Journal of Hydrology 617 (2023) 128761

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

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

Michał Halicki [a,*], Christian Schwatke [b], Tomasz Niedzielski [a]

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

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

ARTICLE INFO

This manuscript was handled by Emmanouil Anagnostou, Editor-in-Chief, with the assistance of Guy Schumann, Associate Editor.

Keywords:
Sentinel-3 altimetry
River slope
Satellite ground track shift
Odra River

ABSTRACT

This study is the first attempt to investigate the bias of the Sentinel-3 altimetry measurements over rivers resulting from the satellite ground track shift and the associated river slope. Altimetry-based water levels are measured at the so-called virtual stations (VS), which are defined as the area where the satellite pass intersects with a river channel. Since the ground tracks of the Sentinel-3 satellites can shift up to 1 km away from the nominal track, the calculated heights over VS correspond to different locations on the river. However, all measurements at a given VS are combined into one time series of water levels, assigned to a single reference position. Because rivers are inclined water bodies, the upstream measurements are characterized by a positive bias, while the downstream measurements reveal a negative bias. In this study, we investigate water levels measured at 16 VS of the Sentinel-3 satellites, located on the middle Odra/Oder River. To correct the measurements for the bias, we calculate the river slope by employing two separate approaches: (1) using *in situ* water levels, referenced to a common vertical datum (Kronsztadt'86), calculating the slope for each satellite measurement time, as well as (2) using the means of water levels from VS, calculating the slope once for the entire study period. The uncorrected water level anomalies, compared to the anomalies from the neighbouring gauges, are characterized by a mean root mean square error (RMSE) of 22 cm. The correction of water levels utilizing both approaches led to similar outputs, and resulted in a statistically significant improvement in mean accuracy by 5.64 cm and 5.74 cm for the gauge-based and VS-based approaches, respectively (i.e. over 25% improvement in mean RMSE). The percentage improvement varied from 4.99% to 53.23%, depending on VS. This study confirms the importance of the bias caused by the satellite ground track shift and the associated river slope, determines its contribution to the overall altimetry measurement error budget, and provides a fully automated approach to correct the time series for the slope effect.

1. Introduction

According to the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2021), climate change will be manifested not only by an increase in the average temperature, but also by the intensification of extreme events, such as droughts, floods and hurricanes. In the face of these changes, as well as due to the demographic and economic growth, access to freshwater will become more and more difficult (Haddeland et al., 2014). Therefore, monitoring of inland waters as well as their sustainable management is of great importance. However, the availability of water level measurements on rivers is decreasing over the recent decades (Hannah et al., 2011). Satellite altimetry has a great potential to become an alternative to *in situ* gauging, since it provides regular measurements in almost the entire Earth.

Initially developed to observe sea level dynamics (e.g. Kosek, 2001; Leuliette et al., 2004; Nerem et al., 1994, 2010; Niedzielski and Kosek, 2009; The Climate Change Initiative Coastal Sea Level Team, 2020), the altimetric method has also shown potential to monitor inland waters, including lakes, rivers and wetlands (e.g. Cazenave et al., 1997; Crétaux et al., 2009; Frappart et al., 2006; Sulistioadi et al., 2015; Tourian et al., 2016). However, there are still a few issues that need to be resolved for satellite altimetry to provide precise, fully useable water level measurements of inland waters. The main problem in utilizing altimetry

* Corresponding author.
E-mail address: michal.halicki2@uwr.edu.pl (M. Halicki).

https://doi.org/10.1016/j.jhydrol.2022.128761
Received 25 April 2022; Accepted 26 October 2022
Available online 9 December 2022

measurements on rivers is their spatial and temporal resolution. The ground track separation on the equator for the currently operating satellites (CryoSat-2, Sentinel-3 and Jason-3) is of 7.5 km, 104 km and 315 km, while their revisit time is of 369, 27 and 10 days, respectively. Further, the accuracy of altimetry-based water levels of rivers is an order of decimetre (e.g. Biancamaria et al., 2017; Halicki and Niedzielski, 2022; Jiang et al., 2020; Kittel et al., 2021), which is still an order of magnitude lower than the accuracy of gauge measurements.

Altimetry measurements over inland waters are conducted at the so-called virtual stations (VS), which are the intersections of satellite ground tracks with river channels. One of the main challenges of inland water observation with altimetry is the proper retracking of the signal returning from the Earth surface, due to the contribution of land contamination to the returned waveforms (Gao et al., 2019). Numerous retrackers were developed and validated over inland waters in order to properly detect the reflection from water surface as well as to mitigate the contamination of the signal due to its reflection from land. Jarihani et al. (2013) studied multiple satellite altimetry data processed with various retrackers over some of the Australian lakes and rivers. Those authors confirmed the general usefulness of this technique in hydrological applications. The performance of several retrackers was studied on a basis of Sentinel-3A altimetry over the Brahmaputra River by Huang et al. (2019) who thoroughly investigated their performance over river sections located on high altitudes with complex terrain. Significant improvement in data quality was brought by the development of the Synthetic Aperture Radar (SAR) mode, which reduced the along-track resolution from 1.64 km to 300 m (Nielsen et al., 2017). Due to this change, the returning waveform is less affected by land contamination. Further, smaller water bodies can now be sensed by the altimeter (Quartly et al., 2020). Another improvement of altimetry products over rivers and lakes came with the development of the open-loop mode, which, due to the *a priori* information about the surface topography, enables controlling the range window position of the altimeter. This leads to a significant increase in the number of VS for satellites operating in this mode (Le Gac et al., 2021).

Despite the above-mentioned progress in altimetry over inland waters, there are still numerous factors affecting its accuracy. Initially, altimetry measurements of river stages were constrained by a minimum river width of 1 km (Birkett, 1998). Along with the technological development of altimetry, the minimum river width decreased below 100 m, and currently it is not a factor limiting the measurements (Santos da Silva et al., 2010). A thorough investigation of such factors was conducted by Maillard et al. (2015) who studied the Envisat and SARAL altimetry over the São Francisco River. Those authors identified three factors, which may affect the altimetric measurement: (1) land cover along the satellite ground track near the river, (2) river channel morphology (width, direction and shape) and (3) land topography near the river channel. The influence of the two first factors was also studied by Halicki and Niedzielski (2022) who investigated the Sentinel-3A altimetry water levels over Polish rivers. The authors found no influence of the river width and land cover on the accuracy of altimetric measurements. However, the complex river channel morphology (the presence of sandbars etc.) and the unfavourable geographical setting of the VS (i.e. the river channel parallel to the satellite ground track or multiple crossings of the river channel by the satellite ground track) occurred more often on VS characterized by lower accuracy.

Due to orbit perturbations, the satellite ground tracks do never perfectly superimpose. For example, the ground track deviation of the Sentinel-3 satellites is of 1 km (https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-3/satellite-description/orbit, accessed on 13.04.2022). However, altimetric measurements on rivers from a given VS are usually combined into one time series, assuming that they were all taken over the same river outlet (cross-section). In a specific geographical situation, i.e. when a river channel is aligned almost parallelly to the satellite ground track, a shift of 1 km might result in water level measurements taken several kilometres upstream or downstream the nominal VS (Fig. 1). Since rivers slope towards the mouth, altimetry-based water levels measured away from the central position of VS are characterized by bias: negative for downstream, and positive for upstream passes (Fig. 2).

The effect of the satellite ground track shift and the river slope on the river altimetry observations, hereinafter referred to as "river altimetry slope bias", was already noticed in the 90s (Birkett, 1998; Koblinsky et al., 1993). For that time, the problem of the river altimetry slope bias could not be solved, since "gradients across wetland and river basins are poorly known, and the altimetry itself can only provide along-track gradients" (Birkett, 1998). Further, Koblinsky et al. (1993) and Birkett (1998) focused mainly on the Amazon River, which, in most of its parts, has a gentle slope of several centimetres per kilometre (e.g. Birkett et al., 2002), therefore the river altimetry slope bias appears to be of minor importance.

To the best of authors' knowledge, the first study to suggest and apply a correction for the bias described above was the work of Santos da Silva et al. (2010) who studied the ERS-2 and ENVISAT altimetry over the Amazon basin. The authors applied a correction by "manually entering a slope value and correcting for the height difference between the mean location of the pass and the location retained for the virtual station". The correction, for most of the altimetry time series, was characterized as a second order correction. Also, Boergens et al. (2016) identified the river altimetry slope bias. The authors corrected the ENVISAT measurements over the Mekong River by using the river slope described in literature. However, due to the lack of gradient values of the Mekong River tributaries, that correction was applied only to the main stream. Also in that work, the improvement in the accuracy was called a "secondary correction".

Both Santos da Silva et al. (2010) and Boergens et al. (2016) described the correction to be of second order. However, their studies employed altimetry data of the ERS-2 and ENVISAT satellites, which operate in the Low Resolution Mode (LRM). The footprint size of altimetric measurements carried out by these satellites is larger than one kilometre. The new altimetry missions (Sentinel-3A/-3B and CryoSat-2) are equipped with the SAR altimeters, the along-track resolution of which is only 300 m. Further, the Sentinel-3 satellites operate in the open-loop mode. Therefore, it would be recommended to study the river altimetry slope bias based on the new altimeter data, which is characterized by a higher accuracy than the ERS-2 and ENVISAT missions.

It is also to be mentioned that both of the previously described approaches used *a priori* information about the river slope which is indispensable for the calculation of the vertical difference. However, the gradient of a given river section can be now calculated with the use of altimetry data. Such calculations were performed in the Amazon River using TOPEX/Poseidon altimetry (Birkett et al., 2002) and using ICESat laser altimetry over the Kongo river (O'Loughlin et al., 2013). The altimetry-based river slope was also calculated by Garambois et al. (2017) and Bjerklie et al. (2018) for the purpose of hydrological modelling. Altimetry-based gradient calculations were also conducted to unify or compare water levels of different VS or *in situ* stations (e.g. Hall et al., 2012; Schneider et al., 2018; Tourian et al., 2016; Villadsen et al., 2015; Xiang et al., 2021).

