High-resolution water surface slope of Polish rivers from multi mission satellite altimetry

Michał Halicki[1,2] Christian Schwatke[2], and Daniel Scherer[2]

michal.halicki2@uwr.edu.pl

[1]Department of Geoinformatics and Cartography, Faculty of Earth Sciences and Environmental Management, University of Wroclaw, pl. Uniwersytecki 1 50-137 Wrocław, Poland

[2]Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), School of Engineering & Design, Department of Aerospace & Geodesy Technical University of Munich, Arcisstraße 21, 80333 München, Germany

01 Introduction

The water surface slope (WSS) of rivers is an essential parameter in hydrological and geomorphic modelling. It determines the transport and erosion capacity of a river; it also allows the calculation of flow velocity and discharge. However, there is a lack of methods to calculate WSS along entire rivers at high resolution.

Satellite altimetry, which is an elevation measurement technique, may be a solution to this problem. Originally developed to monitor sea level dynamics, it is now also used to monitor inland waters. This technique measures water surface elevations (WSE) at river reaches that intersect with satellite ground tracks. These measurements can be used to calculate WSS between neighbouring intersections (Halicki et al. 2023).

In this study we use almost three decades of altimetry measurements to obtain a high resolution WSS of Polish rivers. As presented by Halicki and Niedzielski (2022), altimetry-based WSE over Polish rivers are characterized by high accuracy (Root Mean Squared Error, RMSE, ranging from 0.12 to 0.44 m). By including satellites on drifting orbits, we significantly increase the spatial coverage of the measurements and thus aim to estimate the WSS on every river kilometre.

