cross-section XS13 at Torne River

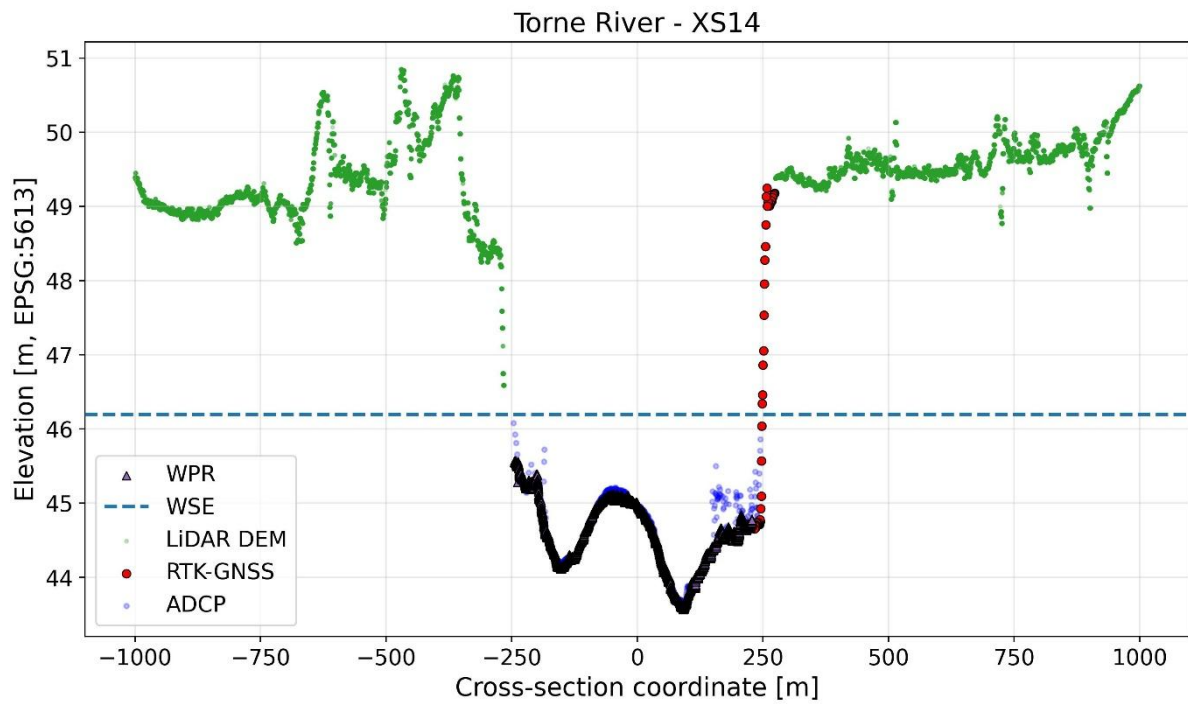


Figure A69. Cross-section XS14 at Torne River

