



## Research papers

# Exploring the potential of Sentinel-3 and Sentinel-6 SAR altimetry measurements for discharge estimation: Case studies from the Rhine and Po rivers

E. Zakharova<sup>a,b,\*</sup>, L. Fenoglio-Marc<sup>c,d</sup>, K. Nielsen<sup>e</sup>, P. Thorne<sup>a</sup>, M. Restano<sup>f</sup>, J. Benveniste<sup>g</sup>

<sup>a</sup> ICARUS Climate Research Centre, Maynooth University, Maynooth, Co. Kildare, Ireland

<sup>b</sup> EOLA, Toulouse France

<sup>c</sup> Bonn University, Bonn, Germany

<sup>d</sup> Chalmers University of Technology, Göteborg, Sweden

<sup>e</sup> National Space Institute, Technical University of Denmark, Kgs. Lyngby, Denmark

<sup>f</sup> SERCO/ESRIN, Largo Galileo Galilei, 1, Frascati (Roma) I-00044, Italy

<sup>g</sup> Formerly, European Space Agency - Directorate of Earth Observation Programmes, Largo Galileo Galilei, 1, 00044 Frascati, Italy



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## ABSTRACT

River discharge is an Essential Climate Variable important for many climate and socio-economical applications. The relative paucity of *in situ* river discharge data makes the development of satellite-based methods for discharge estimation attractive. The main approaches rely on a combination of satellite altimetry, providing the measurements of river water level, and optical satellite sensors, allowing the estimation of river width, and on conversion of these parameters to the discharge. The present paper explores the potential of Sentinel-3A & B and Sentinel-6 SAR altimetry missions for discharge estimation using the Rhine and Po Rivers as a case study. We explore the effect of different approaches of discharge estimation and altimetry data treatment on the accuracy of the obtained discharge. We show that enhanced high-resolution 80 Hz processing of SAR altimetry signal as well as rigorous satellite data selection and filtering protocols, are both beneficial for the accuracy of the water level and the resulting discharge retrieval. Depending on the water level product, an accuracy of 4–16%, expressed as Normalised Root Mean Square Error (NRMSE), is achieved with an empirical rating curve, constructed between each water level dataset and simultaneous *in situ* discharge measurements. With a physical method, based on the Manning equation, an accuracy of 11–26% NRMSE is attained. The latter improves to 8–22% after introducing the variable channel roughness term into the Manning equation. We also demonstrate that for the medium-size Rhine and Po Rivers the errors of 10% (NRMSE) can be potentially achieved with a semi-empirical approach of the discharge estimation based on simplified physical laws (called here Bjerklie equation) after regional adjustment of both conductance and exponential parameters of the equation. We conclude that if similar accuracy will be attained in future for other medium-sized European rivers, such high-quality SAR altimetry-based ECV discharge products would be able to detect the 4–15% of discharge change, which is projected to 2080 in Europe in the intermediate IPCC Shared Socio-economic Pathway scenario SSP2-4.5.

## 1. Introduction

For over 20 years satellite altimetry has been used for discharge (Q) estimation of big rivers with annual flows higher than 100 km<sup>3</sup>: the Ob, Ganges-Brahmaputra, Congo, Amazon River and its tributaries, Yangtze, Lena, Niger, Zambezi, Mississippi, and Yukon among others (Kouraev et al., 2004; Birkinshaw et al., 2014; Papa et al., 2012; Paris et al., 2016;

Sichangi et al., 2016; Tourian et al., 2013 and 2017; Michailovsky et al., 2012; Bjerklie et al., 2018; Scherer et al., 2020 and many others). Conversely, rivers of medium size (20–100 km<sup>3</sup>/yr) were rarely included in such studies because of insufficient accuracy of the water level retrievals demonstrated by conventional low resolution altimetric instruments (onboard TOPEX/Poseidon, ENVISAT, Jason-2 and -3) and/or insufficient temporal sampling frequency of altimetry satellites, which

\* Corresponding author at: ICARUS Climate Research Centre, Maynooth University, Maynooth, Co. Kildare, Ireland.  
E-mail address: [zavocado@gmail.com](mailto:zavocado@gmail.com) (E. Zakharova).

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are unable to represent rapidly changing water regimes more typical in such basins. As a solution a method of densification of altimetry-based water level (WL) observations has been developed for the big Niger River (Tourian et al., 2016). The idea has fostered further development of new approaches with the objective to merge the water level observations from different altimetry missions and estimate discharge (Scherer et al., 2020; Nielsen et al., 2022). A first attempt to estimate the discharge from altimetry water level measurements for rivers of medium size was made for the Zambezi River tributaries (Michailovsky et al., 2012). In the following years, the challenge of retrieving discharge from satellite altimetry observations over medium size rivers was largely demonstrated on the example of the Po River (annual flow of  $\sim 48 \text{ km}^3$ ). For this river the altimetry WL observations from different historical missions were intensively used in isolation (Tourian et al., 2016), coupled with optically/NIR-based Q retrieving approach (Tarpanelli et al., 2019), or in combination with a hydrodynamic model (Domeneghetti et al., 2014). The capability of the conventional low resolution satellite altimetry to provide discharge retrievals for medium size rivers in the Arctic was investigated in Zakharova et al. (2020) on the example of the Pur River with annual flow of  $\sim 24 \text{ km}^3$ .

Radar altimetry allows for retrieving water level time series at the intersection of the satellite ground track and river channel, called a virtual station (VS) henceforth. A conversion of water level to discharge is made via inferred statistical relations with simultaneous measurements of discharge at the nearest gauge station (see for example Kouraev et al., 2004; Zakharova et al., 2006; Papa et al., 2012) or with discharge simulated by a model at the location of the VS (Paris et al., 2016; Schröder et al., 2019). Discharge estimated from tributaries' input (Zakharova et al., 2019) or historical discharge observations combined with a stochastic approach (Tourian et al., 2013; Belloni et al., 2021) can also be used. In parallel to the satellite altimetry-based methods, the use of river width derived from optical satellite instruments as a predictor for the discharge has been intensively investigated (e.g. Smith et al., 2008; Pavelsky et al., 2014) and the combination of the altimetric water level and satellite derived river width demonstrated a good potential for improved accuracy of discharge retrievals (Sichangi et al., 2016). The combination of altimetric and optical instruments allows for increasing of sampling frequency in the temporal domain and, thus, for better characterisation of river flow during hydrological events of synoptic-scale (Tarpanelli et al., 2013b). This is especially relevant for medium and small size rivers, whose watershed runoff regulation capacity is lower than that of big rivers and therefore for which the flood response to precipitation is more rapid and of shorter overall duration. Altimetry is now widely coupled with hydrological and hydrodynamic models (Kittel et al., 2021; Domeneghetti et al., 2014). The satellite WL can be used for validation of WL simulation (Biancamaria et al., 2009) or can be assimilated (Finsen et al., 2014). Model parameters can be calibrated with the help of altimetry water level (Domeneghetti et al., 2014; Huang et al., 2020). Two other methods of discharge estimation based on hydraulic flow laws have been coupled with altimetry measurements: the method invented by Manning (Manning, 1891) and its simplification made by Dingman and Sharma (1997) and developed further in Bjerklie et al. (2003,2005). Both these methods involve simultaneous observations/retrievals of river width from optical or SAR images (Scherer et al., 2020; Zakharova et al., 2020).

In the framework of the preparation for the Surface Water and Ocean Topography (SWOT) mission launch, several approaches to discharge estimation from altimetry, altimetry-optic instrument combination and hydraulic equations involving satellite-derived water level, width and slope were developed (Durand et al., 2016; Durand et al., 2021). The Manning approach is in the foundation of three of the selected SWOT algorithms (Frasson et al., 2021). Many recent studies based on synthetic SWOT-like measurements aimed to evaluate the likely ability and performance of these approaches for different rivers throughout the world using synthetic or satellite derived datasets as an input for these methods (Durand et al., 2016; Oubanas et al., 2018). Since the accuracy of

satellite-derived discharge products is a major challenge for many applications, understanding the role of various factors it affecting, in particular the contribution of various sources of errors (observations error; flow law approximation error; flow law parameter error (Yoon et al., 2016; Durand et al., 2021), when using the three main algorithms for computing the discharge, remains a concern.

A review of the studies published before 2019 assessed the accuracy of the published altimetry-based daily discharge retrievals and demonstrated that the root mean square error normalised on mean annual discharge or on seasonal Q magnitude (NRMSE) was: 5–10% for the largest rivers with annual flow  $>1000 \text{ km}^3$ ; 10–25% for large rivers with annual flow of 200–1000  $\text{km}^3$ ; while it was only 30–40% for medium size rivers with annual flow of 25–100  $\text{km}^3$  (Zakharova et al., 2020). The accuracy reported in several more recent studies published since this review was well within these described ranges: 11–28% for the Mississippi R. ( $\sim 530 \text{ km}^3/\text{y}$ ) (Scherer et al., 2020); 19% for the Niger R. ( $\sim 175 \text{ km}^3/\text{y}$ ) (Lamine et al., 2021). The SWOT discharge product global uncertainties are expected to be within 15% (Durand et al., 2021).