In our study, we aim to thoroughly analyse the river altimetry slope bias. We consider 16 VS of the Sentinel-3 satellites, located on the middle Odra/Oder River, hereinafter abbreviated as Odra River. We also propose a correction based on the distance between each measurement and the reference position of a VS as well as on the river slope of a given river section. The gradient value will be calculated in two separate approaches: (1) using water levels from neighbouring gauges, which will result in the river slope value at each time of the satellite pass, as well as (2) using means of water levels at VS. The gauge-based slope will serve as a reference, since *in situ* readings are of very high quality. Using the up-to-date slope, we will determine the contribution of the river altimetry slope bias to the overall budget of the

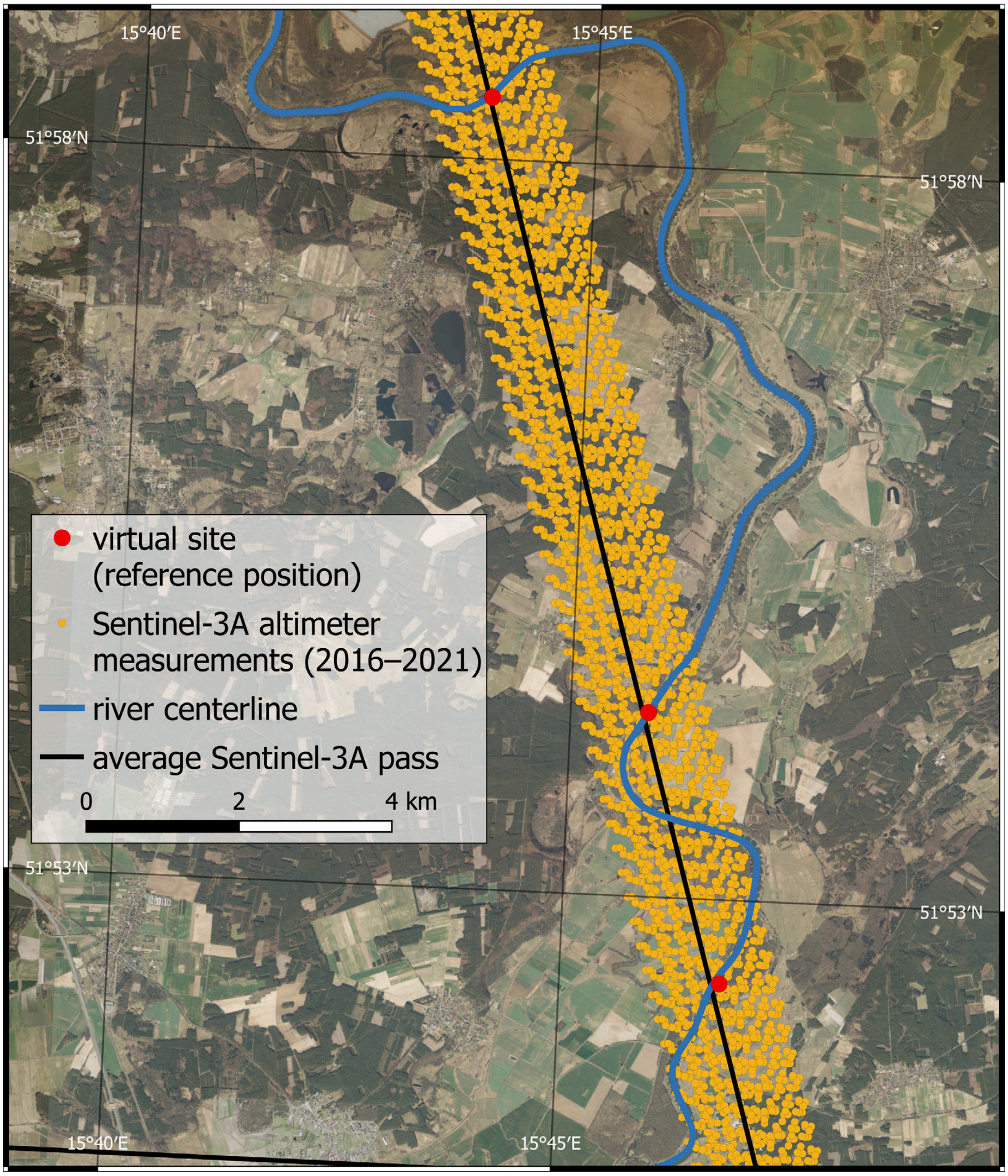

Fig. 1. Altimeter measurements over the middle Odra River illustrating the Sentinel-3A ground track shift.

altimetric measurement error. The second approach will be performed using one river slope value (fixed for the whole study period) for a given river section.

We argue that water level time series corrected for the river altimetry slope bias will be characterized by a lower root mean square errors (RMSE) than the uncorrected measurements. The novelty of this study resides in correcting the highly accurate Sentinel-3 measurements, which, since operating in the SAR mode, are characterized by a small along-track resolution. Further, we propose a fully automatic approach that allows to calculate corrections based only on satellite data, without the need to use manually entered slopes (Santos da Silva et al., 2010) or slopes previously presented in the literature (Boergens et al., 2016). Our solution can be used operationally as it does not require any *a priori* data.

2. Study area

Odra is Poland's second-longest river with length of 854 km. It has its headwaters in Czechia in the Sudetes mountains, but it predominantly flows through the territory of western Poland. Odra is usually divided into the upper Odra (upstream from the Kędzierzyn-Koźle city), the middle Odra (between the Kędzierzyn Koźle city and the mouth of the Warta River) and the lower Odra (downstream the mouth of the Warta River). In its upper part, Odra is a narrow, mountainous river. On the contrary, on its lower part the river is almost flat, with slope values varying from 0.05 m/km to 0.001 m/km (Dubicki et al., 2005). The upper part of the middle Odra is channelled and regulated by numerous hydraulic structures. Considering the above described river characteristics as well as the availability of gauge and altimetry measurements, the study area has been limited to the middle Odra section between the Ścinawa and Kostrzyn nad Odrą gauges (Fig. 3), which is free of water damming structures and its slope ranges from 0.19 m/km to 0.28 m/km (Dubicki et al., 2005).

The study area can be characterized as a lowland, with altitudes below 300 m a.s.l., gently sloping towards the NW direction. Four main tributaries along the studied reach are: Warta, Nysa Łużycka, Bóbr and Barycz, with length of 795 km, 246 km, 278 km and 136 km, respectively. Following the river classification based on width (Meybeck et al., 1996), most of the middle Odra River can be classified as a small river (40–200 m in width). The regime can be classified as nival, moderately

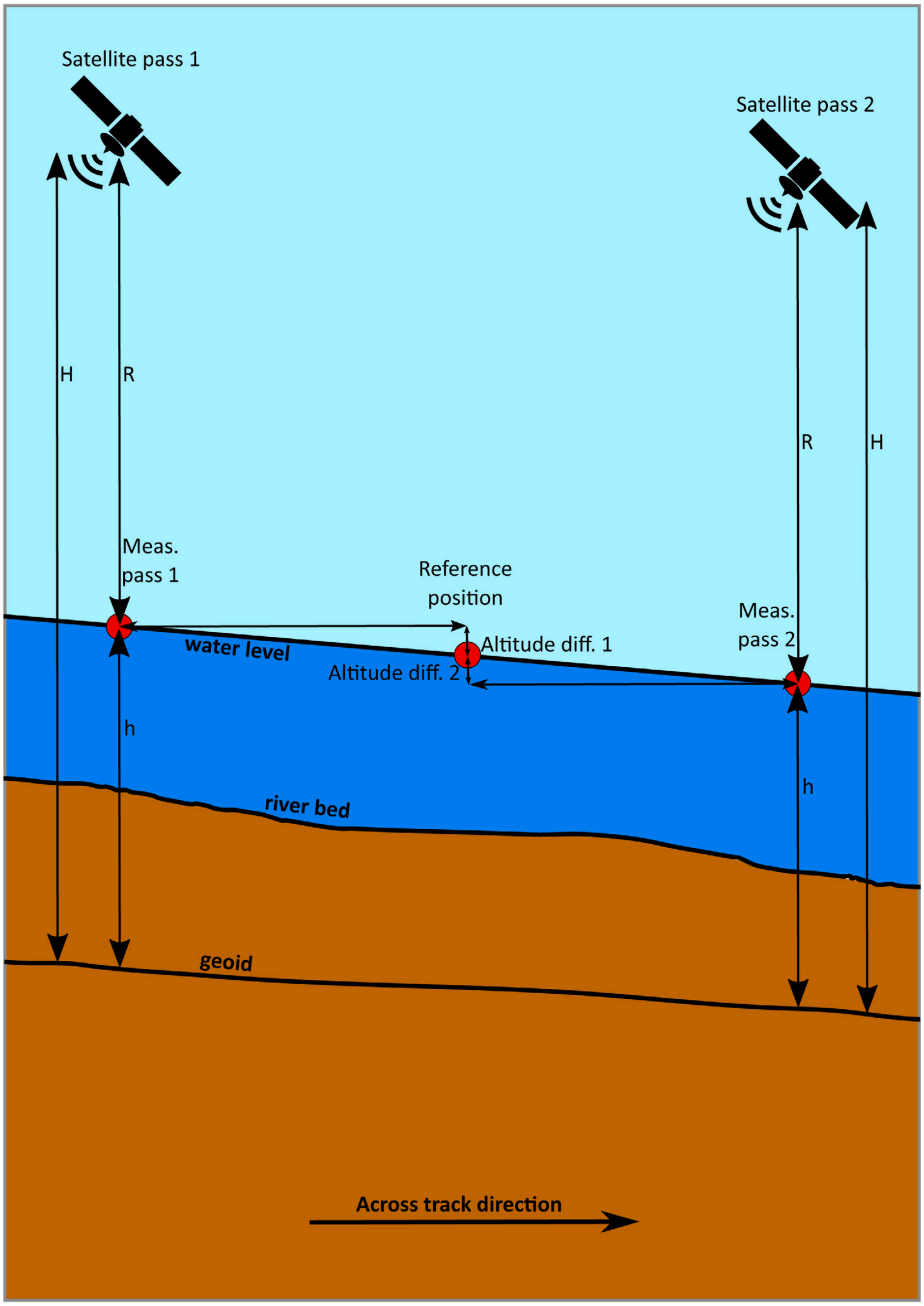

Fig. 2. The altimetry measurement bias resulting from the satellite pass non-repeatability.

developed (Wrzesiński, 2017). This implies that the average flow in the spring month is 130%–180% of the average annual flow, which is driven by snow thawing. The channel of the middle Odra River has undergone numerous regulations during the last two centuries (Kreft and Parzonka, 2007). In particular, the river section considered in this study is characterized by the occurrence of stony groins on both sides of the channel.

3. Data

3.1. Altimetric data

Sentinel-3 is an Earth observation satellite mission developed by the European Space Agency, designed to monitor open oceans as well as coastal areas and inland waters (Fletcher, 2012). Currently, two satellites operate under this mission, namely Sentinel-3A and Sentinel-3B, launched in February 2016 and April 2018, respectively. Both operate on a sun-synchronous orbit, the height of which is of 814.5 km. The ground tracks of this constellation of satellites are spaced 52 km at the equator, and the repeat cycle is of 27 days. One of the instruments carried by these satellites is the Synthetic Aperture Radar Altimeter (SRAL) which uses the Ku-band and C-band frequencies. It operates in the SAR mode between 60°N and 60°S. Considering the on-board tracking mode of Sentinel-3, both satellites operate in the open-loop mode.

In this study, we use the "Non Time Critical" (NTC) Sentinel-3 data provided by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) through the Copernicus Online Data Access (CODA, https://www.eumetsat.int/coda/, accessed on

