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ICE2WSS; An R package for estimating river water surface slopes from ICESat-2

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ABSTRACT

River water surface slopes (WSS) can improve the performance of rating curves for discharge estimates and provides information about river hydraulic processes and phenomena. Utilizing the beam pattern of ICESat-2, the WSS can be estimated by the slope of a linear regression of the water surface elevation and the distance along the river. This paper presents a robust processing scheme for calculating WSS along rivers in the SWOT River Database. We demonstrate the processing scheme for the Amur River basin using four years of data. This yields 7306 WSS estimates across 1693 reaches approximately 10 km in length. The slopes were estimated between 0.60 cm/km and 651.04 cm/km with a median standard error of 0.47 cm/km. The method works for slopes larger than 0.5 cm/km and river widths larger than 50 m.

The software presented in this paper is available as the R package ICE2WSS on Github (https://github.com/lindchr/ICE2WSS).

Software availability

Software name: ICE2WSS (**ICE**Sat-**2** **W**ater **S**urface **S**lopes)
Developer: Linda Christoffersen and Karina Nielsen
First year available: 2023
Program language: R
Cost: Free
Software availability: https://github.com/lindchr/ICE2WSS
License: MIT

1. Introduction

Terrestrial water is a valuable resource that sustains life. Rivers on average carry 40% of the land precipitation to the oceans and inland sinks (Gerten et al., 2008; Oki and Kanae, 2006). Climate change affects hydrological events all over the Earth, making the events more extreme in magnitude and frequency. Understanding how these changes affect river hydraulics and hydrology such as inundation, water surface elevation, and flow patterns is important to decrease the consequences on biodiversity and human lives.

Water surface elevation (WSE) and river discharge are key parameters used in hydrological research and are closely related to water storage, water transportation, and flooding. Globally, the number of gauge stations providing in situ WSE and discharge is decreasing. From 1970 to 2015 the number of gauging stations has decreased by 75% globally (Fekete and Vörösmarty, 2007; Tourian et al., 2013; Biancamaria et al., 2011; Hannah et al., 2011; Paris et al., 2016). This makes satellite-based methods an important alternative to obtain these parameters.

Satellite altimetry has been used to monitor inland waters and retrieve parameters needed for hydraulic modelling for more than 20 years (Bjerklie et al., 2003). Multiple papers have addressed the modelling of rivers using WSE measured by satellites e.g. Tarpanelli et al. (2021), Zakharova et al. (2020), Jiang et al. (2019) and Paris et al. (2016). The river discharge, which is the amount of water flowing through a river cross-section, is of high interest. Unfortunately, no satellites are currently able to measure the river discharge directly. Frias et al. (2023) applied a hydraulic model using satellite altimetry measurements of the channel geometry. Such models determine a relation between the WSE measured by the satellite and the river discharge.

The relationship between WSE and the discharge is widely used in rivers with gauge stations to estimate river discharge. This relation is called a stage-discharge rating curve. Several concurrent measurements of WSE and discharge are made at a station and the relation is plotted for stages representing the variability of the station. The relation often follows a parabolic curve (Herschy, 2009).

During unsteady flow, the energy slope changes due to changes in pressure forces, and the water surface slope diverges from the normal slope (Herschy, 2009). The energy slope can vary over time

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in areas affected by backwater. Backwater is the phenomenon where downstream features affect the water flow upstream due to a change in the energy slope. This can be caused by the return of overbank flow, downstream dams or bridges, ocean tides at the river outlet, features blocking the flow downstream etc. Backwater effects can also be caused by the time lag between peak flow in a tributary and in the main channel. During increasing WSE the controlling elements in the river can be drowned by the increased flow and new downstream elements define the flow thus leading to significant changes in water surface slope (Herschy, 2009; Paris et al., 2016).

The stage-discharge rating curve is only valid in channels with constant energy slopes as the rating curve does not guarantee accurate discharge estimations under varying energy slope (Liu et al., 2022; Meade et al., 1991; Herschy, 2009). The stage-discharge rating curves can be adjusted for the non-uniform flow by incorporating the river fall in the rating curve. This transforms the stage-discharge rating curve into a stage-fall-discharge rating curve, which has proved very useful at backwater-affected reaches (Kennedy, 1984; Herschy, 2009; Liu et al., 2022). The fall can be approximated by the water surface slope (WSS), where the WSS is the WSE difference along a river distance.

Several methods have been used for estimating the WSS. In well-gauged rivers, the WSS can be estimated using the WSE difference between two gauge stations, known as the twin-gauge approach (Kennedy, 1984; Herschy, 2009). Liu et al. (2022) showed how the WSS extracted from twin-gauge stations can improve river discharge estimates in areas affected by backwater. Utilizing stage-fall-discharge rating curves improved the error of the discharge estimate from approx. 150% with classic stage-discharge rating curves to approx. 20% (Liu et al., 2022). The decreasing number of gauge stations entails a reduction in twin gauges as well. Gauge stations are often located far apart and are in-homogeneous distributed globally. This causes the slope estimates to represent an average slope over the full distance between the stations. The low number of in situ twin-gauge stations or local surveys limits the possibility of WSS estimates on a global scale.

Paris et al. (2016) used WSE measurements from satellite altimetry to estimate a monthly WSS at a virtual station on Negro River affected by backwater. Including the WSS in the model improved the discharge estimate from rating curves by 130%–208%. Though the discharge estimates improved significantly, the WSS estimates from nadir satellite altimetry are uncertain as the measurements at different locations on the river are not taken at the same time.

For this purpose, the beam pair configuration of ICESat-2 (NASA's Ice, Cloud, and land Elevation Satellite-2) possesses a great advantage over other satellite altimetry missions. ICESat-2 measures the surface elevation simultaneously with six laser beams grouped in three pairs of two, and pairwise separated by 3.3 km across track (Markus et al., 2017; Neumann et al., 2019). ICESat-2 provides an unprecedented opportunity to measure the water surface slope, here defined as the elevation difference over a given distance, both along-track and across-track on a reach scale. As ICESat-2 measures the WSE at six locations at the same time, it is possible to calculate an instantaneous slope without a time delay between measurements.

Scherer et al. (2022) applied ICESat-2 WSE to derive instantaneous WSS for rivers in Europe and North America. They divided the processing scheme into two parts; along-track and across-track WSS and estimated the WSS with a median error of 2.3 cm/km compared to the slope from corresponding twin gauges. Wang et al. (2022) also illustrated the possibility of using ICESat-2 to extract WSS using a manual approach.