02 Data

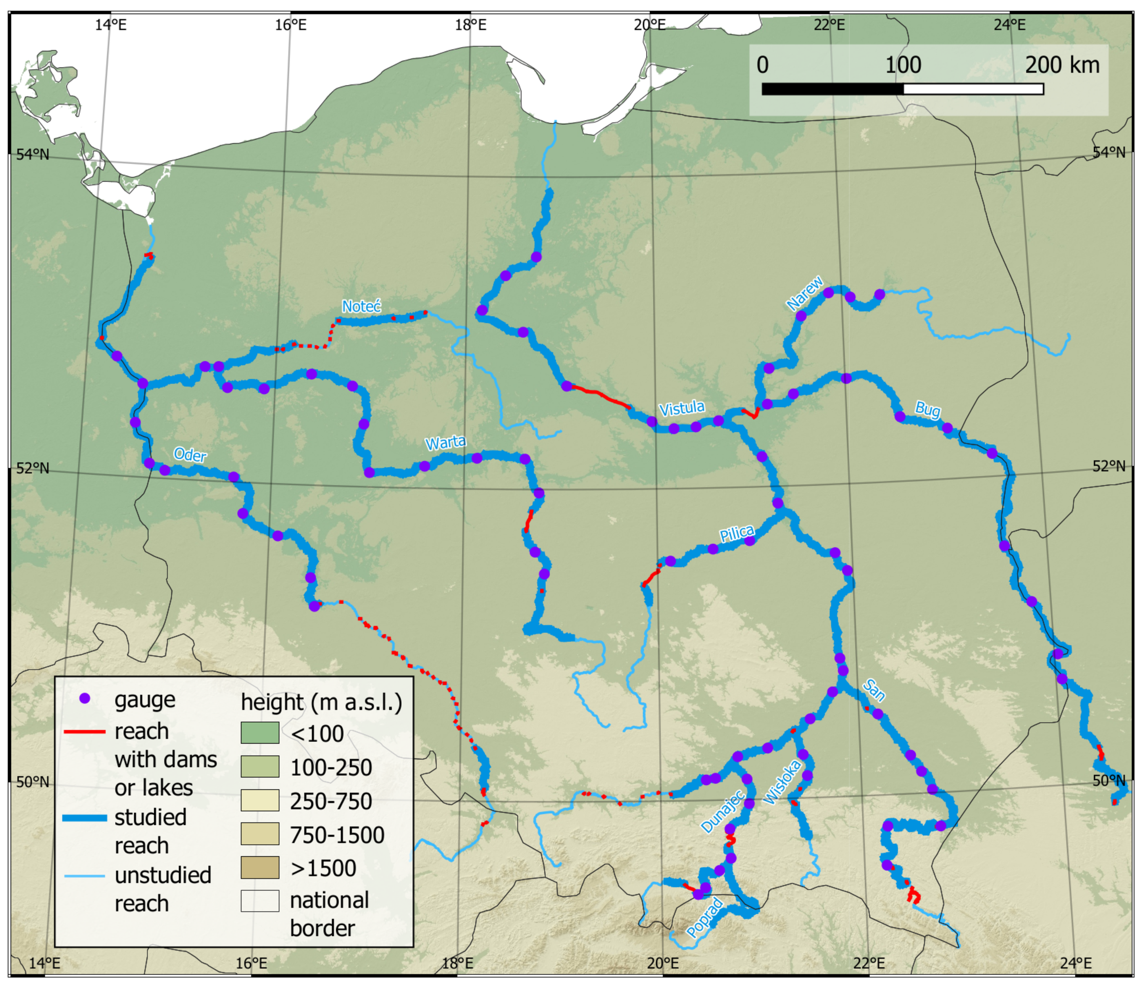

Fig. 1. Study area.

- Study area: 11 Polish Rivers (Fig. 1).
- Altimetry water levels: OpenADB database (Schwatke et al. 2023a).
- River centerlines: SWOT river database (SWORD, Altenau et al. 2019).
- Validation dataset: gauge WSE (Institute for Meteorology and Water Management – State Research Institute, IMGW-PIB).
- Comparison datasets:
  - DEM-based WSS (Altenau et al. 2019, Cohen et al. 2018, Ruetenik 2022),
  - ICESat-2 River Surface Slope (IRIS, Scherer et al. 2022),
  - WSS based on lidar.

03 Methods

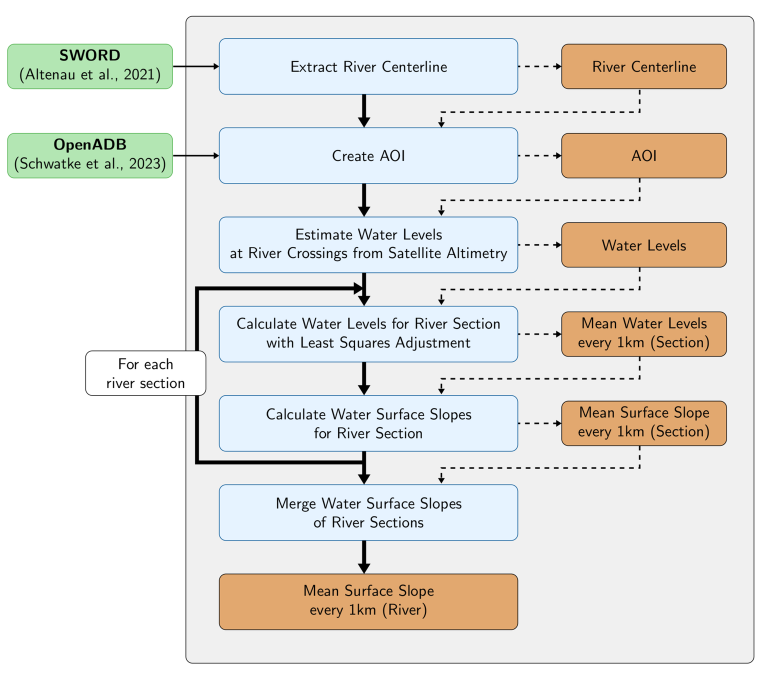

Fig. 2. Flowchart of the processing steps of the new approach to derive water surface slopes for rivers from satellite altimetry.