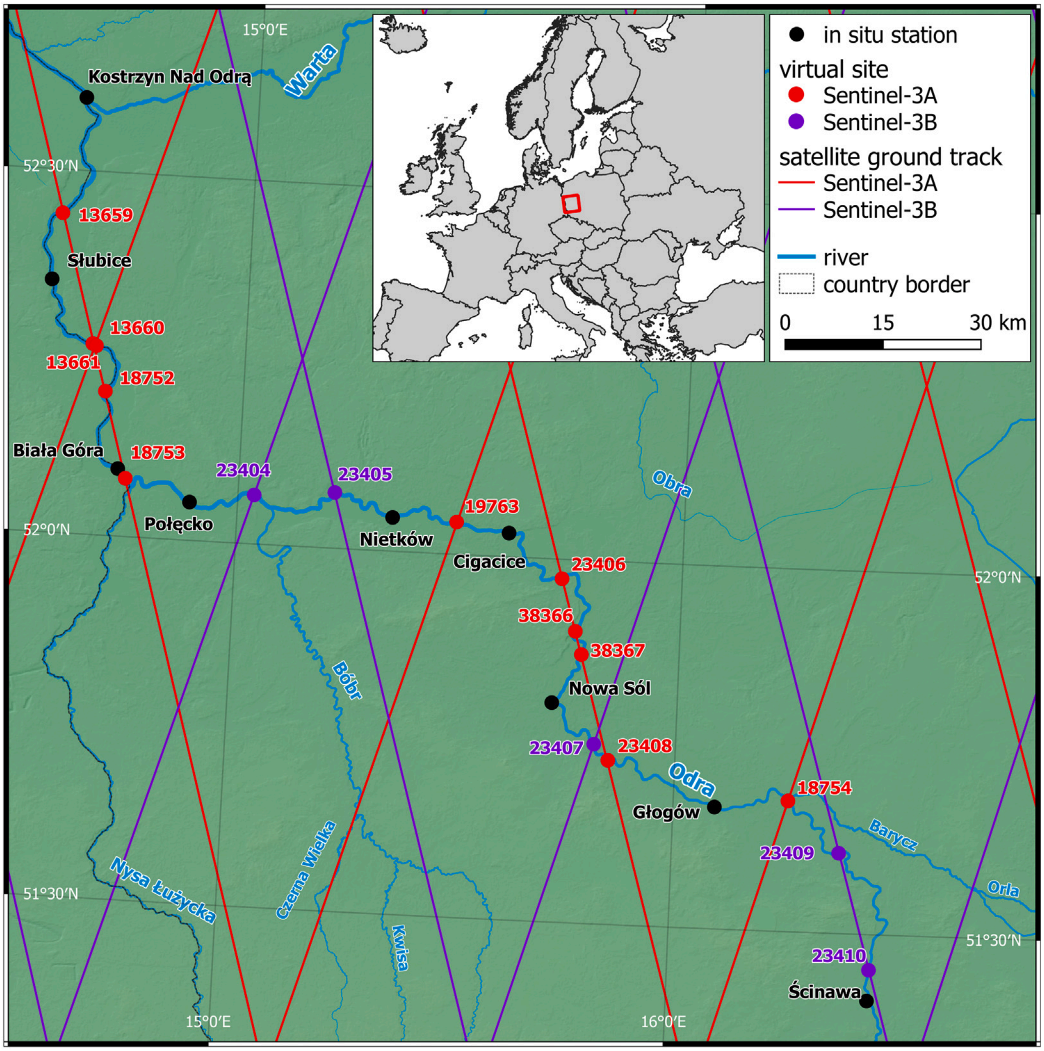

Fig. 3. Study area.

Table 1
List of virtual stations used in this study.

DAHITI-ID	Satellite	Longitude	Latitude	Nearest gauge	Distance to gauge [km]	River width [m]
13659	Sentinel-3A	14.5711	52.4399	Słubice	11.892	155
13660	Sentinel-3A	14.6561	52.2628	Słubice	14.292	190
13661	Sentinel-3A	14.6645	52.2601	Słubice	14.944	200
18752	Sentinel-3A	14.6905	52.1984	Biała Góra	14.752	215
18753	Sentinel-3A	14.7464	52.0802	Biała Góra	1.877	160
18754	Sentinel-3A	16.2541	51.6802	Głogów	14.011	115
19763	Sentinel-3A	15.4911	52.0443	Cigacice	8.526	105
23404	Sentinel-3B	15.0362	52.0673	Połęcko	11.280	140
23405	Sentinel-3B	15.2160	52.0766	Nietków	11.566	115
23406	Sentinel-3A	15.7319	51.9733	Cigacice	14.842	145
23407	Sentinel-3B	15.8187	51.7475	Nowa Sól	11.270	160
23408	Sentinel-3A	15.8515	51.7261	Nowa Sól	15.254	110
23409	Sentinel-3B	16.3706	51.6109	Głogów	28.560	115
23410	Sentinel-3B	16.4457	51.4512	Ścinawa	5.036	120
38366	Sentinel-3A	15.7668	51.9017	Nowa Sól	13.405	145
38367	Sentinel-3A	15.7825	51.8701	Nowa Sól	8.961	130

13.04.2022) service. Based on the Sentinel-3 data, we derived water level time series for 16 VS located on the middle Odra River (Fig. 3), 11 of which are VS of the Sentinel-3A, and 5 of them are Sentinel-3B VS (Table 1). The mean distance between the compared stations is of 12.53 km, and it ranges from 1.88 km to 28.56 km. The river width at the studied VS, measured on a basis of Google Earth imagery, ranges from 105 to 215 m, with a mean of 145 m.

3.2. *In situ* data

The gauge network consists of 9 *in situ* stations (Fig. 3), located closer than 30 km from the VS (Table 1). Water levels from these gauges are used for two purposes: to assess the accuracy of satellite measurements as well as to calculate the river slope of a given section. Readings from the Kostrzyn nad Odrą gauge are used only for the slope calculation, since it is not the nearest gauge to any VS. The water levels are operationally measured by the Institute of Meteorology and Water Management – National Research Institute (Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy, IMGW-PIB) and provided with a time step of 1 h. The time span of *in situ* data ranges from April 2016 to August 2021. IMGW-PIB provided also the gauge zero heights, referenced to the Kronsztadt'86 vertical datum. These values are crucial for the gauge-based slope calculation (see Section 4.2.1). In total, *in situ* data gaps while satellite passes over VS occur in 25 situations, out of 969 considered. However, *in situ* data is missing 49 times when trying to calculate the gauge-based slope value, since for this calculation stages from both neighbouring gauges are indispensable (see Section 4.2.1). All in all, this is still a very low number of missing data and we do not conduct any gap interpolation for this study.

4. Methods

4.1. Water level time series from satellite altimetry

The methodology for the estimation of water level time series for 16 VS using Sentinel-3A and Sentinel-3B is based on the DAHITI approach described in Schwatke et al. (2015). This approach is based on an extended outlier rejection, applied retracking and a Kalman filter step. However, for this study, we added a new outlier criteria based on river centrelines taken from the SWOT River Database (SWORD, Altenau et al., 2021). The SWORD centrelines are used to estimate the exact river crossings of each altimeter track which are later used for the river slope correction. Additionally, a new outlier criteria is applied rejecting all altimeter measurements which are further away than 500 m from the river crossings. Based on the remaining altimeter measurements and the DAHITI approach are water level time series for 16 VS computed. The water levels are given normal heights. All water level time series are freely available on the DAHITI webportal (https://dahiti.dgfi.tum.de, accessed on 13.04.2022).

4.2. Slope calculation

4.2.1. Gauge-based approach

Calculation of the river slope in the gauge-based approach is conducted on a basis of *in situ* measurements: gauge zeros and water levels (above gauge zero). For each satellite pass, water levels from the upstream and the downstream adjacent gauges are juxtaposed. As mentioned in Section 3.2, in 49 situations there is a data gap at one of the gauges. In such case, we decided to compare heights from up to 24 h before or after the altimetric measurement. However, the compared water levels need to refer to the same time: for example in case of data gaps at time t_0 we look for Water Surface Elevations (WSE) at t_{1h} for both gauges, then for the WSE at t_{-1h}, and so on up to 24 h. Due to this operation the calculation of the river slope is impossible only in 20 situations. Finally, the river slope at each of the satellite passes is calculated as follows:

$$Gauge\text{-}based\ slope\ [\mathrm{m/km}] = \frac{(h_u + z_u) - (h_d + z_d)}{d}, \tag{1}$$

where h_u, h_d are the upstream and downstream water levels (above gauge zero) [m], z_u, z_d are the upstream and downstream gauge zeros [m] and d is the along river distance between gauges [km]. The result of this calculation is the mean river slope on the river section between neighbouring gauges.

4.2.2. VS-based approach

As mentioned in the Introduction, the river slope calculation is now possible with the use of altimetry data. The gradient can be determined, if the vertical difference and the along-river distance between the VS are known. One of the approaches for estimating the vertical difference resides in subtracting the means of heights from two adjacent VS (e.g. Tourian et al., 2016). A modified approach was presented by O'Loughlin et al. (2013) who calculated the mean heights of selected months. Another approach is a subtraction of water levels from neighbouring gauges conducted at each measurement epoch, which was applied in the work of Garambois et al. (2017) and Bjerklie et al. (2018). This allows a unique slope estimation for each satellite pass. On contrary, Villadsen et al. (2015) and Xiang et al. (2021) did not calculate the slope directly, but they rather interpolated heights on different locations on the river. The interpolation was a function of the distance from a given location to the river mouth (or any established point on the river), the parameters of which were calculated on a basis of water levels from all VS of a studied river section.

Usually the neighbouring VS are not being observed by the satellite at the same time. Therefore, there should be a maximum time difference between VS which are chosen for the slope calculation. Hall et al. (2012) used only those VS pairs, the measurements of which are maximally one day apart. On the contrary, O'Loughlin et al. (2013) defined the threshold to be of 2 days. In our study, the time shift between observations on VS of one satellite (Sentinel-3A or Sentinel-3B) located on neighbouring, parallel ground tracks is of 4 days, although the distance between them is 104 km at the equator (Fig. 4). However, in case of multiple crossing of a satellite ground track and a river channel, some VS can be observed almost simultaneously (within several seconds), therefore they form an excellent basis for slope calculation. The time shifts between measurements on neighbouring VS of two different satellites or between readings from adjacent VS located on non-parallel tracks are not stable (Fig. 4), therefore before using such pairs for the slope calculation the actual time shift should be verified.

Considering the above-mentioned time delays between VS measurements, as well as knowing the accuracy of altimetry-based WSE on rivers of an order of decimetre, we do not calculate the river slope at each measurement time. For a river section between two VS, one slope value is estimated, using the vertical difference between those stations calculated on a basis of mean WSE values (see Eq. (2)). The river slope is calculated between VS, the measurements of which are maximally 4 days apart (so the neighbouring, parallel passes are included). The slope of such river section is calculated as follows:

$$VS\text{-}based\ slope\ [\mathrm{m/km}] = \frac{\overline{h_u} - \overline{h_d}}{d}, \tag{2}$$

where $\overline{h_u}$, $\overline{h_d}$ are the upstream and downstream means of VS water levels [m], and d is the along river distance between VS [km]. This value represents the slope of the river section between the two VS.

4.3. Distance calculation and water levels correction

The second essential value for the proposed correction is the distance from the altimetric measurement to the VS reference position. In this study, we used the river centreline from the Map of the Hydrographic Division of Poland (Mapa Podziału Hydrograficznego Polski). In most cases, the satellite track crossed the river at each of its passes. For such situations the altimetric measurement location is defined as the intersection between the river line and the current satellite pass. However, on several VS in some cases the satellite did not pass exactly over the river. In these situations the off-nadir correction is applied (Boergens et al., 2016), and the measurement location is defined as the point on the river located closest to the current satellite pass. Finally, the distance is being determined as the length of the river section between the current altimetric measurement and the reference position of the VS.