Two recent major developments in altimetry techniques suggest that the performance for medium sized rivers could be improved. Firstly, there has been a significant improvement in accuracy of water level retrievals from altimeter missions operating in Open-Loop Tracking Command (OLTC) (Biancamaria et al., 2018). Secondly, there has been a marked improvement in the ability of the SAR altimeter to catch the narrow river targets (Deidda et al., 2021; Halicki and Niedzielski, 2021). Taken in combination these recent innovations provide a good potential opportunity for improving the accuracy of discharge estimation for rivers of medium size. In early studies based on TOPEX/Poseidon, ERS-2 or ENVISAT missions' measurements, the accuracy of satellite water level retrievals was mainly in the range of 40–80 cm (Tarpanelli et al., 2013a; Michailovsky et al., 2012). Thanks to new instrument technologies and satellite signal processing, the accuracy of altimetry-derived water level time series (WLTS) has significantly improved and may now reach 3–20 cm even over small and medium size rivers (Biancamaria et al., 2018; Kittel et al., 2021a; Deidda et al., 2021; Halicki and Niedzielski, 2021). Using a combination of WL measurements from advanced (Sentinel-3) and conventional (ENVISAT and Jason) altimetry missions and hydraulic flow laws (in Manning formulation), the accuracy of daily altimetry-derived discharge of 11% was achieved at several locations along the Mississippi River which represents a large river (Scherer et al., 2020). Whether such an accuracy is achievable for medium size rivers with prior-to-SWOT altimetric instruments and simple discharge algorithms has been unclear until recently. Motivated by this lack of assessment a very recent study (Scherer et al., 2024) targeted medium and small rivers and has demonstrated a high variability in accuracy of the discharge retrievals (6–70%) based on Manning equation applied to ungauged river reaches.

In the near future, a significant improvement in accuracy of discharge estimation for medium and small size rivers may potentially be achieved with the SWOT wide swath altimetry measurements, as expected, due to improved spatial resolution and accuracy in the height measurements, as well as due to simultaneous estimation of additional parameters of discharge equations (water slope and width). However, the SWOT, being a research mission, has nominal life for limited period, while the Sentinel-3 and -6 are the operational long-living satellite projects.

In this context, the present paper contributes to assessment of the potential of Sentinel-3A (S3A), -3B (S3B) and Sentinel-6 (S6) SAR altimetry missions, hypothesised to provide water level time series of higher accuracy, for discharge estimation. Three simple methods widely used for discharge estimation with the altimetry measurements in gauged reaches are assessed: (1) empirical Q-H rating curve (RC), (2) Manning formulation based on physical laws and (3) semi-empirical method developed by Bjerklie et al. (2003,2005) and originated from

simplification and modification of the Manning equation. The preference is given to these simple methods considering their easy reproducibility. The detailed study is conducted over the middle reach of the European Rhine River with annual flow  $\sim 50 \text{ km}^3$ , located in Germany. To verify the consistency of obtained results a second middle-size, the river Po, is added. On the Rhine River three segments with different channel geomorphology and satellite – channel configuration are selected, so that the performance of the SAR-altimetry instruments and the discharge estimation methods in different morphological configuration can be evaluated.

We hypothesize that the accuracy of the water level time series is important for accurate discharge estimation. Numerous approaches for data selection, filtering and merging into WLTS have been developed and several portals maintained by different institutions provide on-line access to global altimetry WLTS (Theia-Hydroweb, DAHITI, HydroSat). We use several water level products of different maturity, elaborated using processing chains of different complexity, to assess the effect of their quality on the discharge estimates. The WLTS built by the authors for this study from official Copernicus ESA L2 LAN Sentinel-3 and Sentinel-6 EUMETSAT products derived by applying SAMOSA2 (Ocean) and OCOG retracers (respectively S3 COPOcean, S3 COPOCOG, S6 Ocean, S6 OCOG) represent in our study the datasets of initial (institutional) processing maturity. WLTS based on the SAMOSA+ retracker applied over SAR waveforms at 80 Hz posting rate, issued from the enhanced processing of Sentinel-3 products through the Earth Console ESA Altimetry Virtual Lab SARvatore for Sentinel-3 service (S3 AVLSAM+) (Dinardo et al., 2018), represent along with ESA HYDRO-COASTAL project WLTS (S3 HyCo) the datasets of advanced research maturity. As it is declared by the producing agency, the official Theia-Hydroweb water level dataset (S3 Theia), have a highest operational maturity and, consequently, expected to be of the best accuracy.

The current study aims to assess the capacity of three simple discharge algorithms, applied traditionally with the altimetry measurements, to provide accurate discharge retrievals over the Rhine and Po Rivers, characterised by distinct channel morphology. Several specific questions are addressed. (1) What is the value of advanced methods of altimetry data processing and retracker selection for the discharge accuracy? (2) How sensitive different methods of discharge estimation are to the accuracy of variables retrieved from the SAR altimetry measurements (water level, water depth and water slope)? (3) Is there an effect of the virtual station configuration on the accuracy of the water level and discharge retrievals? (4) Is the achieved accuracy sufficient for future climate monitoring assessments?

The paper is structured as follows. Section 2 introduces the studied rivers and summarises the data used. In Section 3 we provide a description of the methods of discharge estimation applied in this study. Section 4 presents the results of the discharge estimation and validation from Sentinel-3 and Sentinel-6 SAR altimetry for the Rhine and Po Rivers using the three discharge estimation approaches at four locations. In Section 5 we discuss and demonstrate the relative importance of different factors affecting the accuracy of the applied methods of discharge estimation. In the Conclusions we provide an outlook on the results and on the potential of upcoming altimetry-based discharge products for climate monitoring or operational use based upon our and other recently published results.

## 2. Region of study and data

### 2.1. Region of study

The Rhine River is one of the biggest rivers in the Europe with the length of about 1230 km and annual water flow of  $72 \text{ km}^3/\text{yr}$  at the mouth (Ionita et al., 2012). It originates in the Alps and drains into the North Sea. The Rhine is a transboundary river, six countries (Switzerland, Liechtenstein, Austria, Germany and the Netherlands) share its flow. Several big tributaries (Mosel, Main, Aare, Saar and

Neckar) flow into the Rhine. The Rhine River morphology was extensively modified during 19th and 20th centuries (Julich and Lindner, 2006). In-stream river engineering (canalisation, construction of groynes etc) resulted in modification of the flooding regime. However, in recent decades many projects aimed at restoration of flood plain areas for storage of water and reducing the peaks of high floods were implemented in both the upper and lower reaches of the Rhine River (Havinga and Smits, 2000).

The middle reach of the Rhine River located between  $49.5^\circ\text{N}$  and  $50.3^\circ\text{N}$  is selected as the main test site (Fig. 1). Within this reach three hydrometric stations located near Worms, Mainz and Kaub cities provide water level observations and convert them to river discharge. One big tributary: the Main River ( $5.9 \text{ km}^3/\text{yr}$ ), and one small tributary: the Nahe River ( $0.9 \text{ km}^3/\text{yr}$ ), add to the flow of the Rhine within this reach. This studied Rhine River section is not homogeneous from the point of view of valley and channel geomorphology. The north of the selected section (Fig. 1c) represents a narrow gorge-like reach surrounded by hills of 200–600 m height. The river width varies from 250 m to 450 m. However, in large sections of this stretch the channel width is significantly reduced by groynes to support navigation during low flow periods (Julich and Lindner, 2006). In the middle part of the studied section near the Mainz gauging station, the surrounding area is urbanised. The flood plain is reduced and heavily developed. Two islands of 3 km length and 270–410 m width divide the channel into two branches. The river width downstream of the islands is 450–500 m (Fig. 1d). To the south in the area of the Worms gauging station (GS) (Fig. 1e), the Rhine has a large flood plain with cut meanders seen as oxbow lakes and secondary channels. The river width here is 250–350 m.

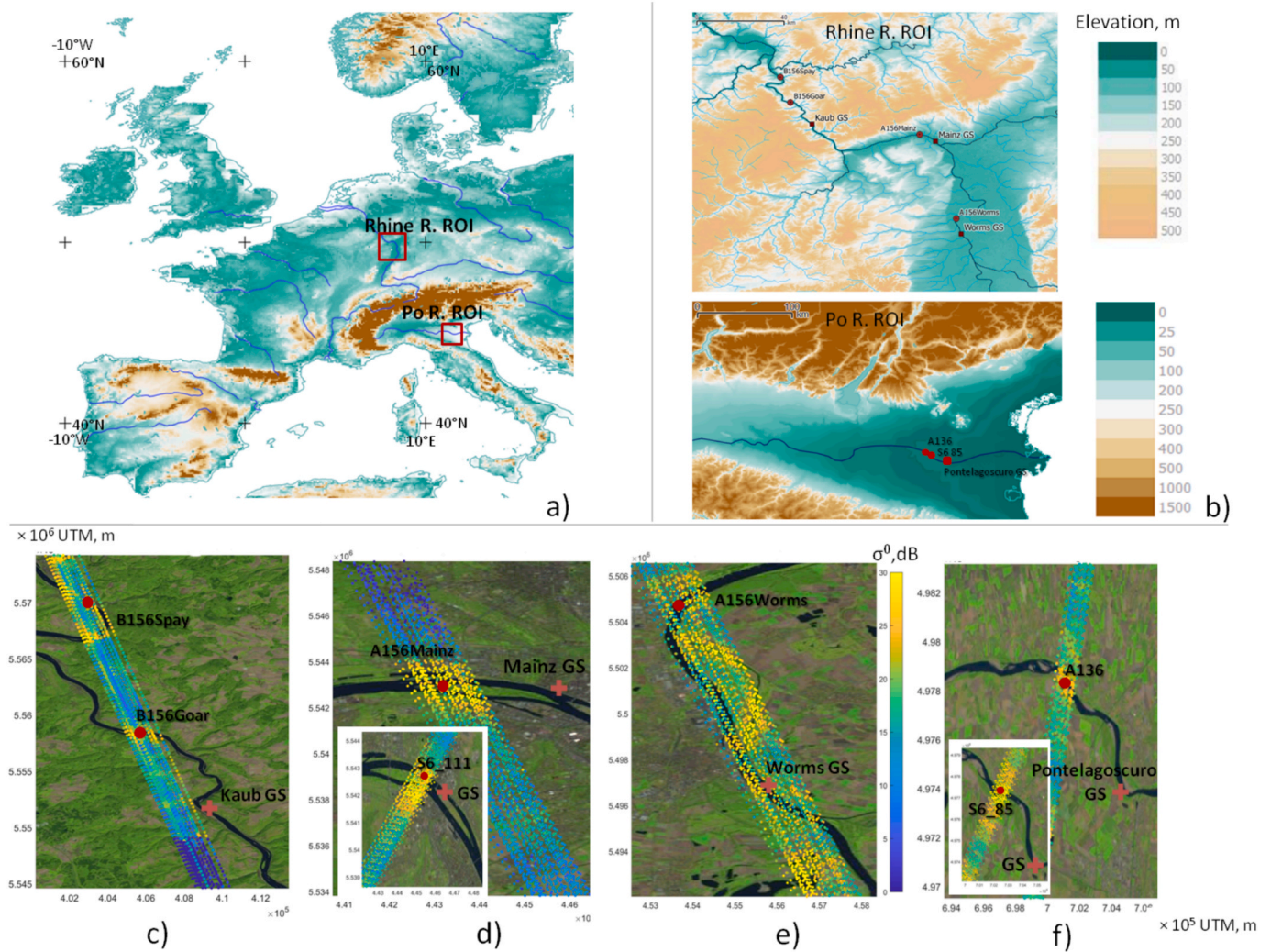
The Po River is the biggest river in Italy. It also originates in the Alps and flows to Adriatic Sea for 650 km. The annual flow is of  $48 \text{ km}^3$ . The studied section is located in the lower reaches near Pontelagoscuro (Fig. 1b and 1f). The banks are low and occupied by arable lands and urbanisation. The floodplain is strongly modified and not topographically pronounced. The channel is composed of sand and experiences a significant erosion characterised by moving sandbars and islands. The channel width varies from 300 to 500 m.