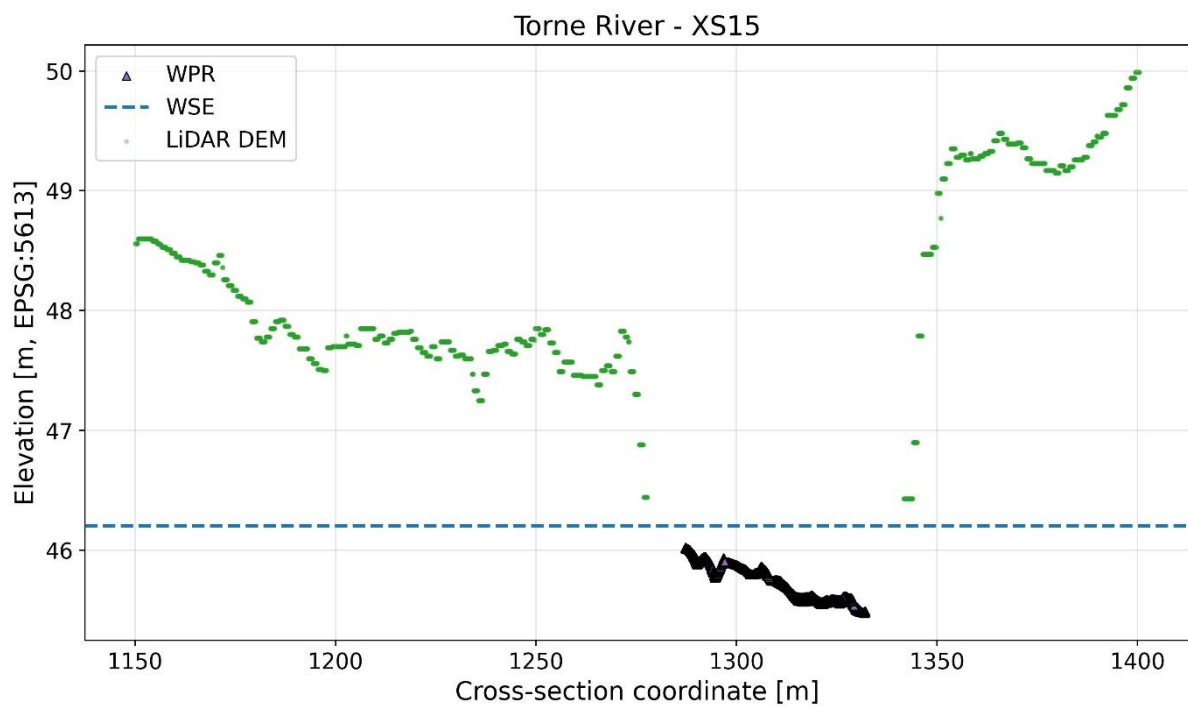


Figure A70. Cross-section XS15 at Torne River

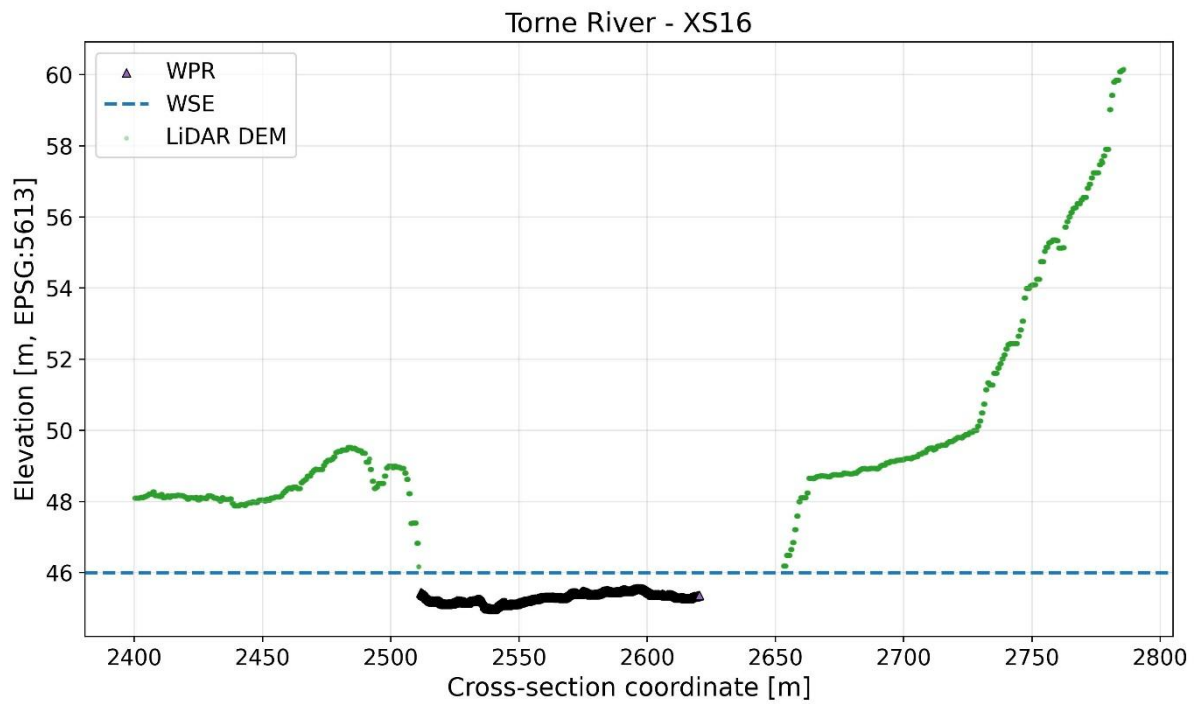