This paper describes the R package ICE2WSS which provides the opportunity to estimate the WSS along the river centre lines in the SWOT River Database (SWORD) using the ICESat-2 ATL13 WSE measurements. ICE2WSS delivers WSS for all intersections between the river reaches and the satellite ground tracks where data is available and of reliable quality. The approach uses linear regression to estimate the slope and is independent of the intersection angle of the river and the satellite ground track.

Implementing the processing scheme as a software package makes the WSS estimates available to many users and reduces the latency from measurements to available WSS estimates. Multiple input settings can be specified by the user, thus making the WSS estimates relevant for many different applications. The end-user of ICE2WSS can be any hydrologist with applications that benefit from including water surface slopes in their work. This can for example be river modellers interested in expanding the stage-discharge rating curves to stage-fall-discharge rating curves in their research area. The slope can further be used to improve the WSE time series at virtual stations for satellites with variable ground tracks (Scherer et al., 2022).

Section 2 describes the essential data sets included in the processing. Section 3 describes the implementation of the method with considerations of computational speed, robustness, and user freedom to specify several parameters. A demonstration of the performance and the user-specified input parameters of the package is provided in Section 4. Results, performance, and application limits are discussed in Section 5.

2. Data description

Two data sets are needed for the water surface slope estimation via ICE2WSS, while a third data set is optional. The processing scheme uses SWORD reaches and nodes as the basis for the slope estimates. The water surface elevation measurements from ICESat-2 ATL13 are assigned to the SWORD nodes, which form the basis of the slope estimate. Water occurrence data can be added as an input parameter to filter ICESat-2 measurements.

2.1. SWORD – SWOT River Database

The SWOT mission (Surface Water and Ocean Topography satellite) was launched on December 15, 2022, and is designed for hydrology observations. One of the products related to SWOT is SWORD (SWOT River Database), which contains several data products describing different river attributes such as network structure, WSE, river width, and river type (Altenau et al., 2021). Utilizing the SWORD data enables the possibility of combining ICESat-2 data with future SWOT data. The SWORD product contains river centre lines and river nodes which are both used in this study. The river centre lines are divided into reaches of approximately 10 km and nodes for every 200 m. SWORD is based on existing global river data sets and combines these into one state-of-the-art data set. The database contains 213 485 reaches with widths down to 30 m and covers the largest drainage basins in the world.

The processing scheme presented in this paper is created such that a new version of SWORD can easily be incorporated to update the slope estimates. In this paper, SWORD version 14 is used. Table 1 describes the SWORD input parameters used for estimating the WSS.

2.2. Surface elevation of inland waters from ICESat-2 ATL13

ICESat-2 was launched in October 2018 and carries a 532 nm green photon-counting laser altimeter (Markus et al., 2017; Neumann et al., 2019). The ground track coverage is up to 88 degrees north and south and has a track spacing of 29 km at the equator. The repeat time is 91 days, and the temporal resolution is therefore low compared to other altimetry missions. The native-resolution data product, ATL03, has a resolution of 0.7 m along-track (Neumann et al., 2021). Combined with the small track separation, the spatial resolution of ICESat-2 is high compared to satellite altimetry missions in a repeat orbit.

ICESat-2 measures the surface elevation simultaneously by six beams divided into three pairs which are separated by 3.3 km. This unique configuration gives the opportunity to derive the slope both along-track and across-track. Several processed data products are based on ATL03.

Table 1
Input data required from SWORD. If a NetCDF file is provided the R package will extract the required parameters.

Category	Name	Unit	Description
Node	x	deg	Longitude.
	y	deg	Latitude.
	node_id	–	Node ID.
	reach_id	–	Reach ID.
	wse	m	Water surface elevation above EGM96 geoid.
Reach	reach_id	–	Reach ID.
	rch_id_dn	–	Downstream reach ID.
	rch_id_up	–	Upstream reach ID.
	slope	m/km	DEM reach slope from MERIT DEM (Yamazaki et al., 2017).

Table 2
Input data from ATL13 which must be provided as text files with data in columns in the described order. Water occurrence is optional. For more details see Jasinski et al. (2021).

Input	Unit	ATL13 NetCDF source name	Description
DecYear	yr	delta_time	Time. Seconds since 2018-01-01 converted to decimal year.
Latitude	deg	segment_lat	Latitude.
Longitude	deg	segment_lon	Longitude.
Height	m	ht_ortho	Orthogonal height above the EGM2008 geoid.
Water ID	–	inland_water_body_id	Water body ID.
Beam	–		Beam number. Beam name converted to a number (1:6).
Occurrence	–		Water occurrence from GSWE. Optional input parameter.

ATL13 is the inland water product that contains water surface elevation including statistics for every 30–100 m (Jasinski et al., 2021).

As the ICESat-2 laser uses wavelength in the visible spectrum, it may penetrate clear water and capture the bathymetry (Parrish et al., 2019; Ranndal et al., 2021; Parrish et al., 2022). The penetration depth depends on the physical reflection properties of the water surface and the wave scattering in the water body. Water in rivers is too turbid for the light to penetrate, and the scattering surface is, therefore, the water surface. The use of a visible wavelength entails the drawback that clouds will block the signal leading to data loss. This is further described in the ATL13 ATBD (Jasinski et al., 2021).

The newest ICESat-2 ATL13 data can be accessed from the US National Snow and Ice Data Center (https://nsidc.org/data/atl13/versions/5). Table 2 describes the ICESat-2 ATL13 input parameters needed for estimating the WSS.

2.3. Global surface water explorer; occurrence

The Global Surface Water Explorer (GSWE) includes a data set describing the occurrence of surface water (Pekel et al., 2016). The occurrence is given as the percentage of time that a given area is covered by water. A value of 100 indicates that the area is always covered by water and 0 means no water. The occurrence is based on 3 million Landsat images and given with a 30-meter resolution. Data is available at https://global-surface-water.appspot.com and must be assigned to the ICESat-2 ATL13 input data (see Table 2).