In all studied reaches the main channels are systematically fixed and narrowed, navigation channels are dredged, sandbanks are removed.

### 2.2. Altimetry data

For discharge estimation, the modern SAR altimetry missions Sentinel-3 and Sentinel-6 are used. Sentinel-3A and -3B satellites are launched in 2016 and 2018, respectively. They fly along a sun-synchronous orbit, and have a 27-day repeat cycle. Sentinel-6 operates at sun-synchronous orbit with 10-day repeat cycle since 2021. The missions are equipped with the dual-frequency Ku/C-band SRAL (Sentinel-3) and Poseidon-4 (Sentinel-6) Synthetic Aperture Radar Altimeters. The instruments operate in open-loop mode (OLTC), i.e., the range window position is based on a *priori* knowledge of terrain altitude derived from a Digital Elevation Model (DEM) stored onboard. This mode allows to correctly position the radar receiving window in complex topographic regions (such as near the Kaub gauging station) giving higher accuracy of the water level retrievals (Biancamaria et al., 2018).

As we hypothesize that the accuracy of the altimetry water level measurements may have constrained scientific interest in altimetry application for the discharge estimation in middle-size rivers to date, five Sentinel-3 datasets obtained from combination of different algorithms at different processing levels: Level 1B (waveforms processing), Level 2 (range estimation by retracers from the waveforms and atmospheric corrections provided) and Level 3 (data selection over rivers and WLTS construction approaches) are included in the study. This diversity of the WLTS datasets allows the assessment of the effect of the accuracy of the water level estimation on the discharge retrievals discussed in the Section 5. The differences in the sources of the data and their processing up to the water level time series are listed in Table 1. The University of



**Fig. 1.** Location of the regions of interest (ROI) (a), gauging (GS) and virtual (VS) stations (b) and satellite ground track/channel configurations at the test sites Kaub (c), Mainz (d), Worms (e) and Pontelagoscuro (f). The Sentinel-6 configurations are in the inserts. The dots colour represents the backscatter values helping to trace the water bodies (backscatter > 25 dB).

**Table 1**

Main characteristics of water level datasets used in this study.

WLTS dataset	L1B and L2 source	Retracker used	Spatial resolution	WLTS generation approach	Maturity level
S3A/S3B COPOcean	Copernicus LAN	Samosa2	~300 m	VS, simple filtering	Initial
S3A/S3B COPOCOG	Copernicus LAN	OCOG	~300 m	VS, simple filtering	Initial
S3A/S3B AVLSAM+	AVL SARvatore	Samosa+	~50 m	VS, simple filtering	Research
S3A/S3B Theia	Copernicus LAN	OCOG	~300 m	VS, advanced filtering	Operational
S3A/S3B HyCo	HYDROCOASTAL, ESA	MWaPP	~300 m	state-space model	Research
S6 Ocean	EUMETSAT	Samosa2	~300 m	VS, simple filtering	Initial
S6 OCOG	EUMETSAT	OCOG	~300 m	VS, simple filtering	Initial

Bonn WLTS (COPOcean and COPOCOG) are based on official operational Copernicus L1B and L2\_LAN data and University of Bonn WLTS generation algorithm (Fenoglio et al., 2021) and differ solely by retracker used (SAMOSA2 and OCOG). The AVLSAM+ dataset is produced using enhanced in spatial resolution Level 1B and Level 2 SAR-Vatore processor output combined with modified SAMOSA+ retracker (Dinardo et al., 2018). This processing may be important for narrow rivers, where the SAR altimetry footprint (~300 m) is comparable with the river width. The HYDROCOASTAL WLTS (HyCo) is generated based on the state-of-the-art research processing schemes for L1B, L2 and L3

products as well as on improved atmospheric corrections (see for the detailed description the Algorithm Theoretical Basis Document, 2022) (<https://www.satoc.eu/projects/hydrocoastal>). For this dataset the processing algorithms most adapted for river targets and developed during last decade are combined in one processing chain. The Theia – Hydroweb Sentinel-3 operational dataset is based on official Copernicus L1B and L2\_LAN product and distinguished from the COPOCOG WLTS by advanced data filtering and editing of the final water level time series (data downloaded from the <https://hydroweb.theia-land.fr/> portal). Additionally, two WLTS datasets, constructed from the measurements of

another SAR altimetry mission Sentinel-6 (launched in 2021) and elaborated based on official EUMETSAT L1B and L2 products are added. All water level time series are constructed at intersections of satellite ground tracks and river channels named after mission track number and nearest city (e.g. A156Mainz, A156Worms, B156Goar and B156Spay, S6\_111Mainz, A136Ponte, S6\_85Ponte see Fig. 1b). As mentioned, the WLTS generation methods differ between various algorithms arising from altimetry measurement selection and by time series filtering and editing approaches. The complexity of these algorithms ranges from simple initial processing (Fenoglio et al., 2021) to more advanced based on state-space model (HyCo WLTS) (Nielsen et al., 2022) and to operational level in the Theia dataset (Hydroweb Product User Manual, 2021). The processing and filtering of time series affect not only the individual values of the water level, but also the detection and removal of potential outliers. River discharge time series for the *in situ* record and various altimetry based water level estimates at the three locations on the Rhine R. are shown in Fig. 2.

Additionally, CryoSat-2 altimetry measurements are used along with Sentinel-3 measurements for the construction of the Rhine along-river mean water profile. This mean profile is used, then, for verification of assumptions made in discharge estimation methods. CryoSat-2, launched in April 2010, has a geodetic orbit with a repeat cycle of 369 days. This orbit configuration enhances the spatial coverage of

altimetric measurements along the river reaches. The satellite carries the Synthetic Aperture Radar/Interferometric Radar Altimeter (SIRAL) and depending on the region the instrument operates in Low Resolution (LRM), SAR or interferometric SAR modes (Wingham et al., 2006). In the middle reaches of the Rhine River CryoSat-2 operated in LR mode. Here, we applied the CryoSat-2 data from the ESA baseline C and D Level 1B data product.

### 2.3. *In situ* data

Water discharge and water level data at four gauging stations located within the studied reaches were used for calibration and validation of altimetry-derived levels and discharge. The German Bundesanstalt für Gewässerkunde (BfG) Hydrological Service measures the water level ( $H_{insitu}$ ) with a high 15 min frequency. The water level is converted to the discharge ( $Q_{insitu}$ ) by BfG Survey and provided with the same 15-minute frequency. The relation  $H_{insitu} - Q_{insitu}$  is unique, considering no backwater or floodplain regulation effects exist within these control sections. In this study we utilised the records that are available for the period 2016–2020.

For the Po River the water level is measured with the same frequency by Italian Agenzia Regionale per la Prevenzione, l'Ambiente e l'Energia (ARPAE). Its daily values are converted to the daily discharges. The