Figure A71. Cross-section XS16 Torne River

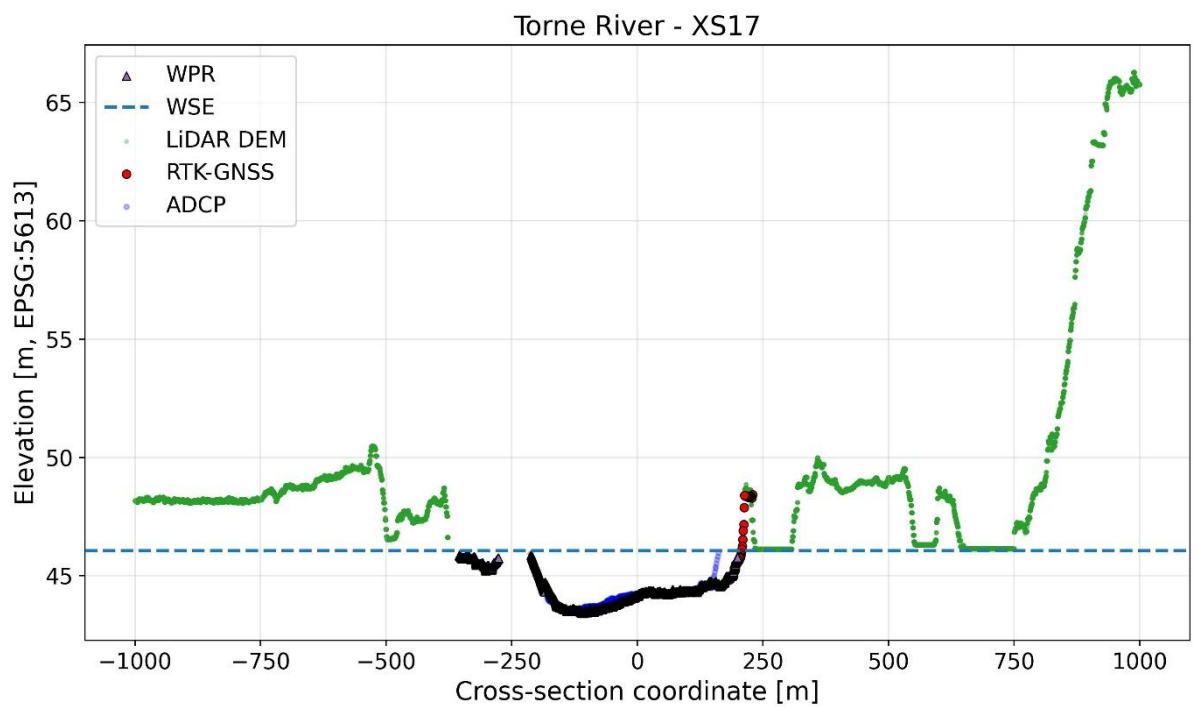


Figure A72. Cross-section XS17 at Torne River