3. Method description

The water surface slope estimation is embedded in the R package ICE2WSS. The program takes SWORD river representation (centre lines and nodes) and WSE data and outputs river WSS estimates based on the input settings. The package is designed for ICESat-2 ATL13 data and SWORD-based centre lines, but the user can provide customized data and river representation, see Section 4. The processing includes four main steps;

- Assigning ICESat-2 data to SWORD centre lines and nodes
- Outlier filtering, data robustness, and exclusion of nearby water bodies
- Dividing data into sections along the river
- Estimating river slopes from linear regression

The WSS is estimated as the slope of a linear regression of heights over a distance. To estimate the WSS we need the elevation of the water surface and the position of the measurements along the river centre line. The elevation of the river surface is measured by the ICEsat −2 satellite and is provided in the ATL13 data product. The methodology presented in this paper is applicable globally where WSE data and river centre lines and nodes are available. An overview of the process is illustrated in Fig. 1.

3.1. Assigning water surface elevations to river centre lines

WSE measurements from ICESat-2 are assigned to the nearest SWORD node to relate the measured elevation to a location on the river. The WSE changes over time, and data used for the WSS estimates must therefore be acquired at the same time. The processing in ICE2WSS is consequently performed one pass at a time.

The WSS of interest is the slope along the flow direction and WSE measurements are, therefore, projected onto the river centre line. The WSE projected onto the centre line is given by

$$\mathbf{b}' = \frac{\mathbf{b} \cdot \mathbf{r}}{\mathbf{r} \cdot \mathbf{r}} \mathbf{r} \tag{1}$$

where $\mathbf{b}$ is a vector representing the beam direction, $\mathbf{r}$ is a vector between the two nearest river nodes, and $\mathbf{b}'$ is the WSE projected onto the river centre line.

3.2. Outlier filtering and data robustness

The SWORD database contains information on the reach type. If the river reach contains a waterfall or dam, the estimated slope along a distance will represent the average slope taking the waterfall into consideration. Reaches representing rivers and lakes on rivers are accepted for slope estimation while dams, waterfalls, and ghost reaches (e.g. reaches of less than 200 m at the headwaters and outlets) are excluded as these can cause misrepresentation of the physical situation.

Depending on the input ICESat-2 data, water bodies close to the river can be included in the data set, for example, lakes with no connection to the river. A nearby lake can have a very different WSE despite the close proximity to the river. Including measurements from nearby lakes can strongly affect the slope estimate. Therefore, only one water body ID (See ICESat-2 ATL13 data description) must be assigned to a SWORD node. The distance from each WSE measurement to the

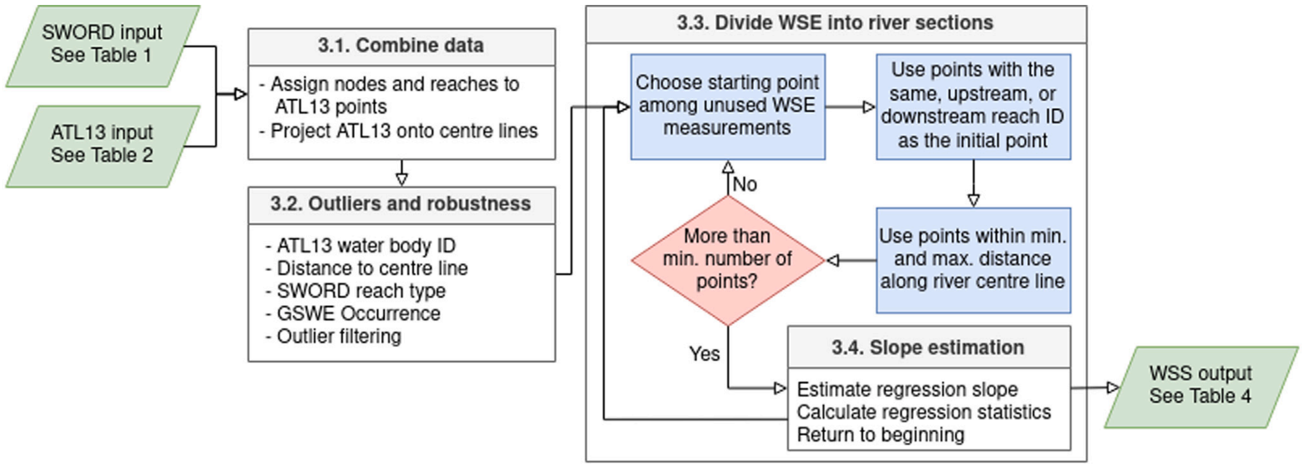

Fig. 1. Flow chart of ICE2WSS processing. The four main processing steps are described in the corresponding sections of the article.

centre line is calculated, and observations with the water ID farthest from the centre line are removed.

Additional error sources in the ATL13 data are removed by excluding statistical outliers in the WSE measurements. If the standard deviation of the WSE assigned to a SWORD node is larger than 0.2 m, outlier filtering is applied. The mean WSE for points assigned to a SWORD node is estimated with a Gaussian Kernel distribution. All measurements outside two times the inter-quantile range of the mean WSE are removed. If the maximum WSE is more than 1.3 m higher than the minimum WSE or the standard deviation is larger than 0.5 m, all measurements assigned to the node are excluded.

If water surface occurrence is provided, a threshold can be defined to exclude data with low water occurrence. This ensures that the measured elevation in fact represents the water surface. The threshold can be defined as an input parameter to ICE2WSS based on the need for conservative slope estimates.

3.3. Dividing measurements into river sections

The distance along the river used for the slope estimation affects the final slope estimate. If long stretches are used the slope will represent an average slope, while shorter reaches will reflect the local slope. The distance along the river accepted by this paper is 400 m as the minimum distance and 8000 m as the maximum distance, based on the following considerations: The ground track will intersect the river in many different configurations e.g. at a right angle (Fig. 2A). In that case, the spacing between the intersections is approximately 6.8 km. The satellite track can also be parallel to the river (Fig. 2C), in which case there are WSE measurements continuously every 30–100 m along the river. The last situation is an intermediate configuration. If the river is meandering between intersections with the satellite, the distance between crossings can be large and a beam can intersect the river multiple times over short distances (Fig. 2B).

Aiming to handle these very different spatial configurations, we divide the river into sections of 400–8000 m as default. This ensures that the slopes over stretches perpendicular to the ICESat-2 track include all six beams while dividing measurements parallel to the river into smaller sections. This is a trade-off between spatial resolution and the availability of data.