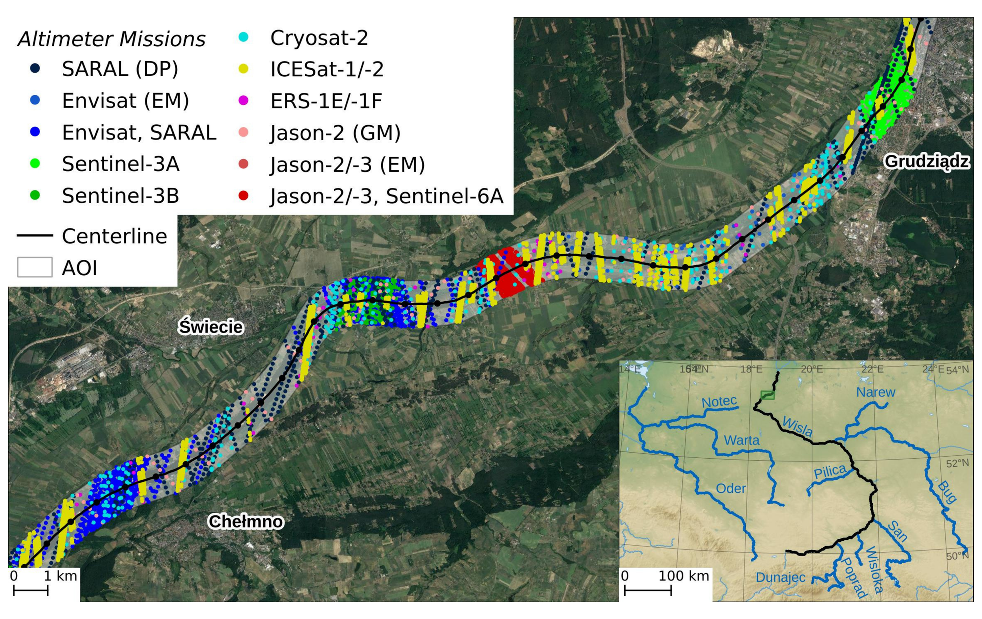

Fig. 3. Vistula River between chainage 52 km and 88 km with SWORD centerline in black and reference points every kilometer as black dots along the centerline. The locations of all high- frequency altimeter measurements within the area of interest (AOI) are colored by each group of missions.

The WSS estimation approach is presented in Figure 2. The processing is divided into river sections not interrupted by dams and reservoirs. Here we present the processing steps on a short section of the Lower Vistula River.

1. Extraction of SWORD centerline (30m) and creation of nodes every kilometer,
2. Creation of AOI using a 1000 m boundary around the SWORD centerline,
3. Extraction of altimeter data and calculation of river crossings and finally water levels - good spatial coverage because of using geodetic and drifting altimeter missions (Fig. 3),
4. WSE calculation for every kilometer along the river using a weighted least squares adjustment with an additional Laplace condition and an a-priori gradient condition (Fig. 4),
5. WSS calculation between adjacent kilometres (Fig. 5).

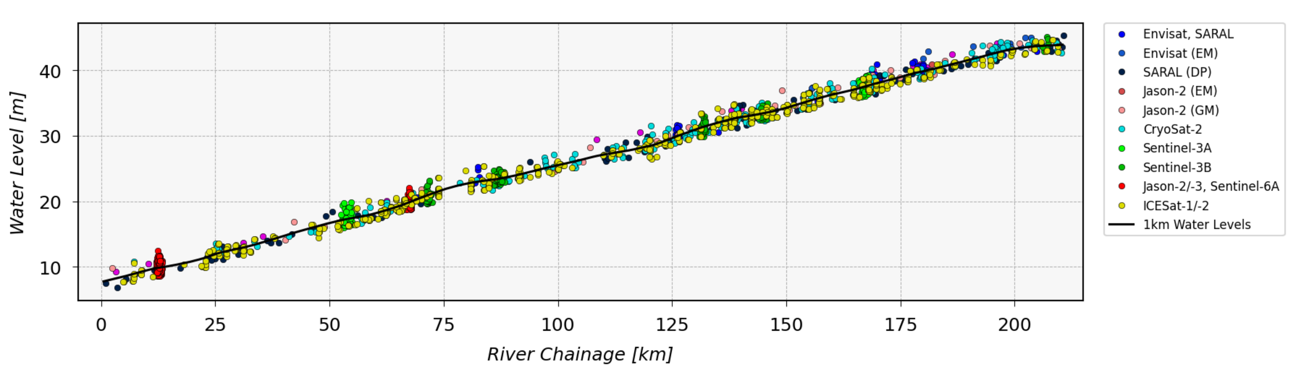

Fig. 4. Input water levels and final heights at the Vistula River (0-211 km).