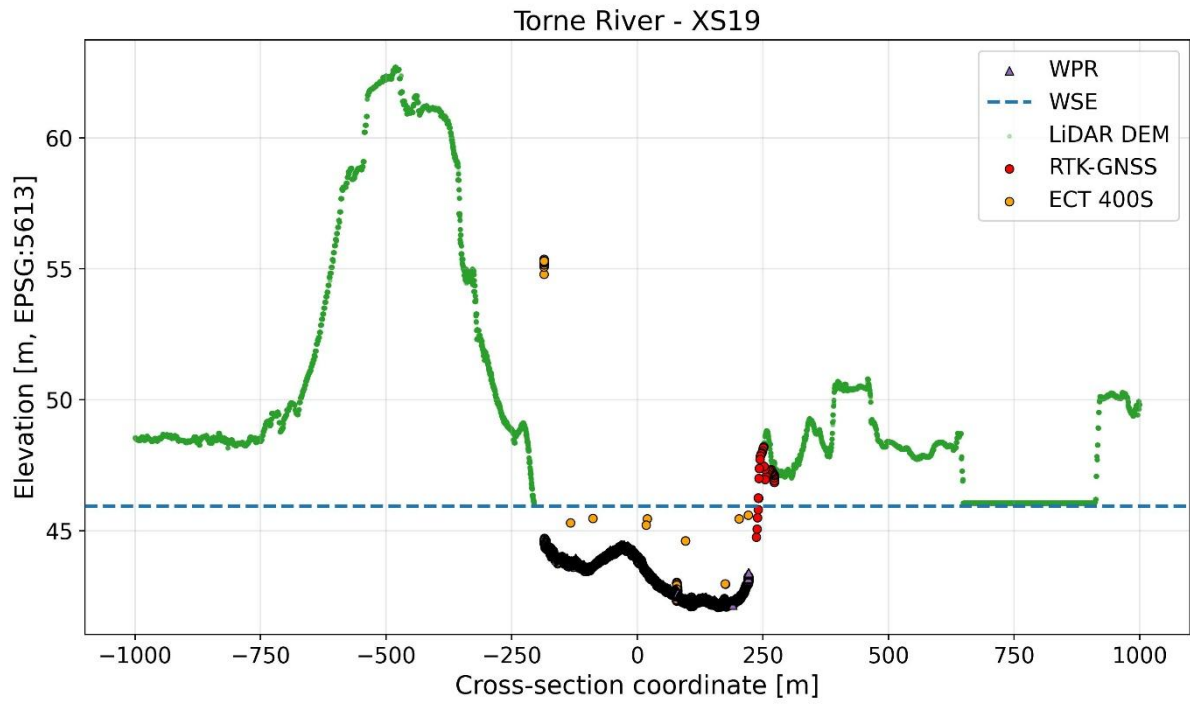


Figure A73. Cross-section XS19 at Torne River

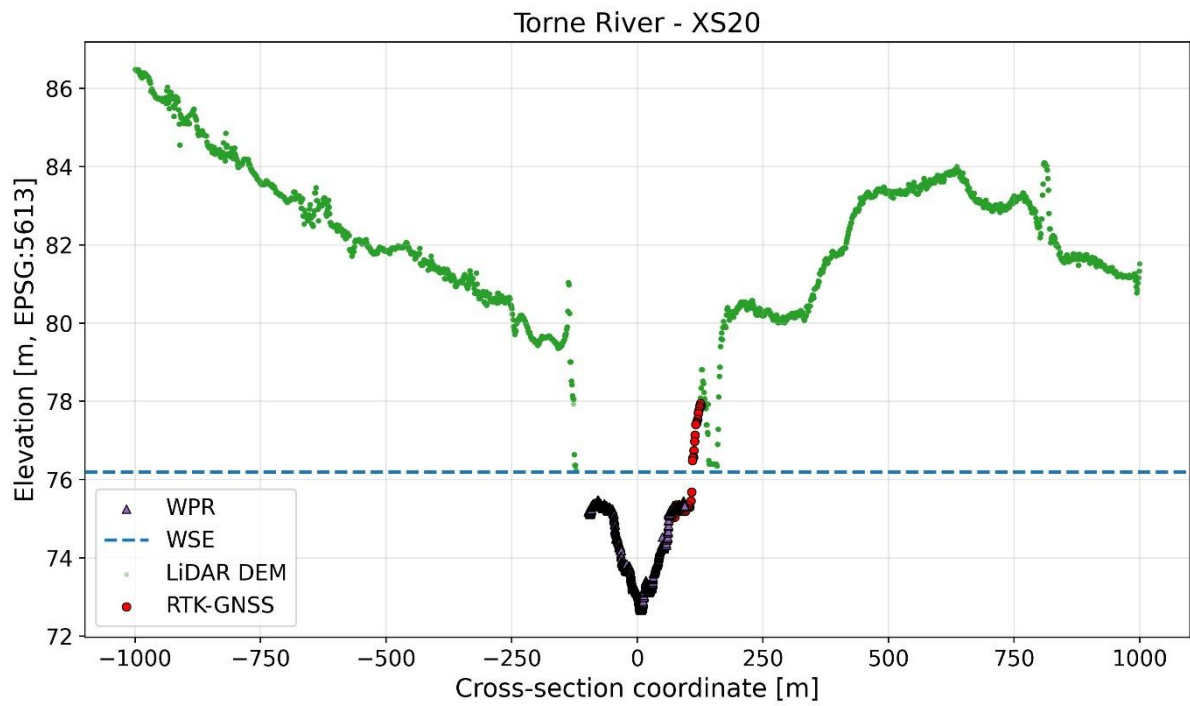