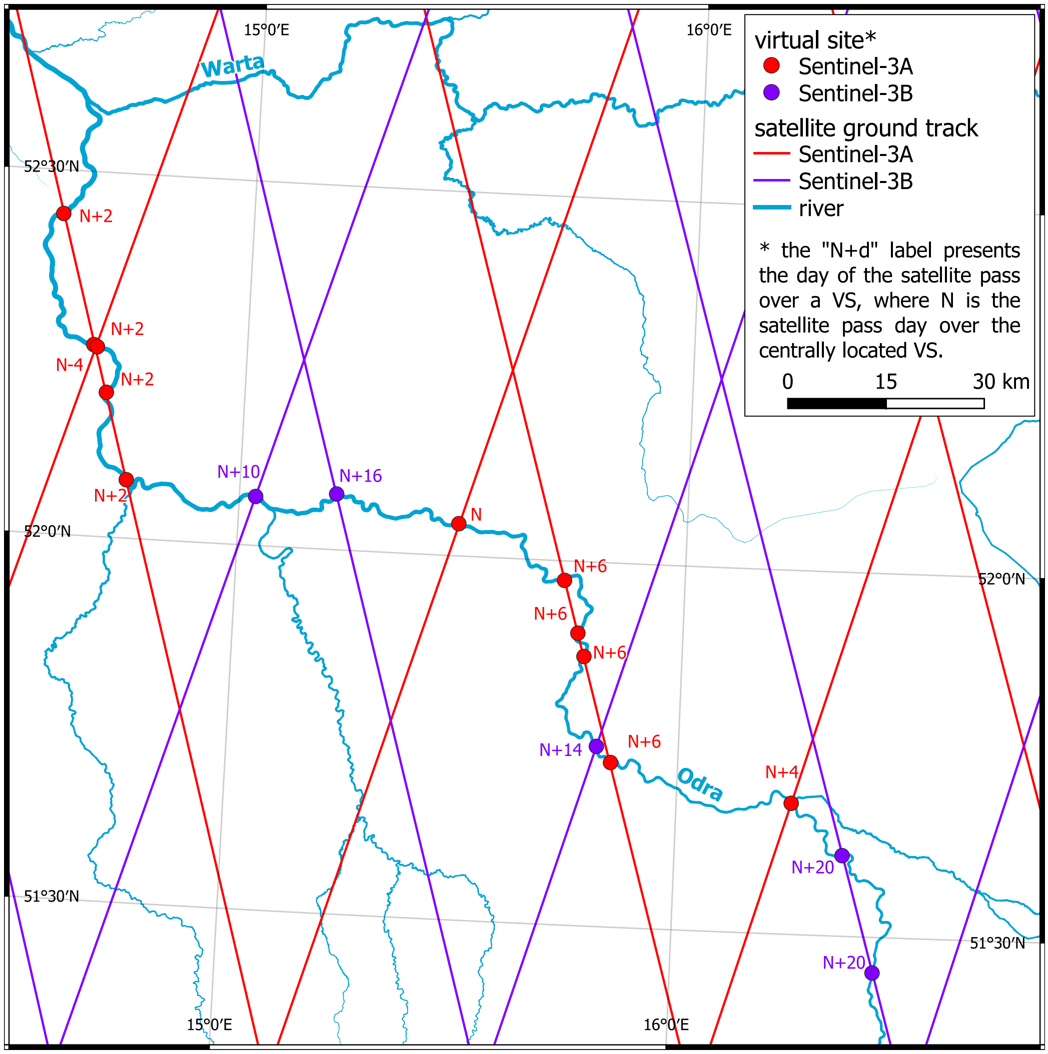

Fig. 4. Time delay occurring between satellite passes over the middle Odra River.

Having established the river slope and the distance from the reference, it is possible to calculate the corrected water levels, which is conducted as follows:

$$Corrected\ WSE = WSE - (RS \cdot D), \tag{3}$$

where WSE is the water surface elevation on a VS [m], RS is the river slope [m/km], and D is the along-river distance from the current altimetry measurement to the reference position of the VS [km]. The value of the correction is subtracted from WSE, since the distance value is set a positive number for measurements upstream and as a negative number for measurements downstream the reference position. Therefore, if the satellite passes downstream the reference position, the measurement is likely to be underestimated, therefore the shift should increase WSE. On the other hand, for measurements taken upstream the reference position, the correction should lower WSE, as it is likely to be overestimated.

Fig. 5 presents the workflow of data processing carried out in this study. After retrieving Sentinel-3A/3B NTC data from EUMETSAT, this data is being processed and corrected in the modified DAHITI approach. These water levels are then corrected for the measurements non-stationarity with the use of the gauge-based slope (calculated for each measurement time separately) and the VS-based slope (calculated once for the entire study area). Finally, all three time series: uncorrected, corrected with gauge-based slope (approach 1) and corrected with VS-based slope (approach 2) are compared with WSE from the adjacent gauges. The comparison is conducted taking into account the time lag between the compared stations, which is thoroughly described in Halicki and Niedzielski (2022).

4.4. Statistical methods

To check if errors of the estimated water levels are reduced as a result of applying slope corrections along the lines of the approach 1 and 2, numerous statistical tests are employed. Three data sets are analysed: (1) RMSE at 16 VS before correction, (2) RMSE at 16 VS after correction based on the approach 1 and (3) RMSE at 16 VS after correction based on the approach 2.

To evaluate the significance of the above-mentioned reduction in RMSE, two pairs of data sets are considered: (1) uncorrected data vs. corrected data using approach 1, (2) uncorrected data vs. corrected data using approach 2. The Welch two-sample Student's T-test is utilized, in which the null hypothesis of equal means of RMSE in two samples is tested against the one-sided alternative that mean RMSE of the corrected water level is significantly lower than mean RMSE of the uncorrected river stages. The choice of the two-sample Student's T-test is due to its considerable power.

To carry out the statistical inference using the two-sample Student's T-test, numerous assumptions must be fulfilled: (1) each of three data

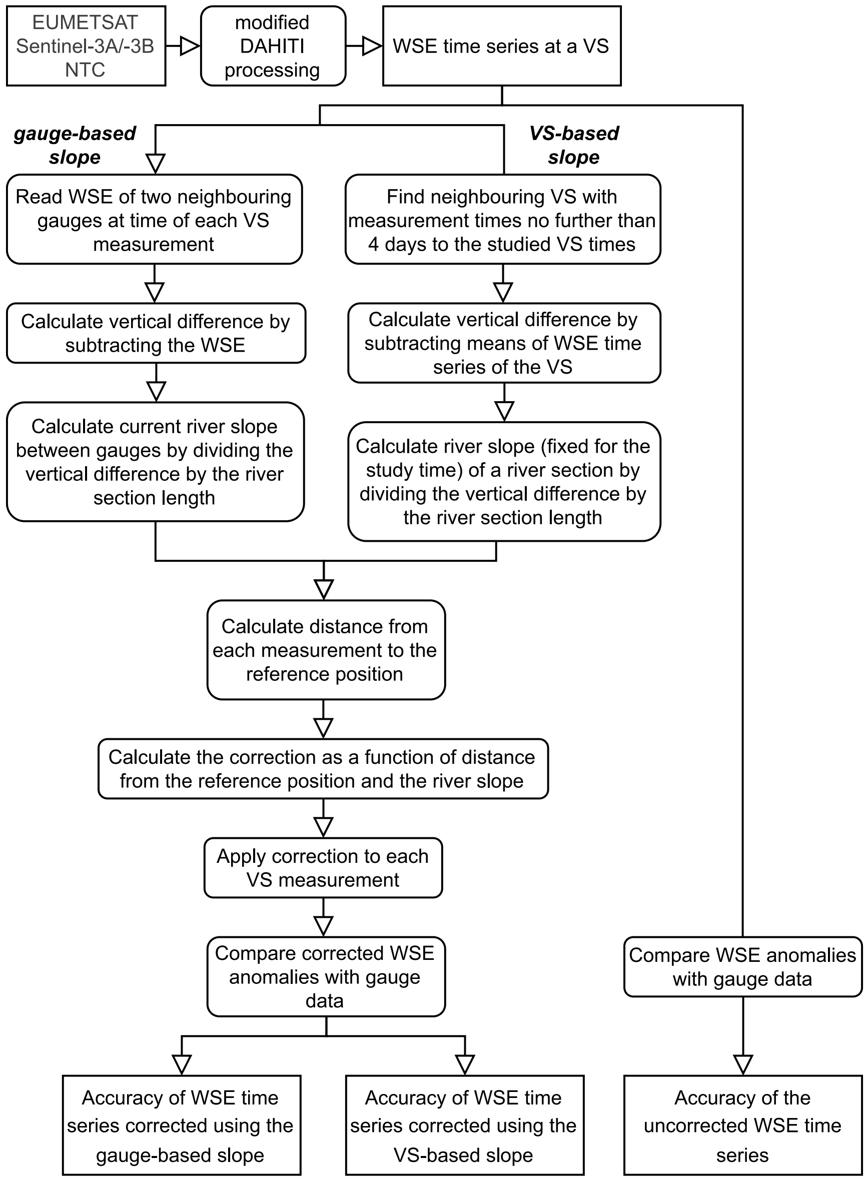

Fig. 5. Flowchart of the data processing. VS — virtual stations, WSE — water surface elevation.

sets must be internally statistically independent, (2) each of three data sets must be normally distributed, (3) variances of data sets juxtaposed in the aforementioned pairs must be equal. First, the hypothesis of independence within each data set is verified using the Ljung–Box test (Ljung and Box, 1978). Second, the normality hypothesis is checked using the Shapiro–Wilk test (Royston, 1995). Third, the F test for comparing variances of normally distributed samples is used.

5. Results

Since rivers are water bodies characterized by an inclined water surface, and the satellite ground track can shift up to one kilometre towards both sides, the altimetric measurements are subject to be biased. This can be observed in Fig. 6 which presents the amount of bias of every altimetry measurement at all studied VS. The bias is calculated as the difference between the altimetry-based water level anomaly compared to the corresponding water level anomaly from the neighbouring gauge. Each subfigure shows the river, the nominal ground track, the reference position of the VS and the altimetric measurement locations (see Section 4.3), the colour of which depends on the bias size. The subfigures present also the arrows which show the flow direction.

On almost every VS the bias of measurements conducted downstream the reference position is negative, which suggests an underestimation of WSE. The opposite effect occurs for measurements conducted upstream the reference position (Fig. 6). The only VS for which this trend is ambiguous is VS 13659. It is also worth noting that the geographical setting of the VS determines the maximum distances between the measurements and the reference position. If the satellite pass is quite parallel to the river channel (e.g. VS 18753, VS 23410), the furthest measurements might be even 2–3 km away from the reference position. For such points, the bias may exceed 0.5 m. Fig. 6 allows also for the identification of VS with measurements taken not exactly over the river channel (VS 18752 and VS 38366). For these measurements we apply the off-nadir correction (Boergens et al., 2016).

The river slope did not undergo significant changes during the study period. Considering the 6-year period and all the studied river sections, the river slope values (calculated with the gauge-based approach) ranged from 0.24 to 0.30 m/km (Table 2). The mean values of the slope ranged from 0.26 to 0.29 m/km. This confirms that the river slope along the middle Odra River is stable. Interestingly, the VS-based approach reveals very similiar slopes. The values range from 0.26 to 0.28 m/km, and they do not differ from the gauge-based mean slope