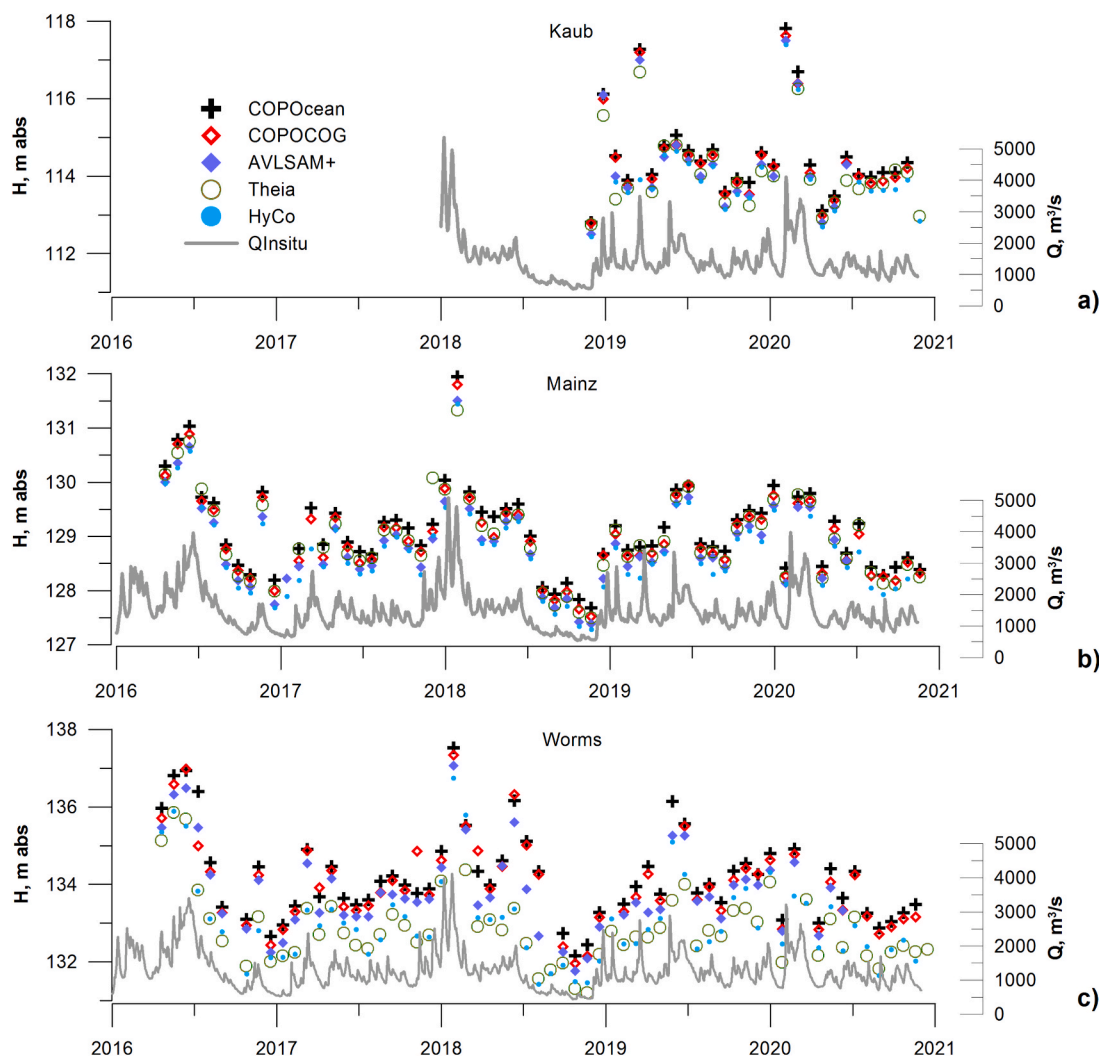


Fig. 2. Water level time series at three virtual stations selected for study and discharge at the corresponding gauging stations. The gauging station series is continuous whereas altimetry based estimates are available periodically at the times of satellite overpass. The VS B156Goar is selected for characterisation of the water regime in the Kaub GS river section.

relation  $WL_{insitu} - Q_{insitu}$  is unique, however, for certain years some adjustments are applied at its extremities. Both parameters (WL and Q) were taken for the period 2021–2023 from the Yearbooks published by ARPAE.

### 2.4. Auxiliary data

#### 2.4.1. Optical/SAR images

For evaluation of the variability of the river width and inundation areas during different phases of the water regime, Landsat-8 RGB optical images and Sentinel-1A and -1B microwave images were used. Landsat-8 images were downloaded from USGS EarthExplorer portal for the dates close ( $\pm 3$  day) to Sentinel-3 river overflights. The Sentinel-1 images originated from ESA Copernicus Sentinel HUB. Landsat-8 images have  $30 \times 30$  m resolution, while the pixel resolution of the Sentinel-1 IW-mode product used here is  $11 \times 13$  m.

## 3. Methods

### 3.1. Along-river water mean elevation profile

To create a mean elevation profile, used for verification of reliability of the water slope estimates derived from WLTS at the locations of the virtual stations, we apply satellite altimetry data from Sentinel-3A/3B and CryoSat-2 missions. The observations were projected to the centerline of the river to create a 1D-space dataset. We set up a simple model to describe the mean elevation as a function of distance  $x$  along the centerline as follows:

$$H_{profile}(x_i) = \alpha(x_i) + \epsilon_i \tag{1}$$

Here  $\alpha$  is a cubic spline defined to be increasing in the upstream direction,  $\epsilon$  is the observation noise term, which here is assumed to follow a skewed mixture distribution of Gaussian and Cauchy. This is to suppress the effect of erroneous observations and to fit the lowest level along the profile.

### 3.2. Discharge estimation

Three methods of discharge estimation are tested in this study: the rating curve (RC) method, the methods based on the Manning equation (Ma) and the methods based on the simplified Manning equation suggested by Bjerklie et al. (2003,2005). Fig. 3 presents the workflow for input data, parameters estimation and methods.

#### 3.2.1. Rating curve (RC)

The RC method is a classical empirical method used in national hydrological Services to convert the water level observation into discharge (Rantz, 1982). The rating curves (H-Q relations) are specific for each gauging station and are constructed from instrumental measurements of the discharge. For high accuracy they need to be constantly verified and updated as the relationship can change due to erosion, vegetation changes, engineering or even climate change.

In this study for each VS, we construct the RCs between VS altimetric water level and daily *in situ* discharge at the nearest gauging station. The RCs are fitted by following equation:

$$Q = \alpha \cdot (H_{alti} - z)^\beta \tag{2}$$

where  $\alpha$  and  $\beta$  are calibrated parameters which depend mostly on river channel morphology,  $z$  is datum at zero-discharge (m),  $Q$  is the discharge and  $H_{alti}$  is the altimetric water level. A monotony of the relationship is verified visually, and the outlying points (if any exist) are verified relative to specific hydrological phases or events (flood rise/fall, low flow period).

#### 3.2.2. Manning method

Manning-based discharge estimation relies on physical laws of open channel flow. This equation underlies the flow routing procedure in many hydrodynamic models (Kittel et al., 2021). The governing equations can be potentially applied to ungauged river reaches (Garambois et al., 2020). However, in practice, several parameters (e.g., roughness coefficient) are calibrated against *in situ* observations of discharge (Biancamaria et al., 2009, Domeneghetti et al., 2014; Huang et al.,

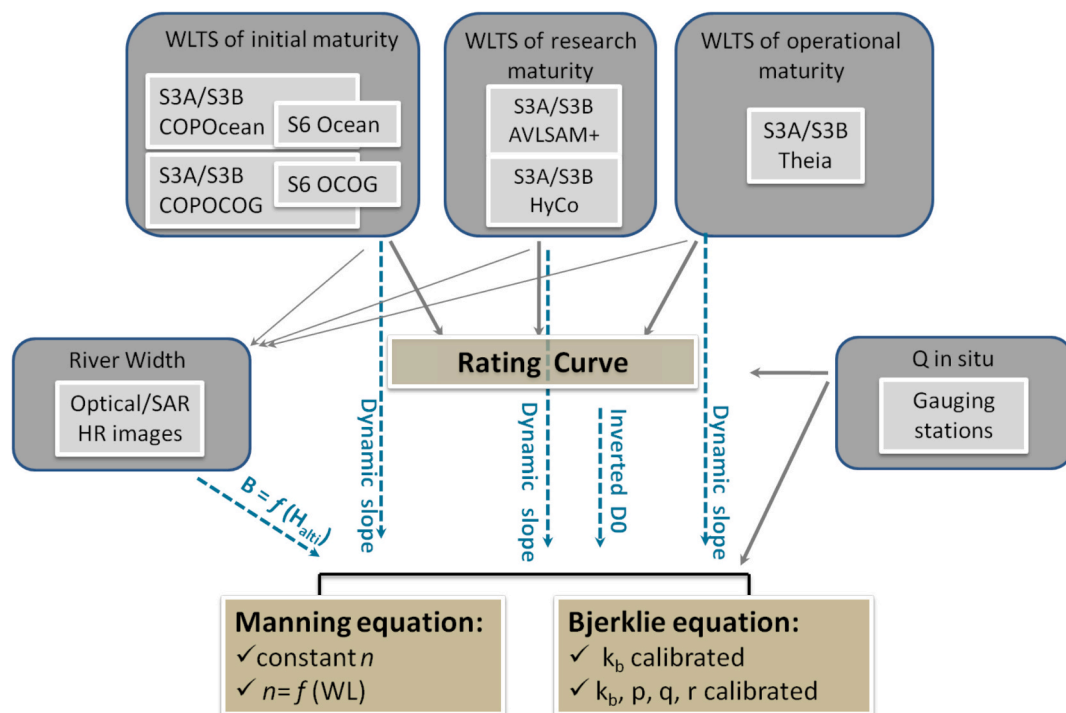


Fig. 3. Workflow of used approaches presenting input variables (grey), derived parameters (blue) and methods (khaki). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2020). The river discharge is estimated as follows:

$$Q = B \cdot (D_0 + \Delta H) \cdot 1/n \cdot R^{2/3} \cdot S^{1/2} \quad (3)$$

where  $B$  – channel width (m),  $D_0$  – reference depth at minimum water level (m);  $\Delta H$  – water height correction at each measurement (m);  $n$  – Manning's roughness coefficient,  $S$  – water surface slope (m/m),  $R$  – hydraulic radius (m) which can be approximated by Eq. (4).

$$R = B \cdot (D_0 + \Delta H) / P, \quad (4)$$

where  $P$  – wetted perimeter (m). This formulation considers a rectangular cross-section. For larger rivers with  $B > 20 \times D_0$  an approximation of the channel by rectangular shape does not introduce high errors in estimation of  $Q$ . For this condition, the wetted perimeter can be replaced by the river top width and the hydraulic radius will represent a mean section depth ( $D_0 + \Delta H$ ).

The channel width can vary with the water level and a relation  $B - H_{\text{alti}}$  are established using the river width, retrieved from optical/SAR images acquired when the altimetry missions overflow the VS. In Zakharova et al. (2020) a fitting of the  $B - H_{\text{alti}}$  relations by power function provided good results.

$$B = a \cdot H_{\text{alti}}^b \quad (5)$$

Nevertheless, to assess if the current formulation is suitable for smaller rivers, we fitted  $B - H_{\text{alti}}$  relations with polynomial functions of first and second degree as well. The river width is evaluated for each studied reach near the four VSs. For this the most linear reach of at least 2 km length is selected within  $\pm 3$  km around mean nominal satellite track position and manually digitised. The mean width is evaluated by dividing the area of the rectangle by its length. Effects of the lower resolution of the Landsat-8 comparing to SAR images is verified for several dates, where simultaneous Landsat-8 and Sentinel-1 images are available. The differences between retrieved mean river width does not exceed 30 m (i.e., the resolution of one pixel of Landsat-8).