The SWORD centre lines contain information on the upstream and downstream reach ID. Measurements are only accepted for the slope estimation if the reach IDs are matching, thus the river reaches have to be subsequent. This ensures that no data from tributaries are included in the slopes of the main stem.

The robustness of the slope estimate is highly dependent on the number of WSE measurements included in the regression. Besides the distance accepted for the regression, the minimum number of WSE measurements can be set. Including a high number of measurements in the slope estimate gives a robust result, but will decrease the number of WSS estimates. Meanwhile, a small value might include more estimates at the risk of sensitivity to outliers. The WSS estimates in this paper are based on a minimum of 10 data points.

3.4. Slope estimation

When data is divided into segments and fulfils all requirements, the slopes are estimated from a linear regression of the distance along the river versus the water surface elevation.

$$y_i = \alpha x_i + \beta + \epsilon_i, \quad \text{where} \quad \epsilon_i \sim N(0, \sigma^2) \tag{2}$$

where β is the intersection with the y-axis, α is the slope of the regression which represents the WSS estimate, and ϵ is the error term assumed to be Gaussian distributed. The ordinary least squares regression assumes that the predictor variables are error-free, that the measurement errors are independent of the values of the predictor, and that the errors are independent.

Three examples of the regression are shown in the right panel of Fig. 2 which corresponds to the spatial configurations shown in the left panel. The configuration where the river and satellite ground track are perpendicular, results in three clusters of measurements across approximately 7 km (Fig. 2D). The parallel configuration results in measurements continuously for approximately 2 km, and the intermediate configuration gives a measurement pattern strongly dependent on the meandering of the river (see Fig. 2F and E, respectively).

The standard error of the slope estimate is used to calculate the 95% confidence interval for the WSS estimate and the p-value indicating the certainty of the estimate. The standard error of the regression is calculated as

$$SE = \sqrt{\frac{1}{N-2} \frac{\sum (y_i - \hat{y}_i)^2}{\sum (x_i - \bar{x}_i)^2}} \tag{3}$$

where y_i is the i'th WSE measurement, $\hat{y}_i$ is the i'th predicted WSE, x_i is the i'th distance along the river, and $\bar{x}$ is the mean distance along the river. The 95% confidence interval is calculated as $CI_{95} = 2SE$. The uncertainty reported in Fig. 2 is the 95% confidence interval for the slope estimate.

4. Demonstration over Amur River basin

A demonstration of the application of ICE2WSS is presented in this section. The study area, input data, and model setup are explained.

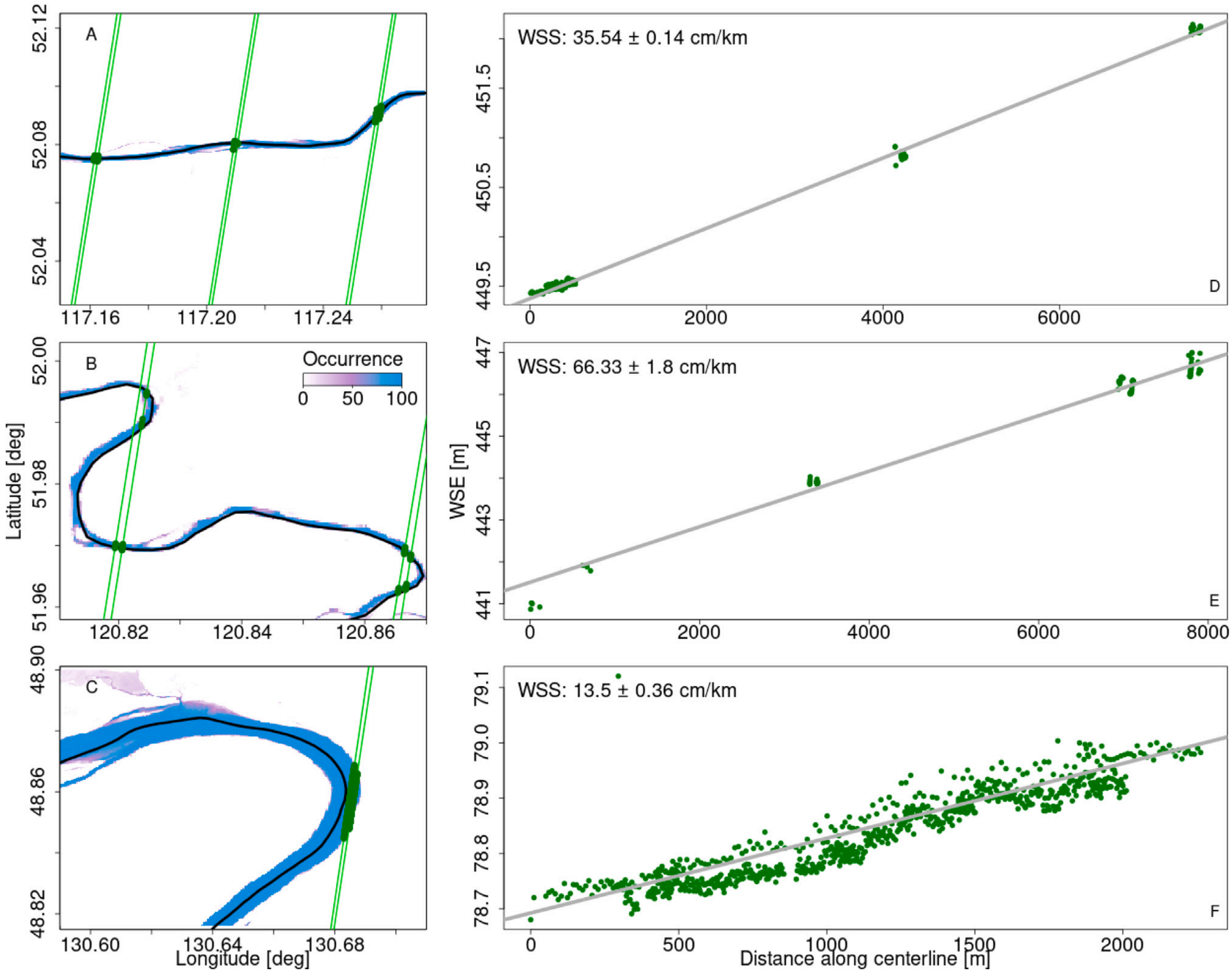

Fig. 2. Left panel is three examples of configurations between ICESat-2 beam pairs and the river. The water occurrence is illustrated by the white-pink-blue colour scale. The black line is the SWORD centre line, the green lines are the ICESat-2 beam pairs, and the green points are WSE measurements of the river. Right panel is three illustrations of WSS estimation through a linear regression of WSE and distance along the river. Green points are WSE measurements projected onto the centre line and the grey line is the linear regression fit. The estimated regression slope and 95% confidence interval (2SE) are reported. Top row: River and beam pairs are perpendicular. Middle row: River is meandering, resulting in multiple intersections with different intersection angles. Bottom row: River and beams are locally parallel.