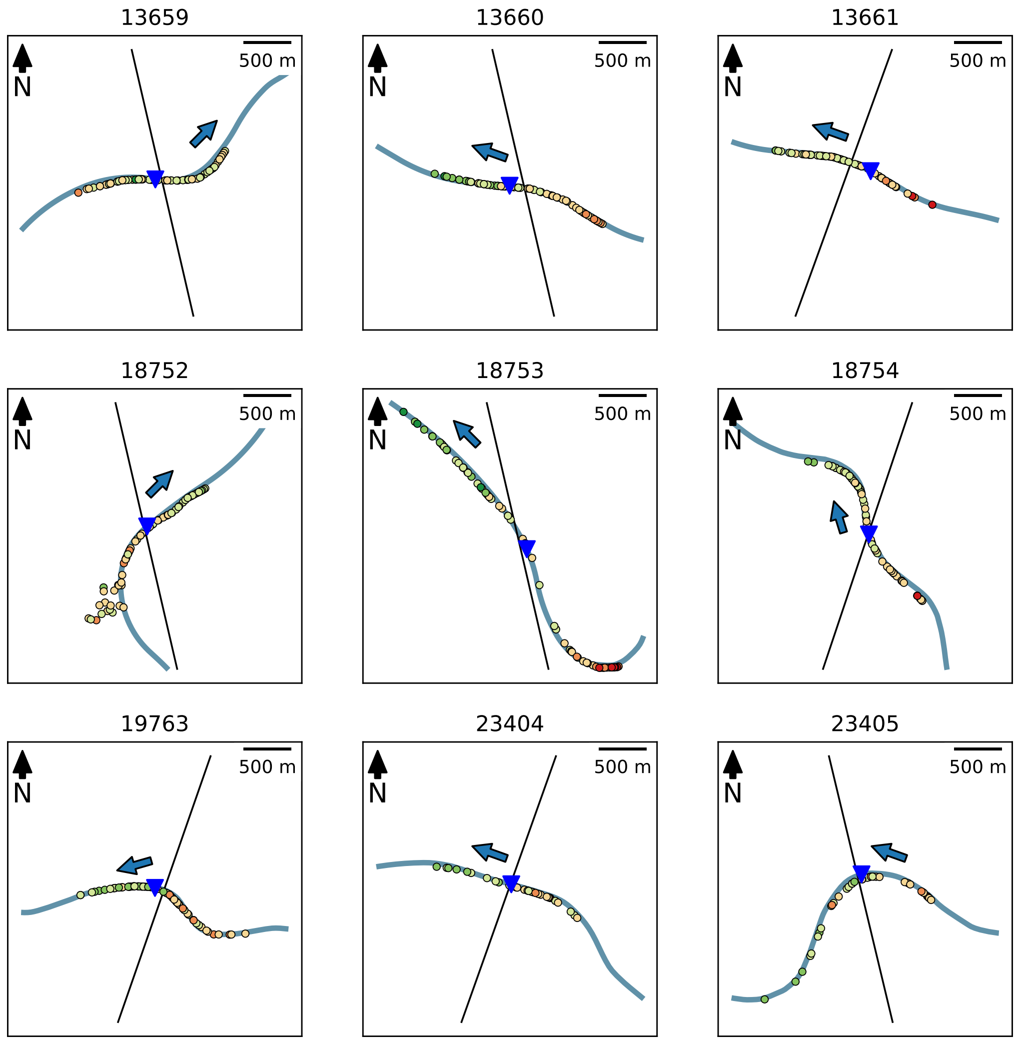

Fig. 6. Bias of satellite measurements at virtual stations on the middle Odra River.

Table 2
River slope [m/km] values at the studied virtual stations.

VS	Gauge-based approach					VS-based approach			
	River section	Section length [km]	Mean slope	Max. slope	Min. slope	River section	Section length [km]	Slope	VS time shift
13659	Słubice–Kostrzyn nad Odrą	33.842	**0.26**	0.28	0.24	13659–13660	26.184	**0.27**	0 days
13660	Biała Góra–Słubice	39.114	**0.27**	0.28	0.26	13659–13660	26.184	**0.27**	0 days
13661	Biała Góra–Słubice	39.114	**0.27**	0.28	0.26	13660–18752	10.070	**0.27**	0 days
18752	Biała Góra–Słubice	39.114	**0.27**	0.28	0.26	18752–18753	16.629	**0.27**	0 days
18753	Połęcko–Biała Góra	15.315	**0.27**	0.30	0.26	18752–18753	16.629	**0.27**	0 days
18754	Ścinawa–Głogów	59.654	**0.29**	0.30	0.28	23409–23410	26.060	**0.28**	0 days
19763	Cigacice–Nietków	20.136	**0.26**	0.27	0.25	18753–23406	86.361	**0.27**	4 days
23404	Nietków–Połęcko	37.945	**0.27**	0.29	0.27	18753–23406	86.361	**0.27**	4 days
23405	Nietków–Połęcko	37.945	**0.27**	0.29	0.27	18753–23406	86.361	**0.27**	4 days
23406	Nowa Sól–Cigacice	41.406	**0.28**	0.29	0.27	23406–38367	17.672	**0.26**	0 days
23407	Głogów–Nowa Sól	36.786	**0.28**	0.30	0.27	38366–23408	29.144	**0.27**	0 days
23408	Głogów–Nowa Sól	36.786	**0.28**	0.30	0.27	38366–23408	29.144	**0.27**	0 days
23409	Ścinawa–Głogów	59.654	**0.29**	0.30	0.28	23409–23410	23.410	**0.28**	0 days
23410	Ścinawa–Głogów	59.654	**0.29**	0.30	0.28	23409–23410	23.410	**0.28**	0 days
38366	Nowa Sól–Cigacice	41.406	**0.28**	0.29	0.27	23406–38367	17.672	**0.26**	0 days
38367	Nowa Sól–Cigacice	41.406	**0.28**	0.29	0.27	38366–23408	29.144	**0.27**	0 days

values by more than 0.02 m/km. This proves the high efficiency of this method, which is based only on satellite data. However, it has to be mentioned that the slope values are calculated for river sections with lengths varying from 15.315 km to 59.645 km for the gauge-approach and from 10.07 km to 86.361 km for the VS-approach. This method would not be applicable on river sections where waterfalls or dams occur.

The accuracy of three WSE time series are presented in Table 3. The RMSE of the uncorrected WSE ranges from 14 cm to 34 cm, with mean of 22 cm. Almost half of studied VS (7 out of 16) are characterized by RMSE lower than 20 cm. After applying the correction using the gauge-based slope, the mean RMSE amounts to 16 cm, which is a reduction of 25.46%. Only in one situation, the applied correction does not improve the accuracy (VS 13659) – the decrease is of 0.4 cm, which

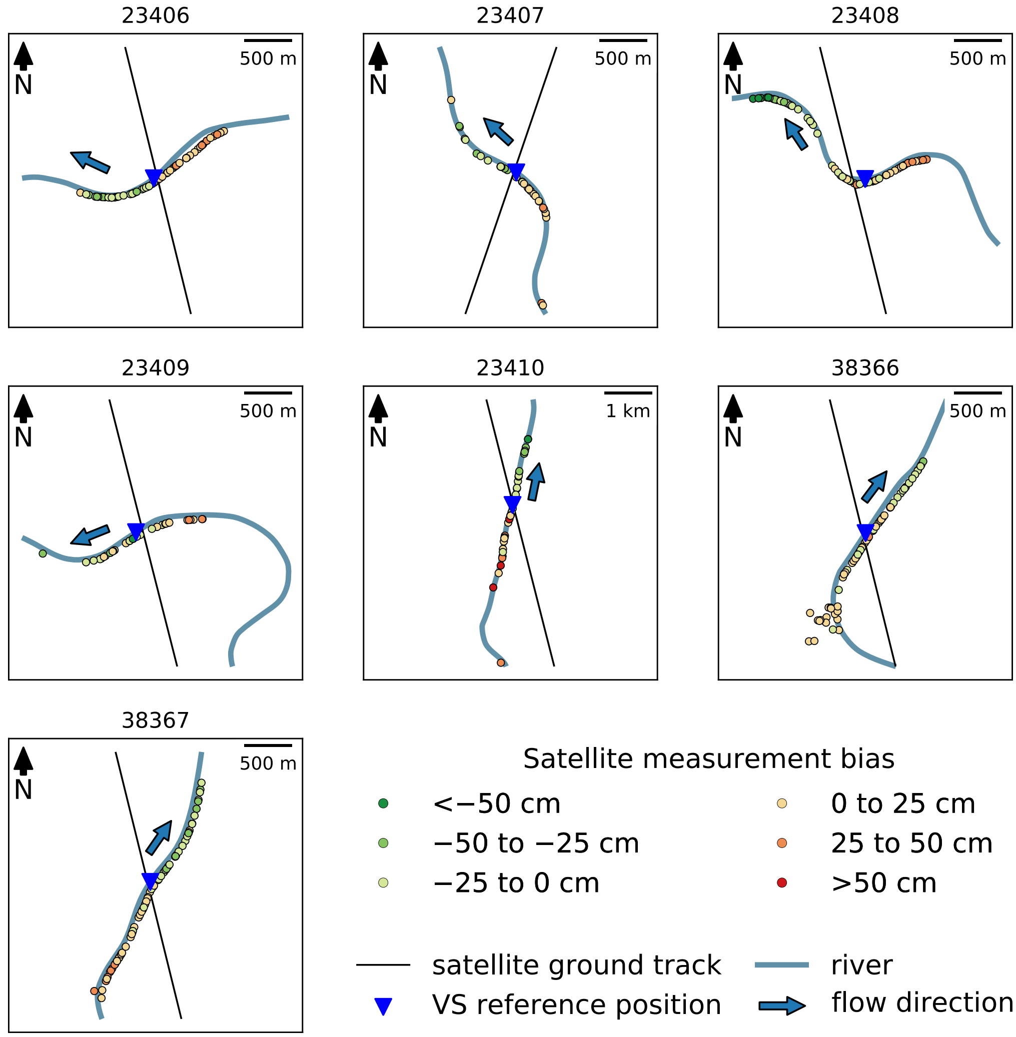

Fig. 6. (*continued*).

is 2.26% of the primary accuracy. For other VS the improvement ranges from 0.7 cm to 13.4 cm, while the improvement percentages vary from 4.99% to 53.23%. The lowest RMSE is of 9 cm (VS 13660), while the highest RMSE occurs for VS 23408 (31 cm). Interestingly, the correction using the VS-based slope results in a very similiar improvement. The mean RMSE is even 0.1 cm lower than the RMSE of WSE calculated using the approach 1. The maximum difference between those two approaches is of 0.7 cm, which is only 6.02% difference. However, the mean difference between these time series is of 0.64%. Therefore, both approaches seem to have a very similiar, high efficiency.

In order to check if the reduction in RMSE of water level determination, attained as a result of applying corrections known as the approaches 1 and 2, is statistically significant, the Welch two-sample Student's T-test has been utilized. The RMSE values juxtaposed in Table 3 have been paired (uncorrected data vs. corrected using approach 1, uncorrected data vs. corrected using approach 2) to check if there is a statistically significant reduction in mean RMSE. In all statistical tests the significance level of 0.05 has been assumed.

Table 4 shows that *p*-values of the above-mentioned test, with the one-sided alternative (which says that after the correction mean RMSE is lower than before the correction), are of 0.0061 and 0.0054 for approach 1 and 2, respectively. It means that at the pre-assumed significance level, the difference between RMSE averages is statistically significant. The one-sided two-sample Student's T-test is powerful, i.e. in our case (16 elements in each group, significance level of 0.05, standard deviation of approximately 6, difference in means of approximately 5.5) its power is of approximately 0.81. It legitimates the inference based on only 16 elements in each group.

To perform the two-sample Student's T-test appropriately, a number of assumptions must be fulfilled (see Section 4.4). It is apparent from Table 4 that all the investigated RMSE data are internally independent, as inferred on a basis of the Ljung–Box test and the associated high *p*-values exceeding 0.4. Also, the Shapiro–Wilk test suggests that it is impossible to reject the null hypothesis of normality at the pre-defined significance level (*p*-values are greater than 0.08). Therefore, three data tests, each representing 16 RMSE values obtained using (or not) different slope correction approaches, are highly likely to follow the normal samples, which is needed to apply the two-sample Student's T-test properly. In addition, variances in groups (uncorrected data vs. corrected data with approach 1 as well as uncorrected data vs. corrected data with approach 2) do not vary significantly that is confirmed by the F-test, the *p*-values of which exceed 0.7. Thus, the assumptions required for the two-sample Student's T-test to be used are met.