One of the important parameters in the Manning equation is the reference mean water depth ( $D_0$ ), which has to be corrected on variable water level ( $\Delta H$ ) at each measurement. The precise mean water depth can only be determined by *in situ* profiling. However, this parameter can be evaluated using topographic/navigation maps (Zakharova et al., 2020), inverted from the Bjerklie equation and historical discharge measurements (Andreadis et al., 2013) or from rating curves using real or modelled discharge (Paris et al., 2016). A set of approaches was recently developed to calibrate/invert the bathymetry parameter by the SWOT Science Team (Durand et al., 2021). In the current study, for each VS, we evaluate the  $D_0$  by the inversion of the rating curves from the Equation 2, where  $z$  represents the datum at zero-discharge. From this value and the minimum altimetric water level value one can obtain an estimation of  $D_0$ .

A roughness coefficient  $n$  characterises the resistance of the channel to the flows. Values are tabulated and a detailed procedure for determining Manning's  $n$  value for natural channels and floodplains is described in Arcement (1989). The most important factors affecting channel  $n$  are the type and size of the bed/bank materials (sand, gravel, cobbles, rock, etc.) and the shape of the channel (depth, irregularities, obstructions, vegetation, meandering, etc.). In this study, the roughness coefficient is calibrated for each VS against *in situ* observations of the discharge.

It is considered that reach-averaged water slopes (averaged at several kilometres), such as those expected from the SWOT mission, will allow the reduction of slope measurement noise (Rodriguez et al., 2020). In this context, we decide to use the water slope calculated for each date of the satellite overflight as a difference between water level at two VSs created by the same satellite track, i.e., between VSs B156Goar and B156Spay and between A156Mainz and A156Worms. For the Po River, for slope calculation the WLTS at virtual station located in 40 km upstream from the reference VS and overflown by S3A several days later is

used.

### 3.2.3. Bjerklie equation method

A simplification of the Manning equation was proposed by Bjerklie et al (2003, 2005) assuming that a wide range of flow conditions can be modelled using (1) a universal value for the conductance coefficient (term inverse to the roughness) and (2) modified values of exponents in the Manning equation. The Bjerklie equation is written as follows:

$$Q = k_b \cdot B^p \cdot D^q \cdot S^r \quad (6)$$

where  $k_b$  approximates the conductance term,  $B$  is the river width,  $D$  is depth ( $D_0 + \Delta H$ ),  $S$  is slope and  $p$ ,  $q$ ,  $r$  are coefficients. In Bjerklie et al. (2003) several sets of  $k_b/p/q/r$  coefficients were tested over US and New Zealand rivers and the set 7.22/1.02/1.74/0.35 was recognised as the best of all providing <20% of errors in discharge estimations. In Bjerklie et al. (2005) five other sets were tested over a larger number of rivers and the set 7.14/1.67/0.33 outperformed all others. Several studies, which coupled satellite altimetry with the Bjerklie equation, used the set provided in the early work (Birkinshaw et al., 2014; Tarpanelli et al., 2013a). After testing different parameter sets published in Bjerklie et al (2003, 2005), we find that all combinations reproduce well the seasonal variability of the discharge but provide systematically high systematic bias for all three locations on the Rhine River. We test two additional sets of parameters: (1) with adjusted conductance term only and (2) with simultaneously calibrated conductance and exponent coefficients. During the calibration, all terms are bounded within specific limits to preserve their physical meaning.

### 3.3. Calibration/validation approaches

For Sentinel-3 the chosen study period 2016–2020 covers a representative set of river regimes and includes both high flood (January 2018) and low summer flow (August 2018) conditions. For Sentinel-6 period both flow regimes were observed on the Rhine River, while on the Po R. 2021–2023 years were characterised by water deficit. For evaluation of performance of discharge estimation, the satellite time series are split into two sub-periods. One sub-period is used for calibration of coefficients of equations (2), (3) and (6 with adjusted conductance term), while the second sub-period is used for validation (Table 2). The time series are split in such a way that the calibration sub-period also includes both high (medium for S6 and Po River) and low flow hydrological phases.

To obtain a robust estimation of the 4 coefficients (conductance and three exponents) in the equation (6) for the Rhine River the calibration is run using  $B$ ,  $D$ ,  $S$  and  $Q_{\text{insitu}}$  variables merged into one dataset from 3 virtual stations. The conductance and exponents are estimated as medians from 200 runs, each of which contains 75% of randomly selected data from the merged set. Validation scores for  $Q_{\text{alti}}$  retrieved at the location of each gauging station are obtained using the entire period of observations and a set of Bjerklie parameters (common for all VSs). For the Po River the calibration is run on a reduced number of observations from one pair of VSs.

To evaluate the performance of each method, Normalised Root Mean Square Error (NRMSE), Pearson correlation coefficient ( $R$ ) and Nash-Sutcliffe (NS) scores are estimated. The NRMSE is obtained after dividing the RMSE value by the average *in situ* discharge calculated using the dates of satellite over-flights for the corresponding (calibration or validation) period.

## 4. Results

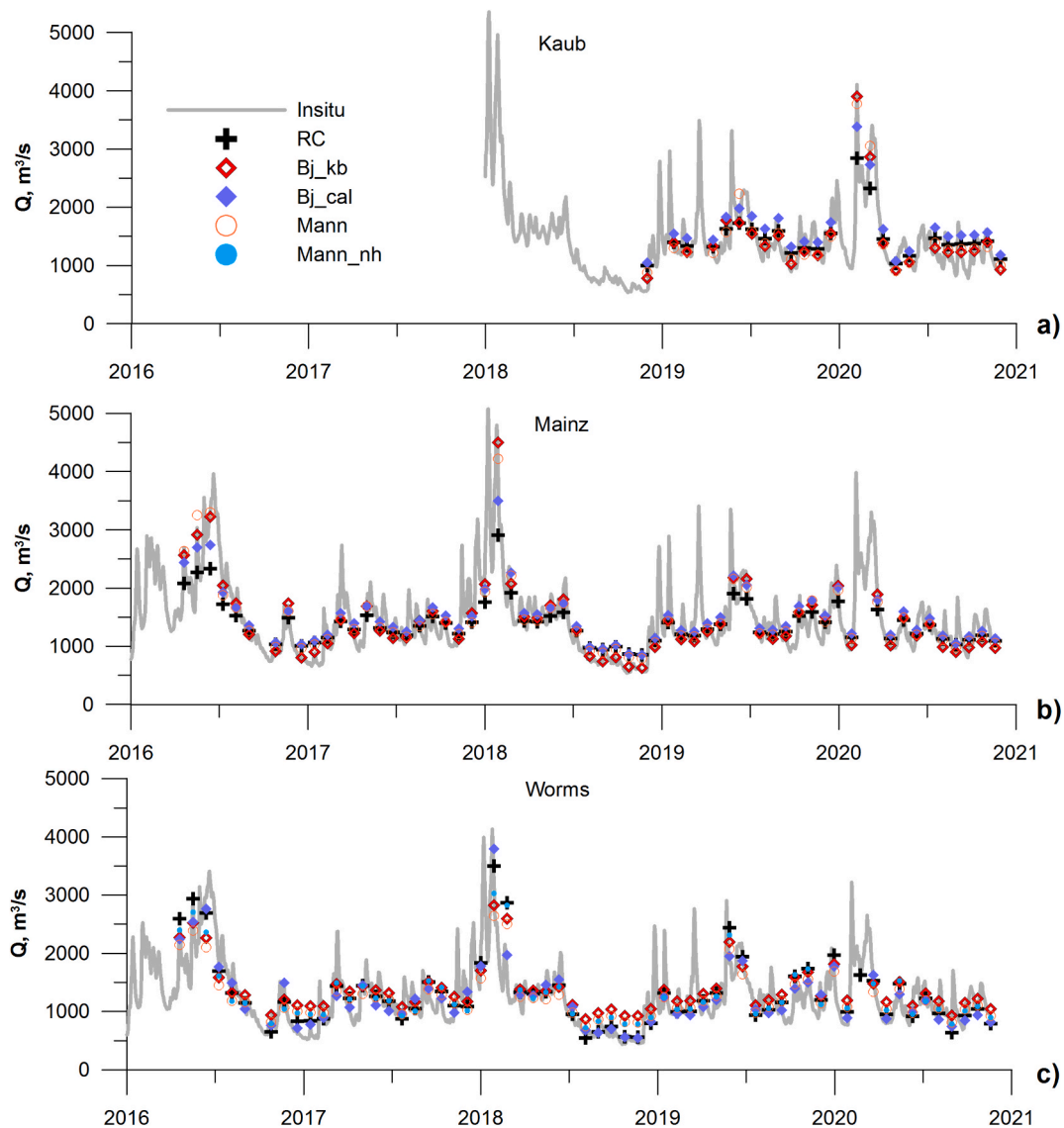
An example of temporal variability of discharge estimated by three different methods from altimetry water level time series constructed using HYDROCOASTAL (research maturity) and Theia (operational maturity) WLTS is presented in Figs. 4 and 5. The validation scores for

**Table 2**

Calibration and validating periods and number of available satellite observations for each period. The beginning of the period corresponds to the satellite launch time, while the end is limited by availability of the *in situ* data.