Figure A74. Cross-section XS20 at Torne River

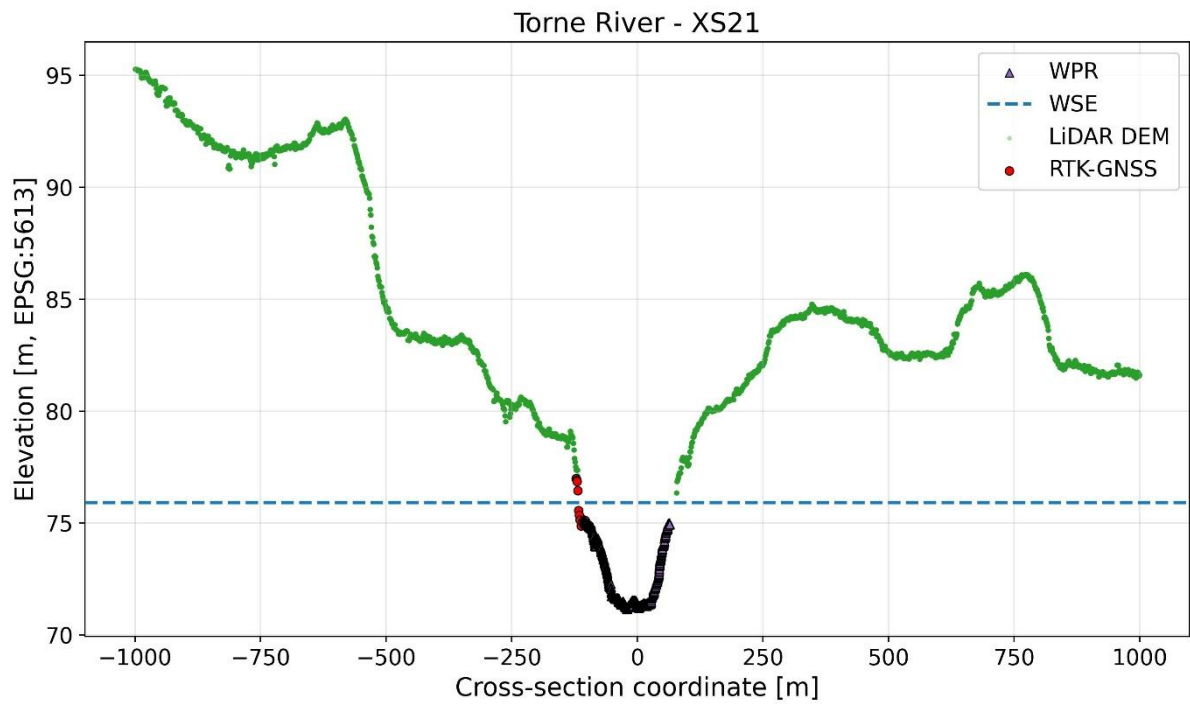


Figure A75. Cross-section XS21 at Torne River