The statistical independence quantified by the Ljung–Box test show that neither the accuracy of the uncorrected WSE time series, nor the correction improvement do not show any spatial dependencies. The lack of dependency is also apparent from Fig. 7. Interestingly, the only VS with a decrease in accuracy (VS 13659) is the most downstream located site. On the other hand, the two VS located in the vicinity of this VS are characterized by an increase of accuracy greater than 30%. Fig. 7 shows that the improvement in the accuracy after applying

Table 3
Improvement of altimetry-based water levels accuracy obtained by eliminating the ground track shift bias.

vs	Approach 1[a]	Approach 2[b]	No correction (3)	Difference (RMSE [cm])			Difference (%)		
	RMSE [cm]	RMSE [cm]	RMSE [cm]	1 vs. 3	2 vs. 3	1 vs. 2	1 vs. 3	2 vs. 3	1 vs. 2
13659	16.88	17.03	16.50	0.37	0.52	−0.15	2.26	3.17	−0.88
13660	9.14	9.17	19.55	−10.41	−10.38	−0.03	−53.23	−53.08	−0.31
13661	11.22	11.27	17.41	−6.19	−6.14	−0.05	−35.54	−35.27	−0.42
18752	13.76	13.74	14.48	−0.72	−0.75	0.02	−4.99	−5.15	0.17
18753	20.03	19.72	33.16	−13.13	−13.43	0.31	−39.59	−40.51	1.56
18754	11.53	11.43	18.01	−6.48	−6.58	0.10	−35.98	−36.54	0.88
19763	14.67	14.64	18.82	−4.16	−4.19	0.03	−22.09	−22.24	0.20
23404	26.00	26.00	29.83	−3.83	−3.83	0.00	−12.83	−12.83	−0.01
23405	16.76	16.72	23.23	−6.47	−6.51	0.04	−27.84	−28.02	0.25
23406	14.88	14.96	20.68	−5.79	−5.71	−0.08	−28.03	−27.62	−0.55
23407	17.20	17.14	22.99	−5.79	−5.85	0.05	−25.20	−25.43	0.32
23408	30.63	30.57	34.35	−3.71	−3.78	0.06	−10.81	−11.00	0.21
23409	16.21	16.27	21.88	−5.66	−5.61	−0.06	−25.90	−25.62	−0.36
23410	20.74	20.12	28.41	−7.68	−8.30	0.62	−27.02	−29.20	3.07
38366	13.40	12.64	14.17	−0.77	−1.53	0.76	−5.44	−10.81	6.02
38367	10.86	10.82	20.61	−9.75	−9.79	0.04	−47.28	−47.48	0.38
MEAN	16.49	16.39	22.13	−5.64	−5.74	0.10	−25.46	−25.94	0.64

[a]Water level time series corrected using the gauge-based slope.
[b]Water level time series corrected using the VS-based slope.

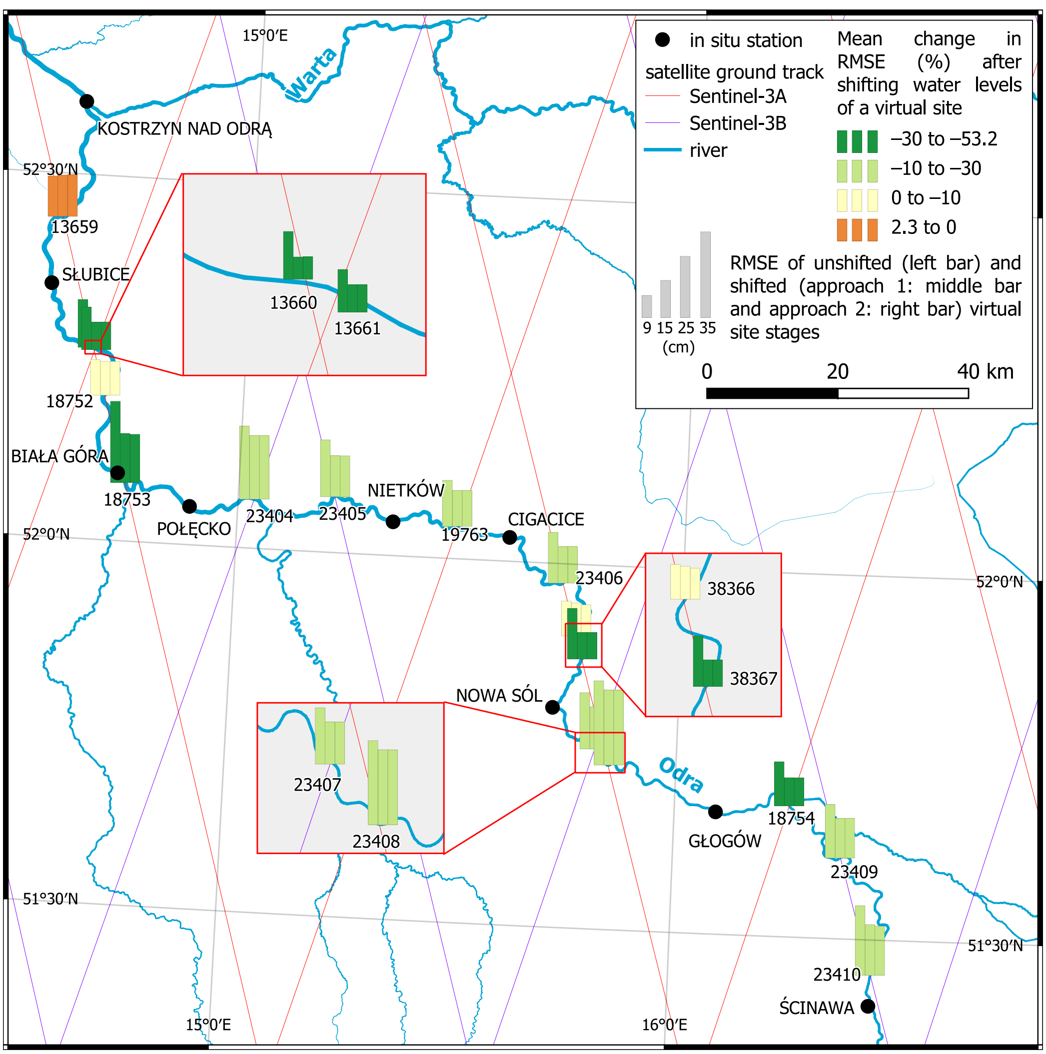

Fig. 7. Accuracy of corrected and uncorrected altimetry water levels.

Table 4
P-values of statistical tests used to infer on the difference between averages of RMSE of water level determination.

	Corrected data (approach 1) *p*-value	Uncorrected data *p*-value	Corrected data (approach 2) *p*-value
Independence within each data set (null hypothesis: independence)			
Ljung–Box test	0.8216	0.4313	0.7877
Normality of each data set (null hypothesis: normality)			
Shapiro–Wilk test	0.0982	0.1357	0.0822
Equality of variances of two data sets (null hypothesis: equal variances)			
F-test	0.7112	0.7022	
Equality of means of two data sets (null hypothesis: equal means)			
Welch two-sample T-test	0.0061	0.0054	

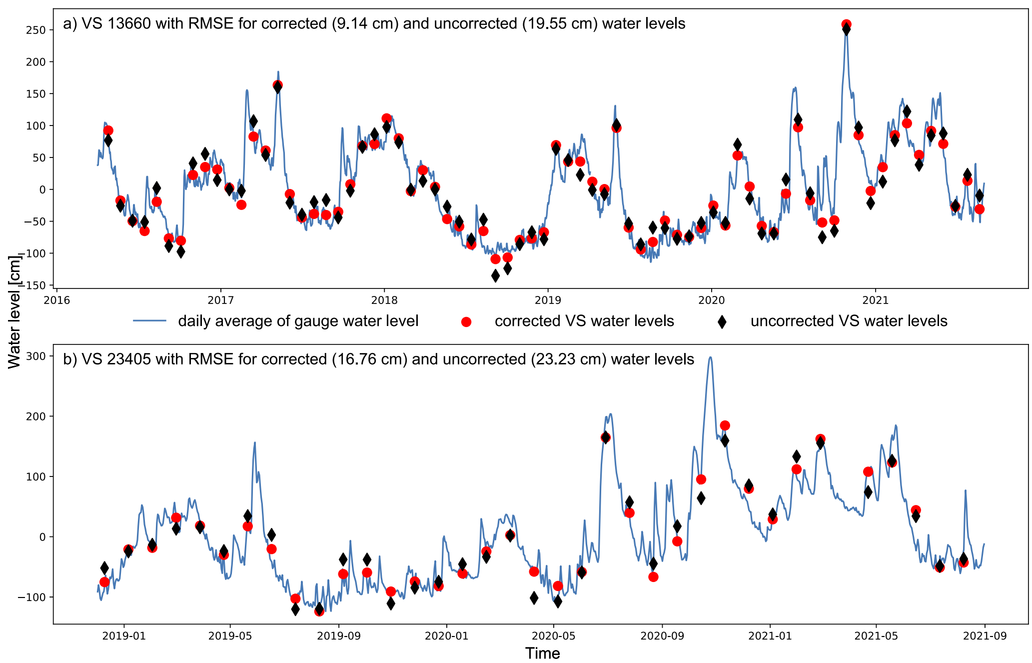

Fig. 8. Corrected and uncorrected altimetry water levels compared to the daily averages of gauge water levels. The correction is performed with the use of the gauge-based slope.

the approach 1 and approach 2 correction is very similiar. The only tributary which flows into the Odra River on a section between a VS and an *in situ* station is the Barycz river. The two VS located on this section are VS 18754 and VS 23409, but despite this tributary, WSE time series from both VS correspond well with the WSE time series from the Głogów gauge.

Due to the correction of the river altimetry slope bias, the corrected WSE anomalies from almost all VS correspond better to the water level anomalies from the neighbouring gauges than the uncorrected WSE. The correspondence with daily averages of gauge water levels is presented in Fig. 8. As example, we present data from two VS: one VS of the Sentinel-3A (Fig. 8a), and one VS of the Sentinel-3B satellite (Fig. 8b). Although in some cases the correction increases the difference between altimetry and gauge data, in most cases the correction moves the water levels closer to the gauge values. Considering the presented graphs, the correction improves the accuracy both during low and high water periods. All graphs showing the corrected (in the approach 1) heights, uncorrected heights, and daily averages of gauge water level anomalies are presented in the supplementary material (Fig. S1).

6. Discussion

Determination of the river slope is a key point in the proposed river altimetry slope bias correction. Since for the studied river section the accurate gauge readings are referenced to a common vertical datum (Kronsztadt'86), it was possible to calculate the river slope at each section for every time of the satellite observation. However, this approach cannot be applied for numerous rivers with missing *in situ* measurements. Therefore, it is essential to propose an alternative for the river slope calculation. This problem can be solved by calculating river gradients using altimetry measurements that cover most of the globe and are publicly available. Further, this approach proved its accuracy in numerous studies (e.g. Garambois et al., 2017; Schneider et al., 2018; Villadsen et al., 2015). In our study, we calculated one slope value for each river section, which was based on the difference between mean height values of the VS. The same approach was applied by Tourian et al. (2016). Also Santos da Silva et al. (2010) used this method, however, only on crossovers of two satellite ground tracks. Since satellites pass over the virtual stations on different days, we decided to calculate the river slope on a basis of VS with measurements maximally 4 days apart. We choose this threshold because this is the time difference between two neighbouring (either ascending or descending) passes of a satellite (Sentinel-3A or Sentinel-3B). On the contrary, Hall et al. (2012) compared VS with measurements maximally two days apart, and O'Loughlin et al. (2013) – maximally one day apart. However, these authors used data from different altimetric missions.

The slope values of river sections of the middle Odra River obtained in the VS-based approach agree well with mean slopes calculated with the gauge readings. The maximum difference between the mean slopes for a given VS is of 0.02 m/km. It is also worth noting, that the mean gradient ranges (0.26–0.29 and 0.26–0.28 m/km for the gauge-based and VS-based approaches, respectively) agree with the slope range of the middle Odra River (0.19–0.28 m/km) presented by Dubicki et al. (2005). An evaluation of the VS-based approach for the river slope calculation was also performed by Bjerklie et al. (2018) who used Jason-2 altimetry over the Yukon River. The authors estimated the slope separately for each satellite measurement time. To verify the obtained gradients, the authors compared them with slopes calculated with the use of laser altimetry from the ICESat mission as well as with values presented in the literature. Both comparisons confirmed the high accuracy of this approach. Although these approaches show promising results, it is to be mentioned that the slope values refer sometimes to river sections with length of several dozens of kilometres. In our study, the longest section was of 86.36 km. The longer the section is, the greater the generalization of the obtained slope becomes. Also, this approach would not be applicable on river sections with dams or waterfalls as the slope is not constant along these sections.