GS Station/Sentinel-3 track	Available period	Training period	Validation period*	Maximum number of observations cal/val*
Worms GS/S3A 156	04.2016–12.2020	04.2016–02.2018	03.2018–12.2020	25/34
Mainz GS/S3A 156/S6 111	04.2016–12.2020	04.2016–02.2018	03.2018–12.2020	25/28*
	01.2021–12.2023	06.2022–07.2023	01.2021–05.2022	25/31*
Kaub GS/ S3B 156	11.2018–09.2020	09.2019–11.2020	11.2018–08.2019	39/37
				13/14
Pontelagoscuro GS/S3A 136/S6 85	04.2016–12.2020	04.2016–12.2018	01.2019–12.2020	9/6*
	01.2021–12.2023	01.2021–02.2022	02.2022–12.2023	17/19
				32/30

\* AVLSAM + time series are available only until July 2020 due to missing of updated atmospheric corrections at the moment of processing order.



**Fig. 4.** Altimetric discharge retrieved from HYDROCOASTAL WLTS with RC, Bjerklie equation with  $k_b$  sole (Bj\_kb) and full calibration (Bj\_cal) as well as with Manning equations with invariant (Mann) and time-variable friction (Mann\_nh) for Kaub (a), Mainz (b) and Worms (c) GS locations.

all WLTS and methods are provided in Table 3 and summarised in the Fig. 6.

#### 4.1. Discharge retrieved with rating curve method

Discharge retrievals based on the rating curve method demonstrat

that using SAR altimetry-derived water level, a high accuracy of 7–8% (NRMSE) of  $Q$  estimates can be achieved over the Rhine River. Our results also show, unsurprisingly, that the accuracy critically varies depending on the accuracy of WL time series used (see Table 3) and can be as good as 4% in the best case or exceed 100% in the worst case. We found that the RC method is highly sensitive to the outliers in the WL

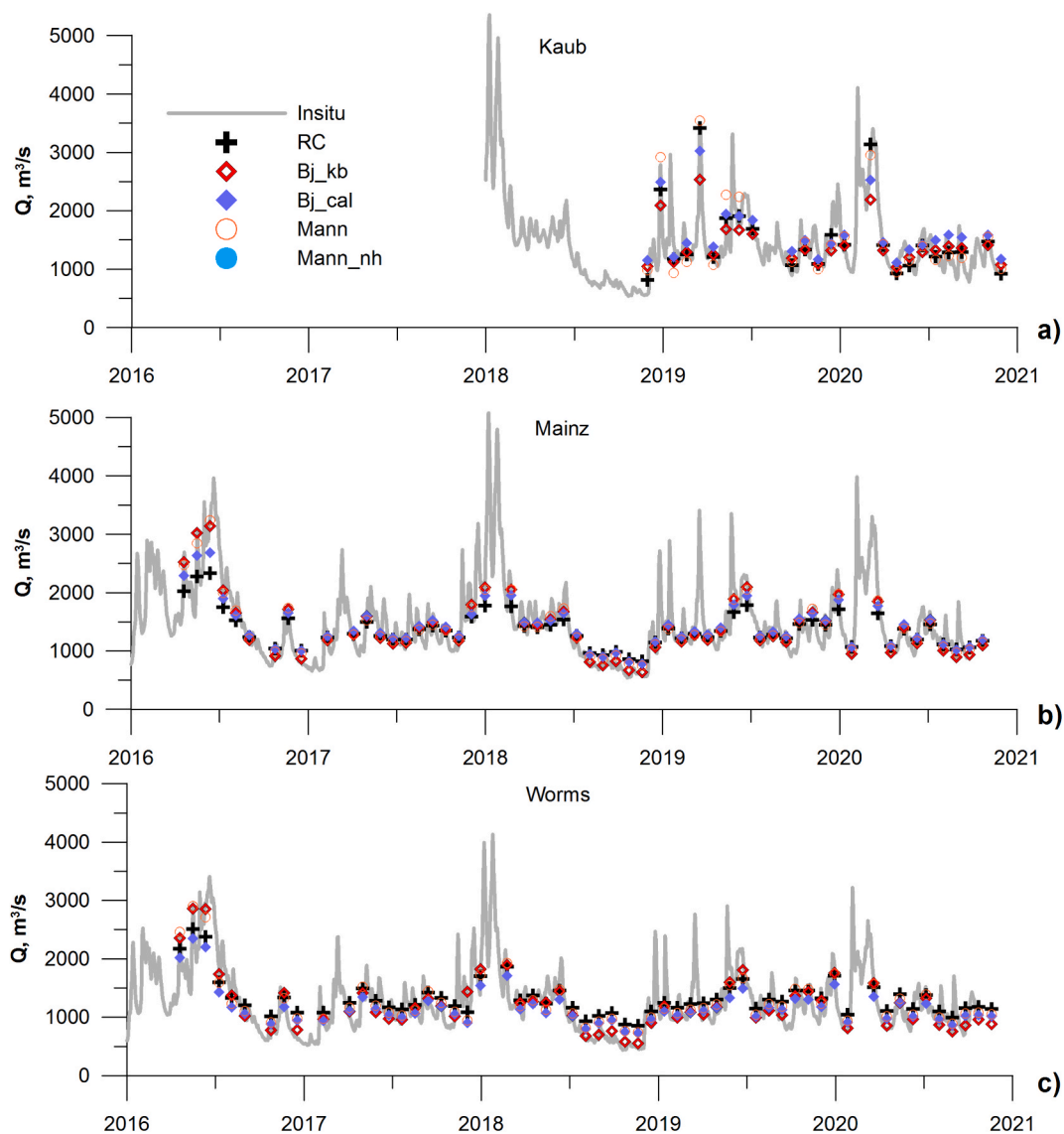


Fig. 5. Altimetric discharge retrieved from Theia WLTS with RC, Bjerklie equation with kb and full calibration as well as with Manning equations with invariant  $n$  (Mann) and with time-variable  $n$  (Mann\_nh) for Kaub (a), Mainz (b) and Worms (c) GS locations.

time series, especially if the time series are short. For gauged river reaches historical records of floods and droughts constitute the basis for outliers identification. However, for ungauged rivers an automated detection and filtering of outliers for short altimetry WLTS is restricted by our insufficient *a priori* knowledge about the typical WL seasonal magnitude and extremes. In some cases, the erroneous water level estimates could be manually detected based on expert knowledge of the water regime of a given river. For the calibration period, outliers can be easily detected from the  $Q-H_{\text{alti}}$  scatter plot. For the validation period, their identification is non-trivial and requires additional ancillary information and assumptions about, for example, flow generating conditions, precipitation amount or drought indexes. For the COPOCOG WLTS for the Kaub reach, the simple removal of several extreme outliers, using a cross-checking with WLTS retrieved with other retracers or with WLTS at the nearest VS of the same Sentinel-3B track, results in the decrease of errors in  $Q$  estimates from 126% to 16%.

#### 4.2. Discharge retrieved with Bjerklie method

The accuracy of discharge retrieved with the Bjerklie equation keeps in range of 13–24% (NRMSE) expected by the developers of the method

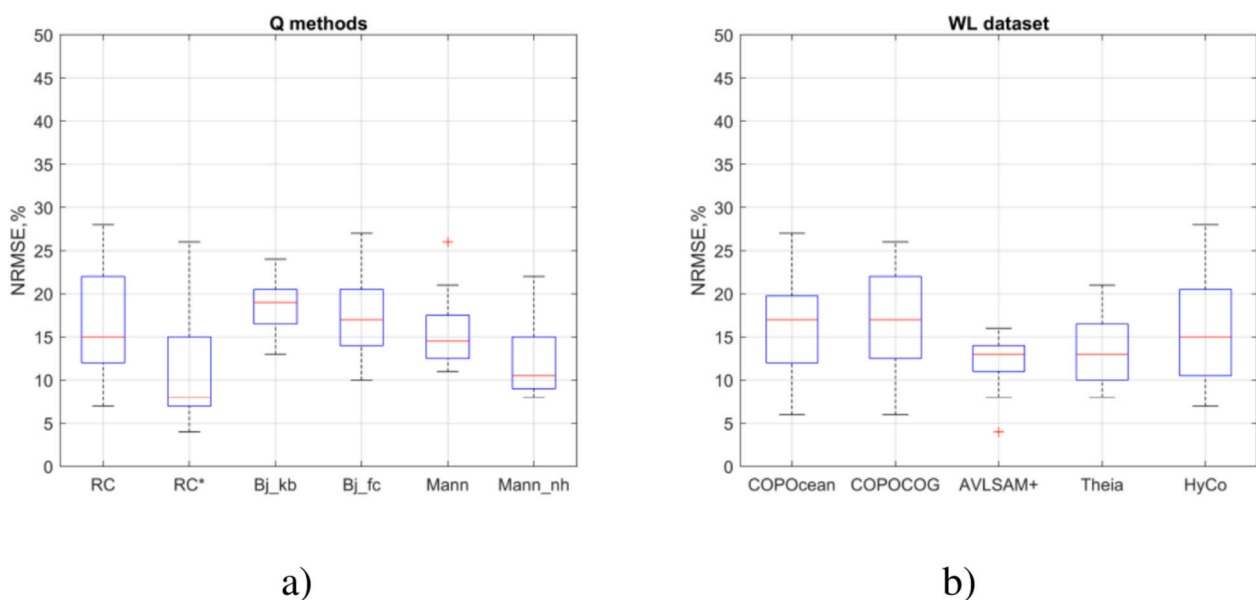
(Bjerklie et al., 2003). However, to attain this accuracy the conductance term  $k_b$  should be re-calibrated. The simultaneous calibration of the conductance and exponent coefficients further improves the accuracy of discharge estimation by 2–6% for half of the WL datasets used in this study. For 3 cases (WL time series retrieved with the ocean SAMOSA2 retracker) additional calibration of exponents results in accuracy degradation by 7–8%. Considering that an adequate calibration of 4 parameters of the equation (6) requires a sufficiently long dataset (at least >50–60 observations) covering an adequately broad range of variability of  $B$ ,  $D$  and especially  $S$  variables, the adjustment of the conductance term only, either for local (at VS location) or regional (several nearest VS-GS pairs) scales can be sufficient for many hydrological tasks targeting the precise evaluation of discharge at average flow conditions. However, the method may be deficient for evaluation of high and low discharges. For the Rhine and Po Rivers, high discharges retrieved with Bjerklie equation are underestimated, while low discharges are overestimated. This issue is resolved after the calibration of the full set of parameters in the Bjerklie equation. The obtained  $p$  (at width term) and  $q$  (at depth term) exponents of the equation (6) have slightly increased in comparison to the initial set (with a median value equal to 1.43 and 2.52, respectively). The  $r$  exponent (a slope term) has

**Table 3**

Scores for discharge retrievals calculated for validation period for the Rating Curve and Manning methods and over entire study period for Bjerklie method.