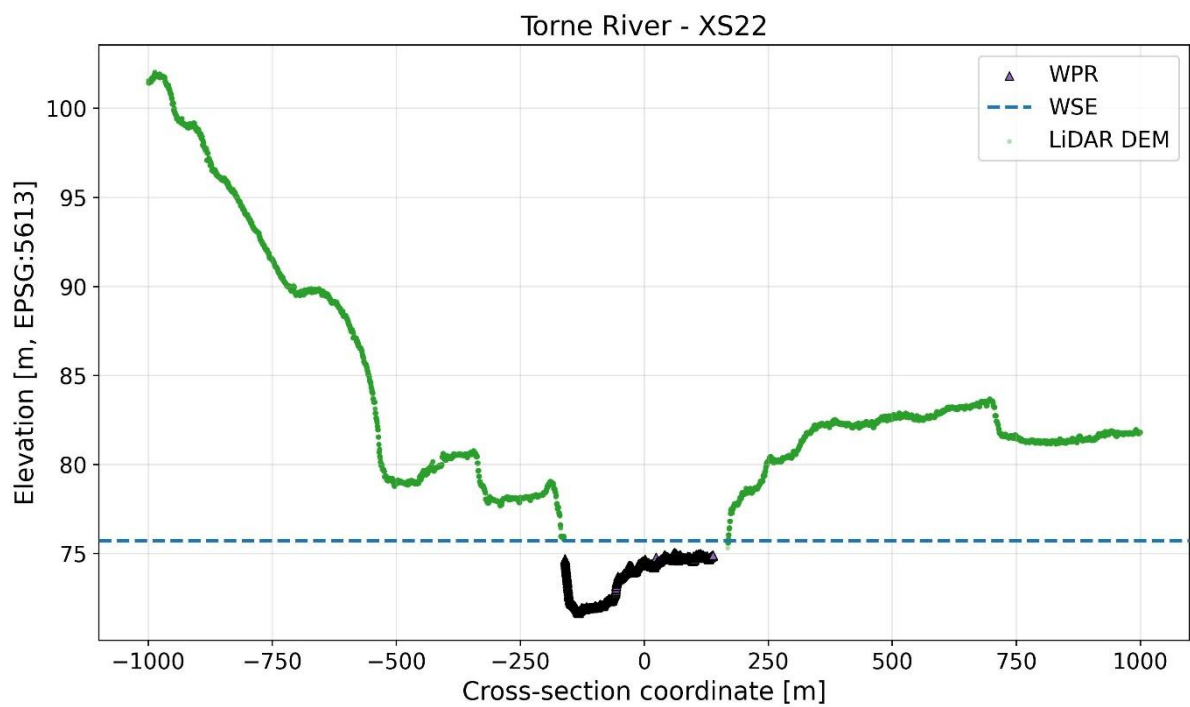


Figure A76. Cross-section XS22 at Torne River

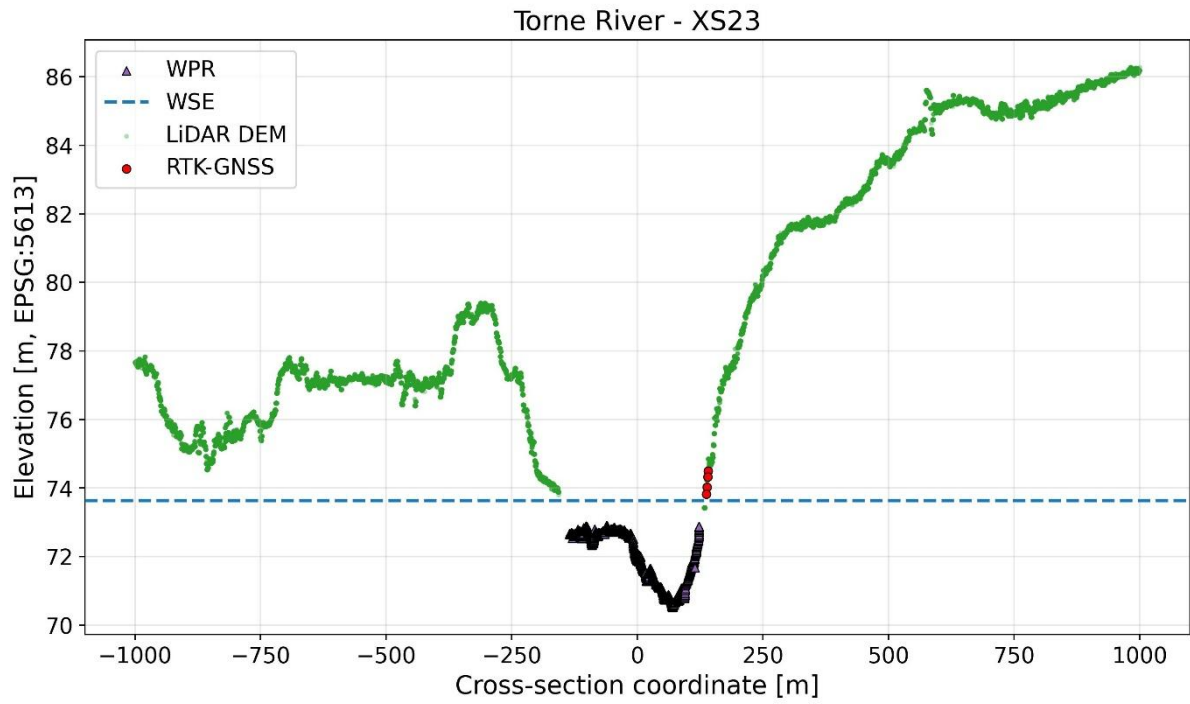