The WSE values at VS of the Sentinel-3 satellites on the middle Odra River, calculated with the modified DAHITI approach, are characterized by high accuracy. The mean RMSE of VS water level anomalies compared with anomalies from the neighbouring gauges is of 22 cm, which is comparable with the mean RMSE for the corresponding VS from the Hydroweb database, which were studied by Halicki and Niedzielski (2022). Comparing 9 VS of the Sentinel-3A satellite considered in both studies, the mean RMSE is of 22 cm and 20 cm for the DAHITI and Hydroweb water levels, respectively. Both results show the high quality of Sentinel-3 data, and they are comparable to other studies which assessed the Sentinel-3 accuracy over rivers (see Table 5 in the paper by Halicki and Niedzielski (2022)).

To the best of our knowledge, the only two studies to apply a correction of the river altimetry slope bias are the works of Boergens et al. (2016) and Santos da Silva et al. (2010). Both authors describe the improvement in accuracy to be of several centimetres in the mean RMSE. Although this is a value comparable with the mean improvement obtained in our work (5.64 cm and 5.74 cm for the approach 1 and approach 2, respectively), there are several differences which have to be mentioned. First of all, both authors used *a priori* data for the river slope borrowed from literature, therefore their approaches are not applicable along ungauged rivers. Further, these studies used ENVISAT and ERS-2 altimeters operating in the LRM mode, which are characterized by a significantly larger footprint than the Sentinel-3 altimeter (operating in SAR mode). Therefore, the accuracy of water levels estimated by these altimeters vary significantly: both Boergens et al. (2016) and Santos da Silva et al. (2010) obtained RMSE values ranging from decimetres up to several metres. Therefore, an improvement in the accuracy of a few centimetres did not seem as a key correction. On contrary, due to the development of the SAR altimeters and the open-loop mode, the accuracy of the Sentinel-3 river altimetry can be of 20–40 cm in RMSE (e.g. Bogning et al., 2018; Halicki and Niedzielski, 2022; Kittel et al., 2021; Zaidi et al., 2021). Therefore, in our study, the correction by more than 5 centimetres represents more than 25% of RMSE, and for some of the VS, the improvement was about 50%.

The research in this study was carried out on the middle Odra River, with slopes varying from 0.24 m/km to 0.30 m/km. The proposed correction strongly depends on this value, so it will certainly be smaller on rivers characterized by a more gentle gradient. For example, the slope of most of the Amazon River is only of 0.01–0.04 m/km (e.g. Birkett et al., 2002). However, there are many stretches of rivers that are wide enough to be monitored by satellites, but also located in mountainous areas. It is in these rivers that, first of all, the correction suggested in this study should be applied, as the slope of these rivers is much greater, which increases the river altimetry slope bias.

The occurrence of the river altimetry slope bias is clearly visible in Fig. 9a. Taking into account all of the altimetric measurements, the bias clearly correlates with the distance from a measurement to the reference position. The Pearson correlation coefficient between the biases (before correction) and the distances from the reference position is of 0.65, which is a strong and statistically significant correlation (at the significance level of 0.05). After applying the gauge-based correction, the biases are deprived of a clear trend (Fig. 9b), and they do not correlate to the distance from the reference position — the Pearson correlation coefficient is weak and equal to −0.16. The occurrence of the river altimetry slope bias is also confirmed by the slope of the regression line presented in Fig. 9a. For the uncorrected data, the slope is of 0.218 m/km. After applying the correction, the slope of the regression line is reduced to −0.041 m/km. This can suggest even a slight overcorrection of the river altimetry slope bias. However, this bias is not the only source of the altimetry error, therefore no inference should be made on a basis of such small correlation coefficient (−0.16) and the associated slope of the regression line (−0.041 m/km). In conclusion, since both approaches proposed in this study showed a very similiar performance, it can be stated that both allow for the elimination of the river altimetry slope bias.

7. Conclusions

Due to orbit perturbations, satellite ground tracks do never perfectly superimpose. Since rivers are inclined water bodies, a non-exact location of water level measurements might lead to certain bias. In previous altimetry missions, the bias was often overlooked because there were factors that contributed to the measurement budget error on a much larger scale. The Sentinel-3 satellites are equipped with the SAR Radar Altimeter and operate in the open-loop mode. Therefore, they provide water level elevations of rivers, the accuracy of which is in the order of decimetres. In this study, we aimed to assess the contribution of the river altimetry slope bias to the overall altimetry measurement error budget, as well as to propose a fully automated approach that allows to calculate corrections based only on satellite data. We studied water levels from 16 VS of the Sentinel-3 satellites, located on the middle Odra River and calculated in the modified DAHITI approach. The accuracy was determined by comparing the water level anomalies from the VS with anomalies from the neighbouring gauges. The contribution to the overall error budget was estimated using *in situ* measurements, which allowed for an individual slope determination for each satellite measurement. The second approach was based on river gradients estimated on a basis of the mean heights of VS. The following conclusions can be drawn:

- RMSE of the uncorrected water level anomalies are characterized by a mean value of 22 cm, ranging from 14 cm to 34 cm.
- The river slope calculation with the use of satellite data provided accurate values, almost identical to those calculated with the *in situ* data.
- The correction with the gauge-based slope allowed for a mean reduction in RMSE by 5.64 cm, which is an improvement of about 25%.
- The correction with the VS-based slope performed very similarly, reducing RMSE by 5.74 cm.
- The decrease in RMSE for the 16 VS is statistically significant for both approaches.
- Only on one VS the correction resulted in a slight decrease of accuracy (less than 1 cm). In the remaining stations the improvement ranged from 0.7 cm to 13.4 cm, which stands for a percentage from 4.99% to 53.23%.

The findings of this study confirm that applying the correction of the river altimetry slope bias can lead to a significant improvement in accuracy. This correction is suggested especially for: (1) altimetry observations carried out in the SAR mode, since they are characterized by a small along-track resolution and high accuracy, and for (2) altimetry observations over mountainous rivers where the measurement biases should be greater, due to the higher river gradients. However, it has to be mentioned that the proposed approach is only applicable to river sections without dams or waterfalls, since they disallow a proper river slope determination. The problem in question might soon be resolved with the launch of the Surface Water and Ocean Topography (SWOT) mission. Thanks to the wide-swath technology, the mission is planned to provide accurate river slope values, which could serve the purpose of the correction of the river altimetry slope bias.

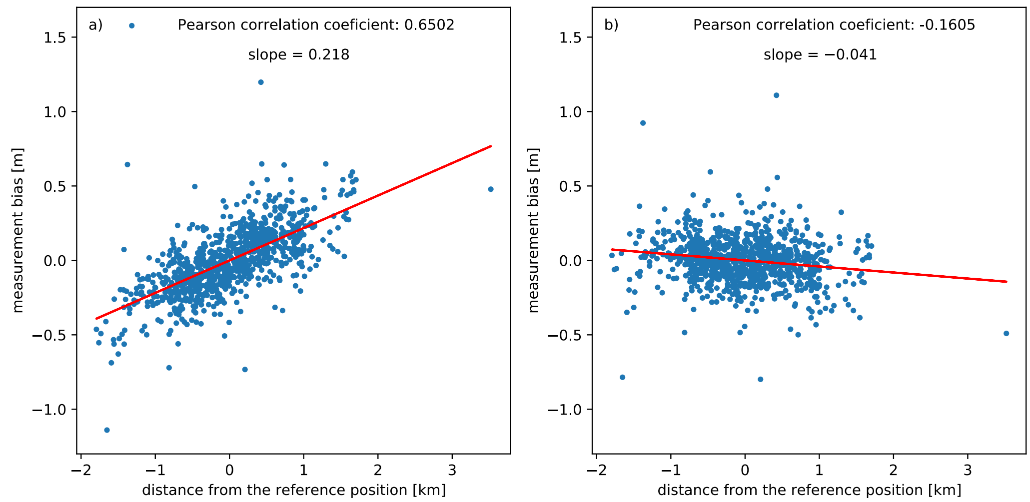

Fig. 9. Water level anomaly biases for the uncorrected (a) and corrected (b) measurements of the 16 investigated neighbouring virtual stations with the distances between the measurement locations and the reference positions.. The corrected biases were obtained using the gauge-based slope.

CRediT authorship contribution statement

Michał Halicki: Conceived the study, Developed software, Formulated conclusions, Wrote the majority of the manuscript, Produced figures. **Christian Schwatke:** Processed satellite data, Contributed to the manuscript, Participated in the discussion. **Tomasz Niedzielski:** Conducted statistical analysis, Contributed to the manuscript, Participated in the discussion.

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.

Acknowledgements

The research performed in this paper has been carried out in frame of the research project No. 2020/38/E/ST10/00295 within the Sonata BIS programme of the National Science Centre, Poland, as well as in frame of the Doctoral School of the University of Wrocław, Poland. This study was based on altimetric data retrieved from DAHITI as well as hydrologic data acquired from the Institute for Meteorology and Water Management – State Research Institute (IMGW-PIB). The research has also been partially supported by the Rector of the University of Wrocław, Poland, by the funds for research and commercialization.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.128761.

References

Altenau, E.H., Pavelsky, T.M., Durand, M.T., Yang, X., Frasson, R.P.D.M., Bendezu, L., 2021. SWOT river database (SWORD). http://dx.doi.org/10.5281/zenodo.3898570, Zenodo.

Biancamaria, S., Frappart, F., Leleu, A.S., Marieu, V., Blumstein, D., Desjonquères, J.D., Boy, F., Sottolichio, A., Valle-Levinson, A., 2017. Satellite radar altimetry water elevations performance over a 200 m wide river: Evaluation over the Garonne river. Adv. Space Res. 59, 128–146. http://dx.doi.org/10.1016/j.asr.2016.10.008.

Birkett, C.M., 1998. Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands. Water Resour. Res. 34, 1223–1239. http://dx.doi.org/10.1029/98WR00124.

Birkett, C.M., Mertes, L.A.K., Dunne, T., Costa, M.H., Jasinski, M.J., 2002. Surface water dynamics in the Amazon basin: Application of satellite radar altimetry. J. Geophys. Res. 107 (8059), http://dx.doi.org/10.1029/2001JD000609.

Bjerklie, D.M., Birkett, C.M., Jones, J.W., Carabajal, C., Rover, J.A., Fulton, J.W., Garambois, P.A., 2018. Satellite remote sensing estimation of river discharge: Application to the Yukon river Alaska. J. Hydrol. 561, 1000–1018. http://dx.doi.org/10.1016/j.jhydrol.2018.04.005.

Boergens, E., Dettmering, D., Schwatke, C., Seitz, F., 2016. Treating the hooking effect in satellite altimetry data: A case study along the Mekong river and its tributaries. Remote Sens. 8, http://dx.doi.org/10.3390/rs8020091.

Bogning, S., Frappart, F., Blarel, F., Niño, F., Mahé, G., Bricquet, J.P., Seyler, F., Onguéné, R., Etamé, J., Paiz, M.C., Braun, J.J., 2018. Monitoring water levels and discharges using radar altimetry in an ungauged river basin: The case of the Ogooué. Remote Sens. 10, http://dx.doi.org/10.3390/rs10020350.

Cazenave, A., Bonnefond, P., Dominh, K., Schaeffer, P., 1997. Caspian sea level from Topex-Poseidon altimetry: Level now falling. Geophys. Res. Lett. 24, 881–884. http://dx.doi.org/10.1029/97GL00809.