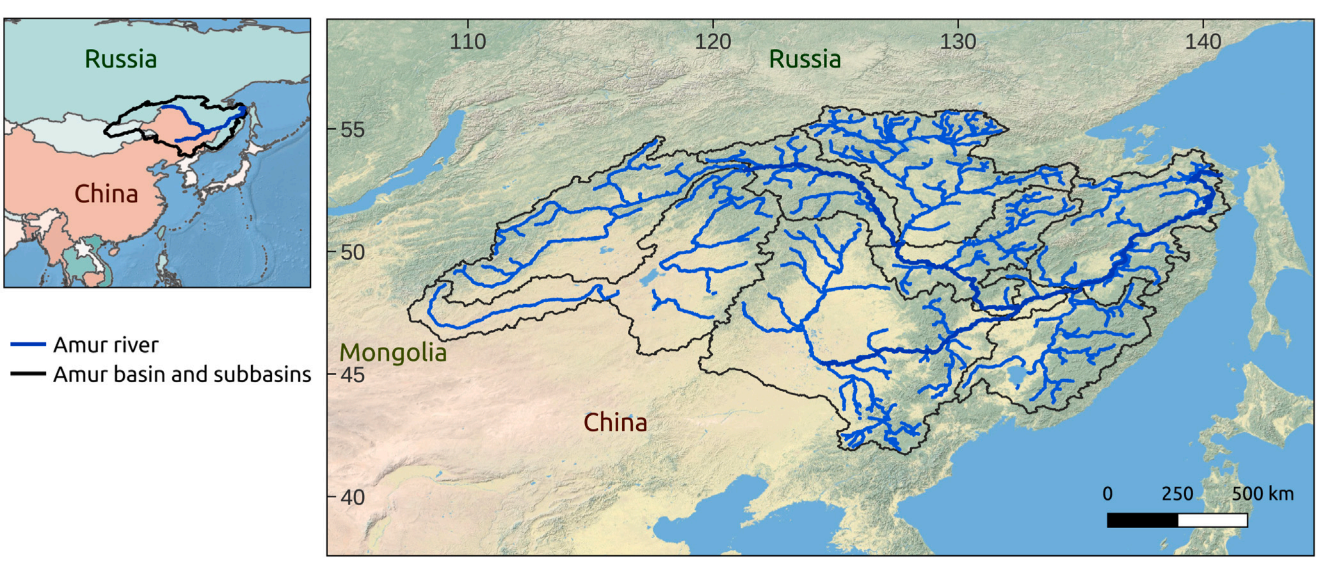

Fig. 3. Case study of Amur River basin located in east Asia. Amur River and its tributaries originate in the Chinese and Russian highlands and flow towards the Strait of Tartary.

Table 3
ICE2WSS input parameters specified by the user.

Name	Input type	Description
Paths	List	List of paths to the output directory, the input ICESat-2 data directory, and the path to the SWORD NetCDF file directory.
Files	List	List of ICESat-2 ATL13 data files to be processed.
SWORD	List	List containing the SWORD version and area (see Altenau et al. (2021)).
Max_reg_dist	Numerical value	Maximum distance for a slope estimate.
Min_reg_dist	Numerical value	Minimum distance for a slope estimate.
Min_reg_p	Numerical value	Minimum number of points in regression.
Occ_thr	Numerical value	Minimum occurrence for data point if occurrence data is provided. If water occurrence is not provided, the default setting is NA.

4.1. Study area

To demonstrate the utilization of ICESat-2 elevations for extracting river water surface slopes we use the Amur River as the study area. Amur River is the world's 10th longest river and lies on the border between China and Russia. It has a total length of 4400 km and a drainage basin of 1.89 million km^2. The width of the river is between a few meters to more than 4 km. It is located between 41 degrees and 56 degrees north (See Fig. 3), and the river basin is therefore affected by snowfall and sub-zero temperatures during the winter.

Amur River has 5 large tributaries contributing to the total discharge. These are Shilka, Argun, Zeya, Songhua, and Ussuri Rivers. Zeya River contributes 16% of the total discharge. Amur River and its tributaries originate in the Chinese and Russian highlands and flow towards the Strait of Tartary. From the conjunction of the Songhua and Amur Rivers, the terrain is flat and the river is dominated by flood plains.

Amur River was chosen as it is a large river with very diverse channel characteristics and water surface slopes. It is therefore considered representative of what one would expect at a global scale.

4.2. Model setup

The R package ICE2WSS has two required data inputs and 7 input parameters. The input data is WSE measurements from ICESat-2 and SWORD nodes and reaches, which is described in Tables 1 and 2. The input parameters are described in Table 3. The first three parameters are lists containing information about data. The last four parameters are settings describing key parameters for the regression estimating the WSS.

ICESat-2 ATL13 data from October 2018 to June 2022 is used for the demonstration in this paper and ATL13 WSE elevations of the rivers are extracted within a buffer zone around the centre line of 0.05 degrees equivalent to approximately 4 km. The surface water occurrence from Global Surface Water Explorer (Pekel et al., 2016) were assigned to each WSE measurement. A threshold of 70% water occurrence is chosen to ensure conservative and consistent WSE measurements. The procedures described in Section 3 are implemented by the command:

```
ICE2WSS(Paths, Files, SWORD=c(‘‘v14’’,‘‘as’’),
    Max_reg_dist = 8000, Min_reg_dist = 400,
    Min_reg_p = 10, Occ_thr = 70)
```

The package output is a text file containing the information described in Table 4.

4.3. Slope estimates for Amur river

The model setup described above results in 10 119 WSS estimates. The output contains all WSS estimates produced, including potentially unreliable or unrealistic slopes. WSS estimate statistics are provided such as R^2, p-value, and the slope standard error. Slopes with an R^2 value below 0.5, and a p-value larger than 0.05 are removed in the following analysis.