Figure A77. Cross-section XS23 at Torne River

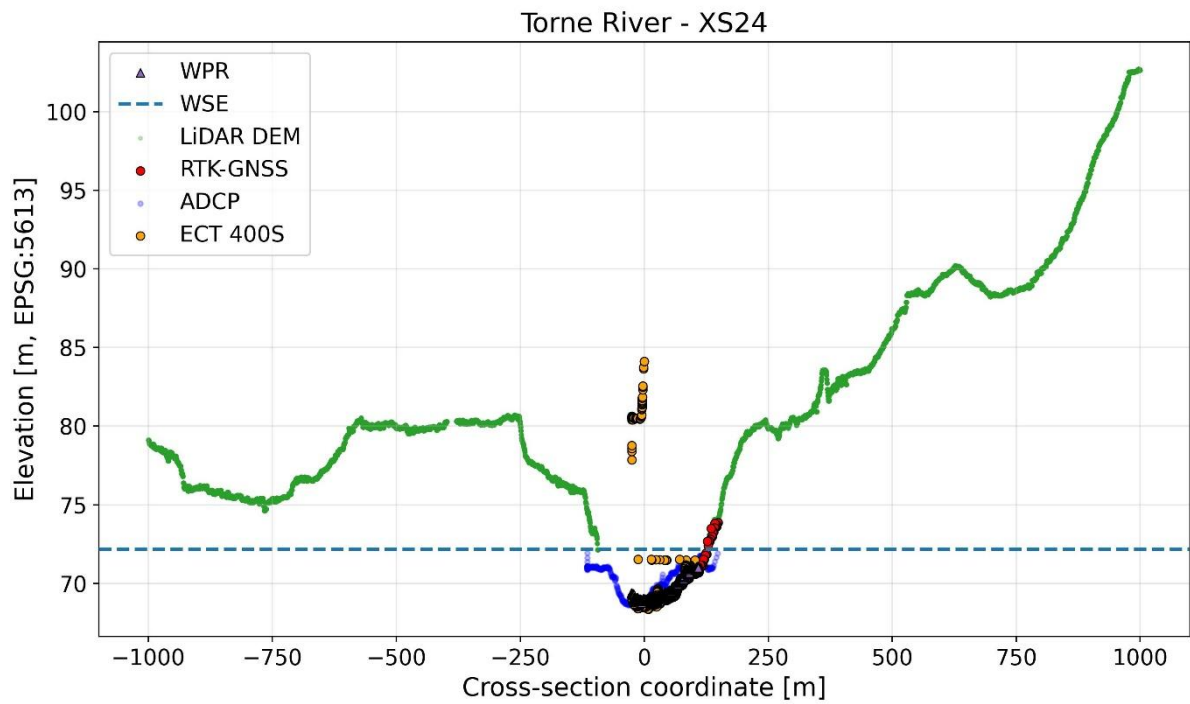


Figure A78. Cross-section XS24 at Torne River