GS Station	WL time series	RC		Bjerklie eq.2003		Manning eq.		WL, uRMSE, m
		NRMSE,%	NS	NRMSE,%	NS	NRMSE,%	NS	
Worms	S3A	19	0.62	1927	0.82 <sup>kb</sup>	19	0.78	0.44
	COPOcean	7	0.94*		0.64 <sup>fc</sup>	22	0.71 <sup>nh</sup>	0.27
	S3A	22	0.86	22	0.77 <sup>kb</sup>	13	0.89	0.49
	COPOCOG	6	0.96*	20	0.82 <sup>fc</sup>	15	0.85 <sup>nh</sup>	0.34
	S3A	13	0.83	1516	0.90 <sup>kb</sup>	13	0.90	0.30
	AVLSAM+	8	0.93*		0.88 <sup>fc</sup>	13	0.90 <sup>nh</sup>	0.20
	S3A	8	0.95	2014	0.76 <sup>kb</sup>	21	0.66	0.22
	Theia	–	–		0.89 <sup>fc</sup>	16	0.77 <sup>nh</sup>	
	S3A	15	0.74	24	0.72 <sup>kb</sup>	26	0.46	0.42
	HyCo	–	–	21	0.79 <sup>fc</sup>	18	0.62 <sup>nh</sup>	
Mainz	S3A	19	0.62	17	0.83 <sup>kb</sup>	14	0.88	0.14
	COPOcean	6	0.96*	24	0.94 <sup>fc</sup>	9	0.95 <sup>nh</sup>	0.12
	S3A	22	0.46	19	0.82 <sup>kb</sup>	16	0.81	0.15
	COPOCOG	6	0.96*	17	0.90 <sup>fc</sup>	11	0.91 <sup>nh</sup>	0.14
	S3A	13	0.83	13	0.83 <sup>kb</sup>	15	0.85	0.12
	AVLSAM+	4	0.98*	14	0.97 <sup>fc</sup>	9	0.95 <sup>nh</sup>	0.11
	S3A	8	0.95	1711	0.82 <sup>kb</sup>	12	0.88	0.19
	Theia	–	–		0.95 <sup>fc</sup>	9	0.93 <sup>nh</sup>	
	S3A	7	0.93	21	0.78 <sup>kb</sup>	14	0.84	0.16
	HyCo	–	–	18	0.97 <sup>fc</sup>	11	0.89 <sup>nh</sup>	
	S6 Ocean	64	<0	–	–	–	–	0.62
		15	0.91*	–	–	–	–	0.44
	S6 OCOG	106	<0	–	–	–	–	1.18
	26	0.72*	–	–	–	–	0.69	
Kaub with B156 Goar	S3B	12	0.93	17	0.69 <sup>kb</sup>	12	0.92	0.20
	COPOcean	–	–	24	0.94 <sup>fc</sup>	8	0.97 <sup>nh</sup>	
	S3B	126	<0	20	0.73 <sup>s, kb</sup>	15	0.88*	2.24
	COPOCOG	16	0.90*	18	0.73 <sup>s, fc</sup>	10	0.95 <sup>s, nh</sup>	0.65
	S3B	14	0.90	13	0.77 <sup>kb</sup>	11	0.82	0.30
	AVLSAM+	–	–	14	0.96 <sup>fc</sup>	8	0.85 <sup>nh</sup>	
	S3B	1211	0.91	16	0.56 <sup>kb</sup>	19	0.85	0.32
	Theia	–	0.93*	11	0.84 <sup>fc</sup>	15	0.93 <sup>nh</sup>	0.25
	S3B	28	0.66	20	0.53 <sup>s, kb</sup>	15	0.40*	0.76
	HyCo	7	0.97*	17	0.96 <sup>s, fc</sup>	8	0.84 <sup>s, nh</sup>	0.19
Ponte-lagoscuro	S3A	17	0.62	–	–	–	–	0.35
	Theia	15	0.84*	–	–	–	–	0.23
	S3A	19	0.93	22	0.85 <sup>kb</sup>	11	0.94	0.48
	HyCo	15	0.97*	10	0.96 <sup>fc</sup>	10	0.95 <sup>nh</sup>	0.30
	S6 Ocean	13	0.82	–	–	–	–	0.30
	S6 OCOG	11	0.89	–	–	–	–	0.28

\* Without outliers, <sup>kb</sup> with calibrated conductance, <sup>fc</sup> with calibrated exponents and conductance, <sup>nh</sup> with variable friction term.



**Fig. 6.** Summary of accuracy of the discharge retrievals expressed as NRMSE regarding the methods and their modifications (a), the WL time series generation routines and algorithms (b). See Table 3 footnotes for methods' symbols. S3A, S3B and S6 altimetry data are used.

decreased to 0.36 (median value) approaching the value of 0.33 in the modified Manning/Chezy equations (Bjerklie et al., 2005). The conductance term has significantly decreased to 0.01–0.39. By using fully calibrated sets of coefficients, only slightly better discharge accuracy is obtained in comparison to the case of sole conductance calibration. However, the distribution of residuals after full calibration become closer to the expected Gaussian if remaining errors are truly random.

#### 4.3. Discharge retrieved with Manning equation

The accuracy of the discharge estimates based on the Manning approach is comparable with that derived with the rating curves. The median NRMSE value for all datasets is 14%. A correct guess of the reference water depth ( $D_0$ ) at each studied river reach allows to constrain well the equation (3) and to avoid the equifinality between parameters  $D_0$  and  $n$  (Pianosi et al., 2016). The values  $D_0$  inverted for each VS from the  $H_{\text{alti}} - Q_{\text{insitu}}$  rating curves from five WLTS converge also well. In the equations (3), (4) and (6) the  $D_0$  averages from five inversions are used for estimation of the mean channel depth ( $D_0 + \Delta H$ ) at each satellite overflight. The channel resistance for a given location (Manning  $n$  coefficient) may vary over time. In general, for bankfull flow conditions, the channel resistance decreases with increasing depth (Larnier et al., 2021). By dividing the calibration water level sub-sets into five quantiles, we specifically estimate  $n = f(H_{\text{alti}})$  for each river reach and WL dataset. The use of the time-variable friction improves the discharge estimates based on the Manning approach by up to 8% for the majority of the WLTS. For several time series, the adjustment of the Manning  $n$  coefficient does not result in improved validation scores. In general, the application of the time variable  $n$  leads to a significant decrease in the difference between estimated and *in situ* discharge at high flow conditions.

## 5. Discussion

The performance of three simple algorithms of discharge estimation from the highest quality processed current altimetry measurements over the medium-size Rhine and Po Rivers is investigated. Four river reaches of different morphology are selected to assess the effect of the geomorphology on the  $Q$  accuracy. We suppose that the availability of high-quality altimetry water level time series is crucial for the accuracy of the obtained discharges for rivers with available discharge ground observations, i.e. gauged reaches. To assess this, five water level datasets with varying level and complexity of data processing are used. These WL datasets demonstrate variable accuracy in different morphological conditions. Consequently, the accuracy of the resulting discharge retrievals varies with method and location used. Nevertheless, the Rating Curve method demonstrates the highest accuracy (8% as the median NRMSE) after removing the WL outliers observed in certain WLTS at all locations. It is followed by the Manning method when considering roughness  $n$  term varies along with the water level (10.5% as the median NRMSE). The simplified Bjerklie method with fully locally calibrated parameters also provides good results with 17% as the median NRMSE. The best accuracy achieved with each method is respectively 4%, 8% and 10%. It is worth noting that such a high accuracy is achieved thanks to availability of the *in situ* discharge data in the vicinity of the VSs allowing an optimal calibration of parameters in discharge algorithms. We conclude from our study that an improved accuracy of the SAR- altimetry input water level time series ( $0.25 \pm 0.15$  m in this study) is one of the major factors responsible for such excellent results observed for medium-size Rhine and Po Rivers. In Scherer et al. (2024) a comparable accuracy was also obtained for certain medium and small rivers applying the Manning-based method with DAHITI WLTS generated with an advanced methods of altimetry data processing (Schwatke et al., 2015).

We find that the RC method is very sensitive to the accuracy of the WLTS. Independently of the choice of WLTS used, a detection of WL

outliers seems to be crucial for the overall accuracy of the final discharge time series. An amelioration of median accuracy of WLTS by 0.14 m due to outliers filtering improves the median accuracy of the RC-derived discharge time series by 13%, while an extreme outliers removal in two cases results in amelioration of WLTS/discharge accuracy respectively by 0.49 m/80% and by 1.59 m/110% (see Table 3). The use of AVLSAM + WLTS (issued from enhanced spatial resolution datasets) is beneficial for narrow reaches (Kaub VS) and in cases of parallel orientation of the satellite track to the river channel (case of Worms VS). The enhanced 50 m along-track resolution of altimetry measurements and L1B-L2 processing chains better adapted for inland waters allowed up to 9% of accuracy gain in discharge estimation. The median accuracy of the Theia-based discharge TS (13.3%) was only slightly below the median accuracy of the AVLSAM+-based  $Q$  time series (13%). Theia WLTS constructed from the same official ESA L2 LAN Sentinel-3 product, using the same retracker and geophysical corrections as for the COPOCOG WLTS, benefits from the well-developed and validated methods of altimetry data selection and filtering. This results in WLTS median accuracy amelioration by 0.26 m comparing to the COPOCOG dataset. It makes this WLTS attractive for using in discharge-related tasks allowing up to 14% gain (114% in utmost case) in discharge accuracy. However, the strict filtering applied to the Theia WLTS may result in rejection of extreme measurements as it is observed at VS B156Goar during the flood event in 2020 (Fig. 2a). An interesting finding of the current study is that the WL and consequently the discharge time series generated with Ocean retracker from official Copernicus LAN L2 products are often comparable or slightly better (in complex VS configuration) than that of the OCOG retracker. Until recently, the latter has been considered to be more suitable for the inland waters in studies based on official L2 altimetry products of conventional (Jasons, ENVISAT) or SAR (Sentinel-3) altimetry missions.