Negative water surface slopes are possible in coastal regions where the tides can create negative slopes at the downstream part of the river. The methodology presented in this paper occasionally produces negative slopes over lakes. This arises as the data uncertainty can affect the regression estimate and thereby produce slightly negative slopes. In the following analysis, these situations are ignored and negative WSS estimates are removed.

The above filtering results in 7306 reliable WSS estimates between 0.60 cm/km and 651.04 cm/km distributed over 1693 SWORD reaches out of the 3360 reaches that intersect with ICESat-2 ground tracks. Thus, 50.4% of the SWORD reaches covered by ICESat-2 tracks are assigned at least one WSS using 4 years of data. On average, each SWORD reach contains 4 WSS estimates and the reach with the highest number of WSS estimates is 22.

Fig. 4 shows the reach average WSS using all four years of data. The WSS is given in cm/km represented by colour. In general, the slope is steep in mountainous regions where the terrain slope is steep too and small in areas with floodplains where the terrain slope is small. A lake is located in the northern part of the drainage basin (at longitude and latitude (128,54)) which is indicated by the small WSS estimates.

Some reaches do not have a WSS estimate even though the reach intersects with ICESat-2 tracks. The most upstream reaches do not have a WSS estimate due to the limited width of the river and the threshold of 70% water occurrence. The downstream part of the river basin, close to the river outlet, does not have any WSS estimates. The slope in this area becomes too small, and the estimate does not exceed statistical significance.

The standard error of the slope estimates lies between 0.02 cm/km and 63.53 cm/km with a median standard error of 0.47 cm/km. The 95% quantile of the standard error is 3.81 cm/km. The WSS and the standard error are shown as a scatter plot on a double logarithmic scale in Fig. 5A. The standard error describes the certainty of the slope estimate given the WSE measurements. In general, the standard error of the estimate increases as the WSS increases. Further, no WSS estimates are produced with a slope less than 0.6 cm/km. The standard error of the estimate is influenced by the distribution of WSE measurements, the number of measurements, and the distance along the river used for the slope estimate.

The slope estimates are compared with the DEM reach slope provided by the SWOT River database. The DEM reach slope describes the slope along a SWORD reach extracted from the MERIT Hydro DEM (Yamazaki et al., 2017). It describes the terrain slope and not the water surface slope. The relation between the WSS found in this study and the DEM reach slope is visualized in Fig. 5B. The median residual between the WSS found in this study and the DEM reach slope is 7.98 cm/km with a 95% quantile of 41.18 cm/km. As the two slopes do not measure the same physical entity, they are not expected to give the same slope value. As the WSS found in this study can be varying with time for a given reach, different WSS estimates are compared to the same DEM reach slope. This explains the horizontal variability in Fig. 5B.

Fig. 5B shows less disagreement between the WSS found in this study and the DEM reach slope for large WSS values. Dynamic effects such as varying backwater affect the slope across a smaller distance for

Table 4
ICE2WSS output parameters provided in output text file placed in the specified output directory.

Name	Unit	Description
DecYear	yr	Mean time of measurements.
Lon	deg	Longitude of the centre point of WSE measurements.
Lat	deg	Latitude of the centre point of WSE measurements.
WSS	cm/km	Water surface slope estimate.
StdError	cm/km	Standard error for regression (see Eq. (3)).
IntersectAngle	deg	Intersection angle between river reach and ICESat-2 beam tracks.
Nobs	–	Number of WSE measurements used for slope estimate.
Resolution	m	Distance along the river where WSE was located.
pVal	–	*P*-value for regression.
R2	–	R-squared value for regression.
WSE	m	Mean WSE used for slope estimate measured above the geoid.
WaterID	–	Unique ATL13 water ID.
Beam	–	String containing all beams used for slope est.
ReachID	–	SWORD reach ID.
NodeID	–	SWORD node ID closest to the centre position of regression.
ReachDEMSlope	cm/km	SWORD DEM slope for reach.