Crétaux, J.-F., Calmant, S., Romanovski, V., Shabunin, A., Lyard, F., Bergé-Nguyen, M., Cazenave, A., Hernandez, F., Perosanz, F., 2009. An absolute calibration site for radar altimeters in the continental domain: Lake Issykkul in Central Asia. J. Geod. 83, 723–735. http://dx.doi.org/10.1007/s00190-008-0289-7.

Dubicki, A., Radczuk, R., Adynkiewicz-Piragas, M., Tokarczyk, T., Mordalska, H., Maciejowska, B., Lisowski, J., Bogusz, A., Krzyścin, K., 2005. Wody powierzchniowe. In: J. Błachowski, D. Zięba (Ed.), Opracowanie Ekofizjograficzne Dla Województwa Dolnośląskiego. DAR - MARK, pp. 79–92.

Fletcher, K., 2012. Sentinel-3: ESA's global land and ocean mission for GMES operational services. ESA Communications.

Frappart, F., Minh, K.Do., L'Hermitte, J., Cazenave, A., Ramillien, G., le Toan, T., Mognard-Campbell, N., 2006. Water volume change in the lower Mekong from satellite altimetry and imagery data. Geophys. J. Int. 167, 570–584. http://dx.doi.org/10.1111/j.1365-246X.2006.03184.x.

Gao, Q., Makhoul, E., Escorihuela, M., Zribi, M., Seguí, P.Quintana., García, P., Roca, M., 2019. Analysis of retrackers performances and water level retrieval over the Ebro river basin using Sentinel-3. Remote Sens. 11 (718), http://dx.doi.org/10.3390/rs11060718.

Garambois, P.A., Calmant, S., Roux, H., Paris, A., Monnier, J., Finaud-Guyot, P., Samine Montazem, J., 2017. Hydraulic visibility: Using satellite altimetry to parameterize a hydraulic model of an ungauged reach of a braided river. Hydrol. Process 31, 756–767. http://dx.doi.org/10.1002/hyp.11033.

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111, 3251–3256. http://dx.doi.org/10.1073/pnas.1222475110.

Halicki, M., Niedzielski, T., 2022. The accuracy of the Sentinel-3A altimetry over Polish rivers. J. Hydrol. 606, 127355. http://dx.doi.org/10.1016/j.jhydrol.2021.127355.

Hall, A.C., Schumann, G.J.P., Bamber, J.L., Bates, P.D., Trigg, M.A., 2012. Geodetic corrections to Amazon river water level gauges using ICESat altimetry. Water Resour. Res. 48, http://dx.doi.org/10.1029/2011WR010895.

Hannah, D.M., Demuth, S., van Lanen, H.A.J., Looser, U., Prudhomme, C., Rees, G., Stahl, K., Tallaksen, L.M., 2011. Large-scale river flow archives: Importance, current status and future needs. Hydrol. Process. 25, 1191–1200. http://dx.doi.org/10.1002/hyp.7794.

Huang, Q., Li, X.D., Han, P.F., Long, D., Zhao, F.Y., Hou, A.Z., 2019. Validation and application of water levels derived from Sentinel-3A for the Brahmaputra river. Sci. China Technol. Sci. 62, 1760–1772. http://dx.doi.org/10.1007/s11431-019-9535-3.

Intergovernmental Panel on Climate Change, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment. Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Jarihani, A.A., Callow, J.N., Johansen, K., Gouweleeuw, B., 2013. Evaluation of multiple satellite altimetry data for studying inland water bodies and river floods. J. Hydrol. 505, 78–90. http://dx.doi.org/10.1016/j.jhydrol.2013.09.010.

Jiang, L., Nielsen, K., Dinardo, S., Andersen, O.B., Bauer-Gottwein, P., 2020. Evaluation of Sentinel-3 SRAL SAR altimetry over Chinese rivers. Remote Sens. Environ. 237, 111546. http://dx.doi.org/10.1016/j.rse.2019.111546.

Kittel, C.M.M., Jiang, L., Tøttrup, C., Bauer-Gottwein, P., 2021. Sentinel-3 radar altimetry for river monitoring - A catchment-scale evaluation of satellite water surface elevation from Sentinel-3A and Sentinel-3B. Hydrol. Earth Syst. Sci. 25, 333–357. http://dx.doi.org/10.5194/hess-25-333-2021.

Koblinsky, C.J., Clarke, R.T., Brenner, A.C., Frey, H., 1993. Measurement of river level variations with satellite altimetry. Water Resour. Res. 29, 1839–1848. http://dx.doi.org/10.1029/93WR00542.

Kosek, W., 2001. Long-term and short period global sea level changes from TOPEX/Poseidon altimetry. Artif. Satell. 36 (3), 71–84.

Kreft, A., Parzonka, W., 2007. Problematyka modernizacji budowli regulacyjnych na granicznym odcinku dolnej Odry (Issues related to the modernisation of river regulation structures on the border section of the lower Odra river). Infrastruktura i Ekologia Terenów Wiejskich 4 (2), 123–134.

Le Gac, S., Boy, F., Blumstein, D., Lasson, L., Picot, N., 2021. Benefits of the Open-Loop Tracking Command (OLTC): Extending conventional nadir altimetry to inland waters monitoring. Adv. Space Res. 68, 843–852. http://dx.doi.org/10.1016/j.asr.2019.10.031.

Leuliette, E.W., Nerem, R.S., Mitchum, G.T., 2004. Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. Mar. Geod. 27, 79–94. http://dx.doi.org/10.1080/01490410490465193.

Ljung, G.M., Box, G.E.P., 1978. On a measure of lack of fit in time series models. Biometrika 65, 297–303. http://dx.doi.org/10.2307/2335207.

Maillard, P., Bercher, N., Calmant, S., 2015. New processing approaches on the retrieval of water levels in Envisat and SARAL radar altimetry over rivers: A case study of the São Francisco river. Brazil. Remote Sens. Environ. 156, 226–241. http://dx.doi.org/10.1016/j.rse.2014.09.027.

Meybeck, M., Friedrich, G., Thomas, R., Chapman, D., 1996. Chapter 6 - rivers. In: Chapman, Deborah (Ed.), Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring. UNESCO/WHO/UNEP, Taylor and Francis, London–New York, pp. 247–248.

Nerem, R.S., Chambers, D.P., Choe, C., Mitchum, G.T., 2010. Estimating mean sea level change from the TOPEX and Jason altimeter missions. Mar. Geod. 33, 435–446. http://dx.doi.org/10.1080/01490419.2010.491031.

Nerem, R.S., Schrama, E.J., Koblinsky, C.J., Beckley, B.D., 1994. A preliminary evaluation of ocean topography from the TOPEX/POSEIDON mission. J. Geophys. Res. 99 (24565), http://dx.doi.org/10.1029/94JC01431.

Niedzielski, T., Kosek, W., 2009. Forecasting sea level anomalies from TOPEX/Poseidon and Jason-1 satellite altimetry. J. Geod. 83, 469–476. http://dx.doi.org/10.1007/s00190-008-0254-5.

Nielsen, K., Stenseng, L., Andersen, O., Knudsen, P., 2017. The performance and potentials of the CryoSat-2 SAR and SARIn modes for lake level estimation. Water 9 (374), http://dx.doi.org/10.3390/w9060374.

O'Loughlin, F., Trigg, M.A., Schumann, G.J.P., Bates, P.D., 2013. Hydraulic characterization of the middle reach of the Congo river. Water Resour. Res. 49, 5059–5070. http://dx.doi.org/10.1002/wrcr.20398.

Quartly, G.D., Nencioli, F., Raynal, M., Bonnefond, P., Garcia, P.N., Garcia-Mondéjar, A., de la Cruz, A.F., Cretaux, J.F., Taburet, N., Frery, M.L., Cancet, M., Muir, A., Brockley, D., Mcmillan, M., Abdalla, S., Fleury, S., Cadier, E., Gao, Q., Escorihuela, M.J., Roca, M., Bergé-Nguyen, M., Laurain, O., Bruniquel, J., Femenias, P., Lucas, B., 2020. The roles of the S3MPC: Monitoring, validation and evolution of Sentinel-3 altimetry observations. Remote Sens. 12, http://dx.doi.org/10.3390/rs12111763.

Royston, P., 1995. Remark AS R94: A remark on Algorithm AS 181: The W test for normality. Appl. Stat. 44 (547), http://dx.doi.org/10.2307/2986146.

Santos da Silva, J., Calmant, S., Seyler, F., Rotunno Filho, O.C., Cochonneau, G., Mansur, W.J., 2010. Water levels in the Amazon basin derived from the ERS 2 and ENVISAT radar altimetry missions. Remote Sens. Environ. 114, 2160–2181. http://dx.doi.org/10.1016/j.rse.2010.04.020.

Schneider, R., Tarpanelli, A., Nielsen, K., Madsen, H., Bauer-Gottwein, P., 2018. Evaluation of multi-mode CryoSat-2 altimetry data over the Po river against in situ data and a hydrodynamic model. Adv. Water Resour. 112, 17–26. http://dx.doi.org/10.1016/j.advwatres.2017.11.027.

Schwatke, C., Dettmering, D., Bosch, W., Seitz, F., 2015. DAHITI – An innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. Hydrol. Earth Syst. Sci. 19 (10), 4345–4364. http://dx.doi.org/10.5194/hess-19-4345-2015.

Sulistioadi, Y.B., Tseng, K.H., Shum, C.K., Hidayat, H., Sumaryono, M., Suhardiman, A., Setiawan, F., Sunarso, S., 2015. Satellite radar altimetry for monitoring small rivers and lakes in Indonesia. Hydrol. Earth Syst. Sci. 19, 341–359. http://dx.doi.org/10.5194/hess-19-341-2015.

The Climate Change Initiative Coastal Sea Level Team, 2020. Coastal sea level anomalies and associated trends from Jason satellite altimetry over 2002–2018. Sci. Data 7, 357. http://dx.doi.org/10.1038/s41597-020-00694-w.

Tourian, M.J., Tarpanelli, A., Elmi, O., Qin, T., Brocca, L., Moramarco, T., Sneeuw, N., 2016. Spatiotemporal densification of river water level time series by multimission satellite altimetry. Water Resour. Res. 52, 1140–1159. http://dx.doi.org/10.1002/2015WR017654.

Villadsen, H., Andersen, O.B., Stenseng, L., Nielsen, K., Knudsen, P., 2015. CryoSat-2 altimetry for river level monitoring - Evaluation in the Ganges-Brahmaputra river basin. Remote Sens. Environ. 168, 80–89. http://dx.doi.org/10.1016/j.rse.2015.05.025.

Wrzesiński, D., 2017. Typologia reżimu odpływu rzek w Polsce w podejściu nadzorowanym i nienadzorowanym (Typology of the river regime in Poland in the supervised and unsupervised approach). Badania Fizjograficzne Nad Polską Zachodnią 68, 253–264. http://dx.doi.org/10.14746/bfg.2017.8.19.

Xiang, J., Li, H., Zhao, J., Cai, X., Li, P., 2021. Inland water level measurement from spaceborne laser altimetry: Validation and comparison of three missions over the Great Lakes and lower Mississippi river. J. Hydrol. 597, http://dx.doi.org/10.1016/j.jhydrol.2021.126312.

Zaidi, A.Z., Vignudelli, S., Khero, Z., Ghauri, B.M.K., Muzaffer, R., Naeem, B., Panhwar, V., Zafar, S., ul Haque, S., 2021. Indus river water level monitoring using satellite radar altimetry. Adv. Space Res. 68, 641–651. http://dx.doi.org/10.1016/j.asr.2020.03.044.