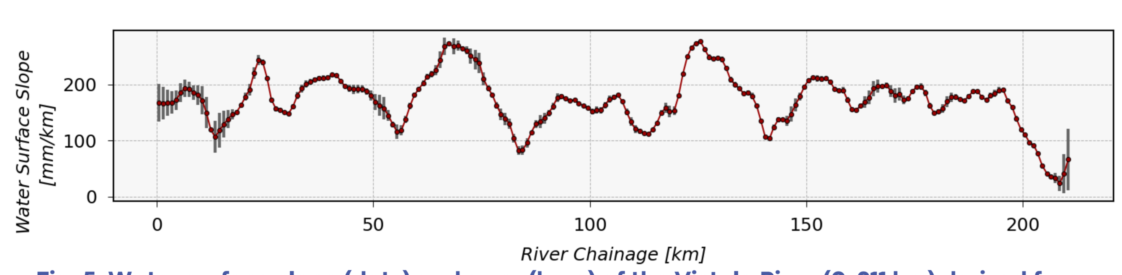

Fig. 5. Water surface slope (dots) and error (bars) of the Vistula River (0-211 km) derived from multi-mission satellite altimeter.

04 Results

The WSS of 11 Polish rivers is presented on Figure 6 and its also freely available at https://doi.org/10.5281/zenodo.7709474 (Schwatke et al. 2023b). For most rivers, the WSS ranges from 0 to 500 mm/km. The WSS of most of the rivers is strongly variable in the spatial domain, e.g. the WSS of the Vistula River changes by up to 200 mm/km every few kilometres.

WSS variations can also be clearly seen in Figure 7. The WSS variations on the Vistula are up to 250 mm/km. The graph also includes WSS errors (gray, vertical bars), which are related to the vertical errors of WSE in each of the 1 km bins. In general, large errors appear at the edges of the sections due to the lower number of WSE measurements.