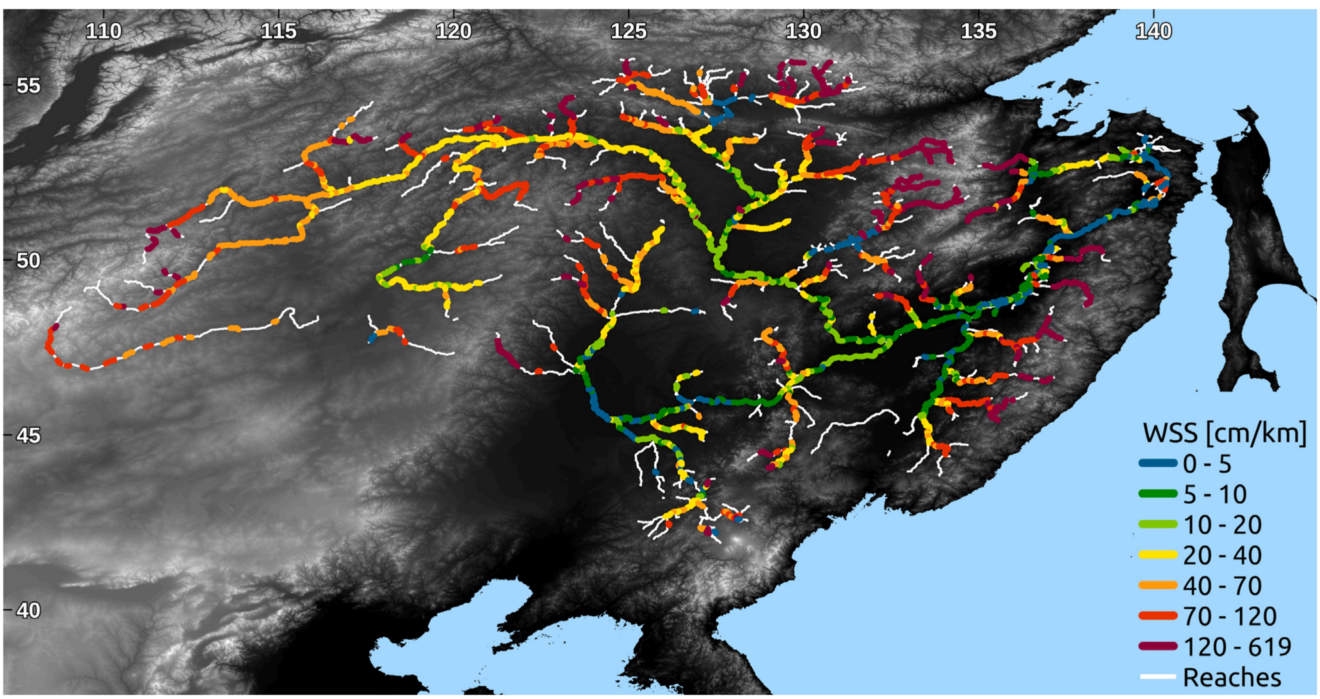

Fig. 4. Median WSS assigned to SWORD reaches in the Amur Basin based on ICESat-2 data from October 2018 to October 2022. Flat slopes are indicated by green colours while steep slopes are indicated by red colours. A lake is located on the river at latitude 54 degrees and longitude 127 degrees, which is apparent from the small WSS values at this location.

large slopes than for small slopes. The WSS, therefore, becomes closer to the DEM reach slope and becomes more stable.

In addition to the WSS estimate and the statistics of the estimated uncertainty, the output file contains several metrics which are provided in Table 5. The minimum number of WSE measurements required for a WSS estimate was set to 10 points while no maximum number of points was defined. The median number of measurements used for the WSS estimates is 67 while the maximum number is 2911. Many WSE measurements increase the certainty of the WSS estimate and vice versa.

The resolution describes the distance along the river where the WSE measurements are distributed. The resolution is related to the intersection angle between ICESat-2 and the river. The 25% quantile of the resolution of 4277.1 m indicates that the lower boundary for the resolution is not a defining parameter in the WSS estimates.

The intersection angle describes the angle between the ICESat-2 beam direction and the local reach direction. If the satellite crosses the river several times (e.g. situation B in Fig. 2), the reported intersection angle is the mean of all the intersection angles of the regression data. WSS estimates with an intersection angle larger than 60 degrees have a smaller median standard error (0.40 m) than estimates with an intersection angle smaller than 30 degrees (0.65 m).

The river widths reported by the SWORD centre lines for WSS estimates go down to 30 m. Though, after a visual inspection the actual river widths do not go below 50 m (with a water occurrence of 70%), and the reports of WSS estimates on rivers more narrow than 50 m are faulty estimated widths in the SWORD centre lines.

5. Discussion

This study aims to automatically estimate river water surface slopes (WSS) from ICESat-2 data. A robust and consistent approach has been presented and the resulting river slopes for the Amur River basin have been presented. Due to the configuration of the six laser beams of ICESat-2, the river slope can be estimated independently of the angle between the satellite track and the river.

The investigation of the Amur River basin using four years of data suggests reliable WSS estimates. The WSS lies between 0.6 cm/km

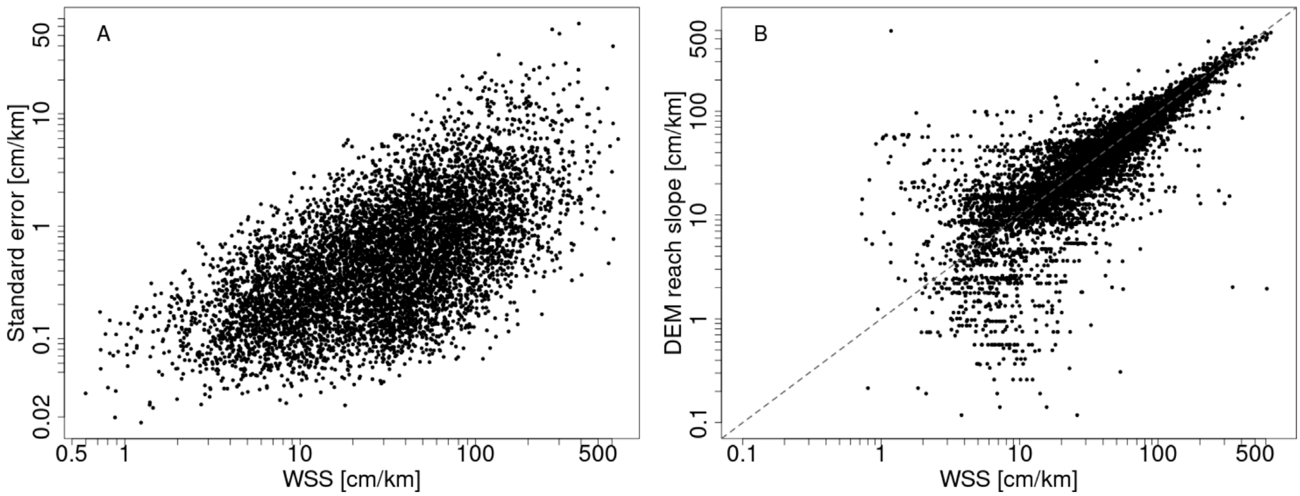

Fig. 5. Left panel is the estimated WSS and standard error of the estimate plotted on a double logarithmic scale. Right panel illustrates the WSS and DEM reach slope from SWORD reaches. DEM reach slopes that are known to be erroneous are removed from the comparison.

Table 5
Auxiliary information about WSS estimate in Amur river basin based on ICESat-2 data from October 2018 to October 2022.

Name	Unit	Minimum	25% percentile	Median	Mean	75% percentile	Maximum
WSS	cm/km	0.60	13.11	32.20	53.05	66.99	651.04
SE	cm/km	0.02	0.20	0.47	1.10	1.15	63.53
N obs	–	10	29	67	159	173	2911
Resolution	m	401.07	4277.11	5897.26	5608.29	7248.05	7999.99
Int. angle	deg	0.20	42.03	62.00	57.52	76.30	90.00

and 651.04 cm/km with a median standard error of 0.47 cm/km. The slopes were compared to the DEM reach slope and show reasonable agreement. The average residual between the WSS found in this study and the DEM reach slope was 7.98 cm/km. The WSS found in this study is a local, time-dependent slope while the DEM reach slope is constant and describes the slope of the terrain. It was therefore not expected that these slope estimates would align completely. The disagreement between these slope estimates can partly be explained by time-varying dynamic effects of the flow, such as the backwater effect.