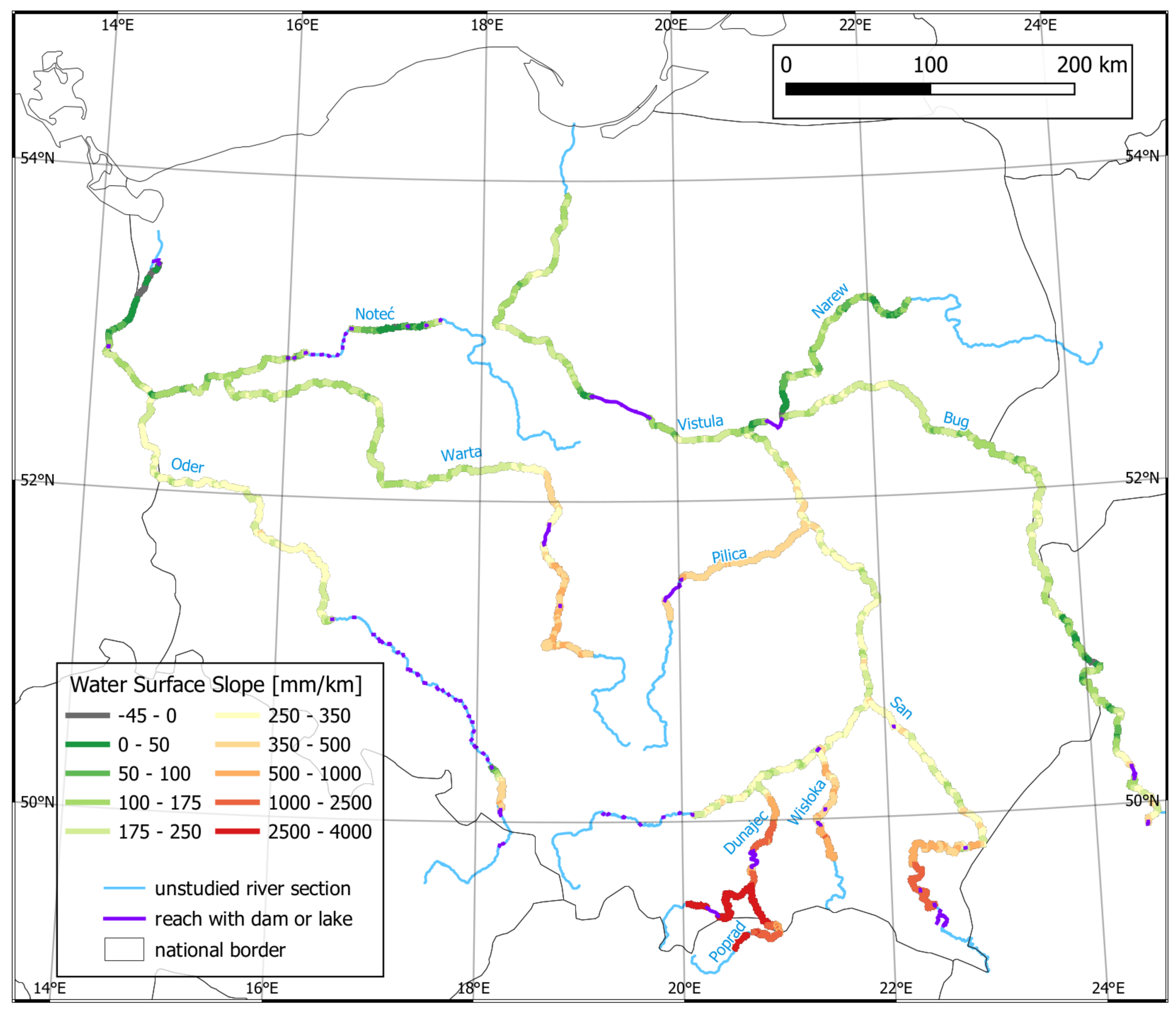

Fig. 6. Water Surface Slope of the 11 investigated Polish rivers.

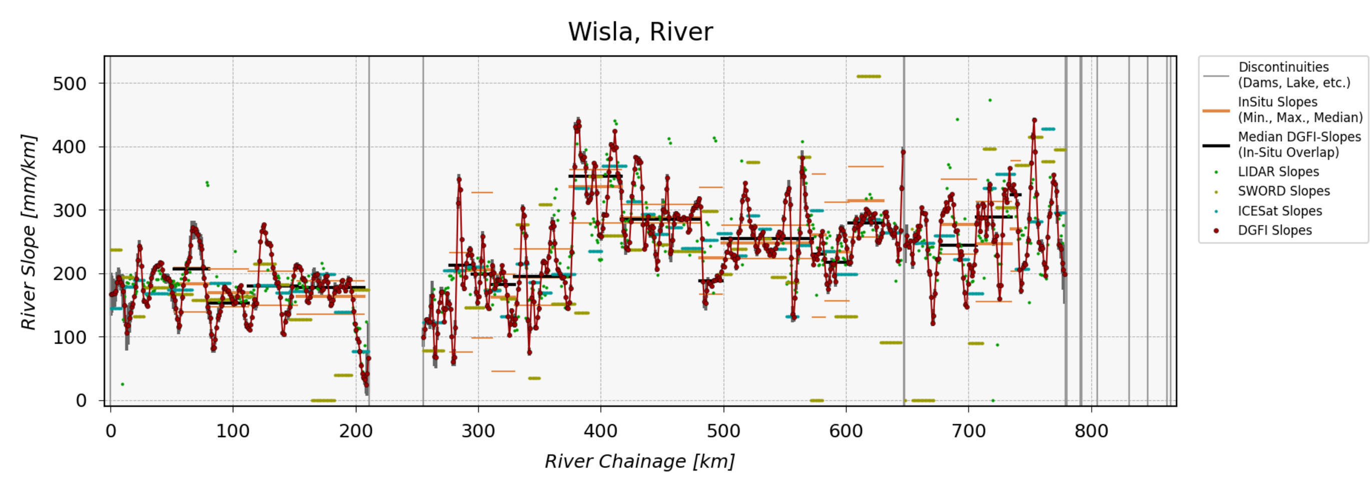

Fig. 7. Water Surface Slope results (red) for Vistula River. WSS from gauges (orange), ICESat-2 (cyan), SWORD (yellow), and lidar (green) are shown for comparison. Vertical lines (gray) show flow disturbances.

Tab. 1. Summary of WSS accuracies based on satellite altimetry, DEM, lidar and ICESat-2 validated against WSS between neighbouring gauge stations.