The standard error of the regression estimate reported in this paper is the statistical belief in the regression slope value. This might therefore not represent the full uncertainty of the measurement.

Scherer et al. (2022) were the first to estimate WSS using ICESat-2 ATL13. They split the slope estimation into two groups; across-track and along-track. They found that the across-track and along-track estimation performed with a mean absolute error, MAE, of 2.4 cm/km and 6.1 cm/km, respectively, compared to in-situ twin-gauges. Scherer et al. (2022) removed estimates with an intersection angle greater than 65 degrees to reduce the estimation error. The method presented in this paper does not apply a maximum intersection angle as the results suggest that the method is sufficient to estimate WSS independently of the intersection angle with a satisfactory degree of precision. Globally, gauge stations are located far from each other, strongly limiting the number of twin-gauge stations. Slope estimates from in situ stations give one value across many tens or hundreds of kilometres. Slopes estimated in the current study cover up to eight km and therefore represent a local slope and are thus not compared to an average twin-gauge slope.

ICESat-2 WSE measurements have an accuracy of less than 10 cm (Jasinski et al., 2021). These errors propagate to the WSS estimates. The WSS uncertainty is affected by the distance along the river centre line and the number of points used. Small WSS estimates are therefore more affected by the measurement uncertainty than large WSS estimates. Small WSS estimates, therefore, demand a larger slope resolution to have an acceptable slope standard error. Further, the standard error of the WSS estimate is also affected by the number of WSE measurements. For WSS estimates smaller than 0.6 cm/km the measurement uncertainties exceed the slope, and the WSS can therefore not be determined with statistical significance.

The processing scheme presented in this paper is subject to a series of limitations related to the SWOT River Database and the precision of WSE data. The SWOT River Database is an automated global database and is therefore not manually inspected. It is subject to continuous improvements and the effect of wrongly produced SWORD reaches will decrease over time.

The processing scheme presented in this paper can produce negative WSS estimates. As previously mentioned, tidal forces can produce negative slopes in the downstream part of a river. Further, in areas with very small slopes, such as lakes, data uncertainty can dominate the regression analysis and produce small negative slopes. Slightly negative slopes over a lake can be included in an analysis as they indicate that the WSS is close to zero.

Meanwhile, negative slopes can also arise due to errors in the input data. The following situations can produce erroneous negative slopes

- In areas where the river splits up into two or more parallel sub-reaches, the reach ID of the upstream and downstream reaches can be miscategorized. This can result in distances along the river that are reversed, resulting in negative slopes.
- In areas where the river splits up into two or more parallel sub-reaches, and the SWOT River database fails to represent all sub-reaches, WSE measurements from multiple channels will be included as one reach.
- In some reaches, the order of the node IDs is reversed, thus reversing the distance along the centre line, and thereby producing a negative WSS estimate.
- If measured data represent other items than the river at interest the slope will consequently be untrustworthy. This can occur if data is falsely measured over a nearby lake, tributary, or dried river bed.

Knowledge of the river WSS can be utilized in many disciplines within river hydrology and many studies have demonstrated the use of slope estimates from twin-gauging stations. Liu et al. (2022) applied the methods in areas with backwater effects to improve the accuracy of discharge estimates. The limited number of twin-gauging stations around the world (and the general trend of a decreasing number of gauging stations) strongly limits the application of the method.

This study seeks to form a basis for slope estimation without the use of in-situ twin gauges. The global slope estimates from this study can contribute to the expansion and utilization of WSS in river modelling. Even if the slopes estimated from satellite altimetry exhibit larger errors than in-situ data, the availability of slopes from altimetry still possesses increased knowledge of the properties of rivers.

The state-of-the-art measurement configuration with 6 laser beams has a great advantage in estimating slopes over other satellite altimetry missions using only one beam. However, ICESat-2 also possesses major drawbacks. The repeat time is 91 days, which results in poor temporal resolution. The number of slope estimates at a river location is highly dependent on the local weather and cloud cover at the time of overflight. During 4 years, ICESat-2 overflies a river location 12 times, though, on average only 4 WSS estimates are produced per river reach.

The SWOT satellite is the next advance in the field of hydrology and Earth observation. The method developed in this study is expected to be transferable to data from the SWOT satellite. Applying the method to SWOT data with better spatial and temporal resolution may further improve the accuracy of river WSS estimates. The SWOT satellite will have a resolution that enables observation of rivers with widths down to 50 m. Water bodies will be monitored every 5th–10th day depending on the location (Biancamaria et al., 2016).

6. Conclusion

The water surface slope of rivers is of great interest to hydrologists and modellers. The WSS can be estimated based on ICESat-2 ATL13 measurements of the water surface elevation. This paper utilizes the beam configuration of ICESat-2 to estimate the WSS using a regression of the water surface elevation across a distance along the river. A robust and consistent approach has been developed and the resulting river slopes for the Amur River basin have been evaluated. The WSS has been estimated between 0.60 cm/km and 651.04 cm/km with a median standard error of the estimate of 0.47 cm/km. The method presented in this paper is independent of the intersection angle between ICESat-2 and the river.

The WSS can be estimated for rivers wider than 50 m and for slopes larger than 0.60 cm/km. For slopes smaller than 0.60 cm/km the data errors will exceed the WSS value and the slope can therefore not be determined with statistical significance. For more narrow rivers the regression will become too uncertain due to the limited number of WSE measurements.

Other limitations to the performance are associated with the visual wavelength of ICESat-2 laser beams and the SWOT River Database. The SWOT River Database is continuously updated and the influence of mistakes in the database is therefore expected to decrease. ICESat-2 cannot penetrate cloud cover and bad weather which limits the number of river overflights where data is collected. This limits the number of WSS estimates and therefore limits the interpretation of the temporal variation of the WSS.

This paper successfully processes the river water surface slopes automatically using a robust method that is applicable everywhere in the world where ICESat-2 data is available, rivers are included in the SWOT River Database, and the river is wider than 50 m. The implemented processing scheme is made available through an R package, ICE2WSS.

CRediT authorship contribution statement

Linda Christoffersen: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Peter Bauer-Gottwein:** Conceptualization, Methodology, Writing – review & editing. **Louise Sandberg Sørensen:** Conceptualization, Methodology, Writing – review & editing. **Karina Nielsen:** Conceptualization, Methodology, Software, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code is available online on GitHub and link is provided in the article. Data used in the article is open access online.

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