		RMSE [mm/km]					
River	*Gauge sections*	This Study	Ruetenik (2022)	Cohen et al., (2018)	Lidar	Scherer et al. (2022)	Altenau et al. (2019)
Vistula	82	12.0	34.6	442.3	16.7	16.0	68.2
Oder	46	5.9	27.1	362.6	15.7	33.1	40.2
Warta	67	25.1	31.7	634.2	37.7	32.4	63.6
Bug	45	4.3	20.2	451.7	42.3	6.2	29.1
Narew	10	10.3	26.2	508.3	21.7	9.2	30.2
San	11	80.3	50.7	294.2	184.9	86.5	96.9
Pilica	3	3.0	67.7	496.2	182.6	5.2	68.0
Dunajec	9	69.1	232.0	2741.7	167.5	386.0	272.9
Mean	-	26.2	**65.2**	**731.8**	**86.1**	**80.5**	**84.4**

The RMSE for the whole rivers ranges from 3 mm/km to 80 mm/km, with an average of 26 mm/km. For 6 rivers the estimated WSS showed the highest accuracy when compared to other WSS sources. The improvement was particularly significant for mountain rivers.

04 Conclusions

- High-resolution water surface slopes (WSS) for 11 Polish rivers have been determined from almost 30 years of cross-calibrated multi-mission altimetry measurements.
- For the 8 rivers studied where in-situ data is available, we obtained a mean root mean square error of 26 mm/km, which decreases to 10 mm/km if 2 mountain rivers are excluded.
- For 6 rivers, the estimated WSS showed the highest accuracy compared to WSS datasets based on digital elevation models, ICESat-2, or lidar.

BIBLIOGRAPHY

Altenau E. H., Pavelsky T. M., Durand M. T., Yang X., d. M. Frasson R. P., Bendezu L. (2021). SWOT river database (SWORD). Zenodo. doi: 10.5281/zenodo.5643392

Cohen S., Wan T., Islam M. T., Syvitski J. (2018). Global river slope: A new geospatial dataset and global-scale analysis. Journal of Hydrology, 563, 1057-1067. doi: 10.1016/j.jhydrol.2018.06.066.

Halicki M., Niedzielski T. (2022). The accuracy of the Sentinel-3A altimetry over Polish rivers. Journal of Hydrology, 606 , 127355. doi: 0.1016/j.jhydrol.2021.127355

Halicki M., Schwatke C., Niedzielski T. (2023). The impact of the satellite ground track shift on the accuracy of altimetric measurements on rivers: a case study of the Sentinel-3 altimetry on the Odra/Oder River. Journal of Hydrology, 617, 128761. doi: 10.1016/j.jhydrol.2022.128761.

Ruetenik G. A. (2022). Introducing RiverProfileApp, a web application for near global, exploratory, longitudinal river profile analysis. International Journal of Digital Earth, 15 (1), 679-689. doi: 10.1080/17538947.2022.2055173.

Schwatke C., Dettmering D., Passaro M., Hart-Davis M., Scherer D., Müller F. L., . . . Seitz F. (2023a) (In Review). OpenADB: DGFI-TUM's Open Altimeter Database. Geoscience Data Journal, xxx , xxx-xxx. doi: 10.1016/j.rse.2015.05.025.

Schwatke C., Halicki M., Scherer D. (2023b). High-Resolution Water Surface Slopes from Multi-Mission Satellite Altimetry. Zenodo. doi: 10.5281/zenodo.7709474

Schwatke C., Halicki M., Scherer D. (2023c) (In Review). Generation of high-resolution water surface slopes from multi-mission satellite altimetry. doi: 10.22541/essoar.167979550.06401677/v1.

Scherer D., Schwatke C., Dettmering D., Seitz F. (2022). IRIS: ICESat-2 River Surface Slope. Zenodo. doi: 10.5281/zenodo.7098114

We acknowledge the financial support of the National Science Centre, Poland, through the project no. 2020/38/E/ST10/00295 and the financial support of the Deutsche Forschungsgemeinschaft - Project number 324641997, Grant DE 2174/10-2. We thank the IMGW-PIB for the in situ data. The article on this study is currently in review (Schwatke et al. 2023c).