For two methods based on physical laws (Manning and Bjerklie), the relation between discharge and WL accuracy is not observed (Fig. 7). This implies that for these methods other factors, for example, observation errors of width and slope, flow law approximation error and flow law parameter error may play a more important role.

In this study, uncertainties in river width variable originate (i) from the evaluation of river width from images for selected dates of Sentinel-3 overflights and (ii) from the approximation of  $B-H_{\text{alti}}$  relationships. For selected optical/SAR scenes, the procedure of width evaluation is repeated 3 times. The difference (interpreted as an error) does not exceed 50 m (15%) with a median of 35 m (close to the Landsat pixel resolution). The use of  $B-H_{\text{alti}}$  relation instead of simultaneous width and WL satellite observations was examined for the big Ob River (Zakharova et al., 2020). In this study we demonstrate that in case of the smaller Rhine and Po Rivers this approach is also effective to preserve original altimetry-based observational frequency of output discharge time series, independently on complexity of the VS morphology in our region of study. The development of an accurate functional  $B-H_{\text{alti}}$  relation from satellite observations for the studied Rhine and Po Rivers is challenging

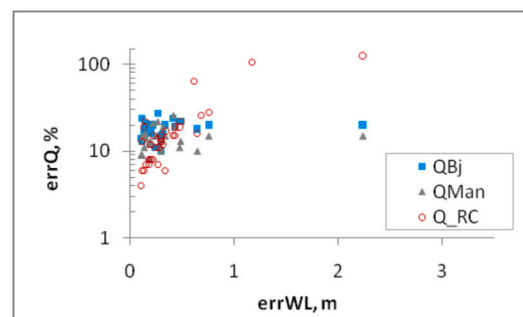


Fig. 7. Relation between discharge errors (NRMSE in %) and errors in WLTS for three methods.

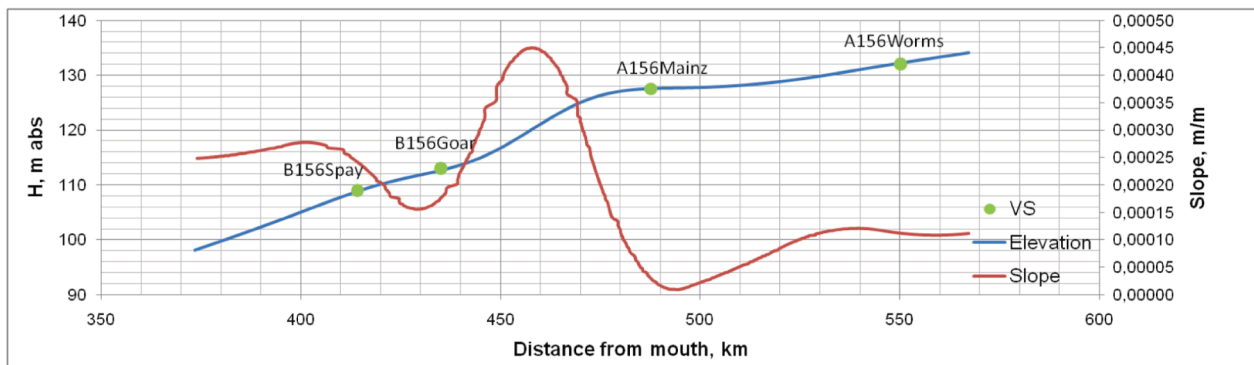
because of (i) a limited number of joint overflights of optical/SAR and Sentinel-3A and 3B missions and (ii) a low seasonal variability of the river width at all studied VSs. However, the fitting accuracy expressed as RMSE does not exceed 9 m for all datasets and VSs. This result also argues for the broader application of this approach for locations with weak control of width parameter on the discharge.

Water slope variable used in Bjerklie and Manning equations in our study is derived from satellite water level measurements for each date of discharge estimation. It implies that WLTS accuracy should be sufficient for its estimation. Any erroneous retrievals of the water level have a critical effect on the water slope estimates resulting in unrealistic  $S$  values and, consequently, unrealistic discharge estimates. For VSs originated from the same satellite ground track, a verification of the slope between VS could be a second order control on the WL quality and on non-evident outliers. We expected that the slope may be functionally related with the water level. However, the relation between  $S$  and  $H_{\text{alt}}$  is observed for AVLSAM + WLTS at A156Mainz VS only (Fig. 8b). For other datasets and locations, slope values increase only during very high WL (Fig. 7c). As the slope is estimated from WL difference at VSs of the satellite ground tracks located within 19–55 km, it represents only a rough approximation of the real water slope at the location of the VSs. For assessment of reliability, the slope derived from different WLTS is compared with the high resolution multi-mission profile (Fig. 8a). Our median slope at the location of VS B156Goar and A156Worms (18 cm/km) agrees well with those obtained from the multi-mission profile. A more substantial difference is observed for the A156Mainz VS: 8 cm/km vs 3 cm/km derived from CryoSat-2/Sentinel-3. Nevertheless, our lowest  $S$  estimates (5 cm/km) approach that extracted from the mean river profile (see Fig. 8). The effect of observation errors of water level, water slope (from altimetry) and water width (from optical/SAR satellites) on accuracy of the discharge estimations is assessed for the

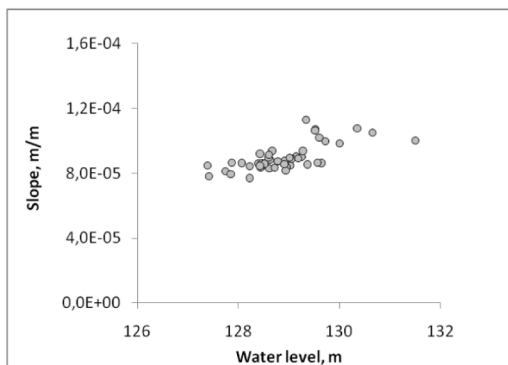
Manning method using a sensitivity test.

### 5.1. Sensitivity tests

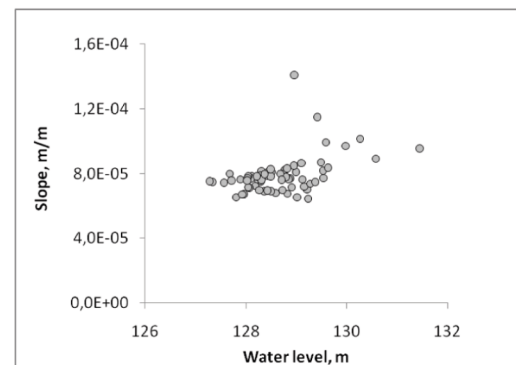
A specificity of the studied river reaches is the low seasonal variability of river width and, consequently, its weak control on the water discharge. As a result, a perturbation of the width variable by 10–14% introduced in the Manning formulation, does not lead to degradation of accuracy of the discharge estimations. However, the perturbation of the width variable by 15–20% results in an increase of  $Q$  errors by up to 12%, and introduces a significant systematic bias in  $Q$  estimates. The Manning equation expresses low sensitivity to the perturbation of the slope variable as well. We found that for the medium-size Rhine and Po Rivers to achieve the discharge accuracy of 15% with physically-based algorithms, the water slope may be time invariant and approximated by values derived from along-river mean water elevation profile. Introduction of  $\pm 10\%$  errors in  $S$  estimates, once the Manning friction parameter  $n$  has been calibrated, decreases the  $Q$  accuracy by only 2%. The  $S$  errors of  $\pm 30\%$  still allow to produce the discharge time series with acceptable errors of less than 25%. However, a systematic bias between altimetric and *in situ* discharge becomes high after allowing slope perturbation by more than  $\pm 30\%$ . We also perform a sensitivity test of the Manning formulation to the errors in the satellite water level measurements and find that the introduction of random errors within 15% (or 64 cm) to the WLTS deteriorates the discharge accuracy from 13% to 25%. With 20% WL errors, only the two highest discharge episodes are reproduced correctly, while the  $Q$  retrievals for middle and low flow periods do not follow the temporal variability recorded in the *in situ*  $Q$ . This test supports our hypothesis on the importance of selection of water level processing chains for generation of accurate water level and accurate discharge time series for such rivers.



a)



b)



c)

**Fig. 8.** Along-river mean water elevation profile and slope and location of Sentinel-3A and 3B virtual stations used for discharge estimation (a). Relation between water slope and level at A156Mainz VS for (b) AVLSAM+ and (c) HyCo WLTS demonstrating common situation for datasets used in the study.

### 5.2. Uncertainty due to flow law approximation

Simplifications and assumptions in flow law formulations may introduce additional errors in the final discharge estimates. For example, in this study for the Manning method we use the approximations developed for open channels with steady and uniform flow conditions. This assumption is unlikely to hold true in many cases. Another simplification is related to estimation of the hydraulic radius  $R$  from the equation (4). The applied formulation considers a rectangular cross-section, which is acceptable for  $B \gg 20 \times D_0$  conditions. This condition is still true for all four studied reaches with  $D_0$  varied in 4–8 m range and  $B$  varied in 350–500 m range. The rectangular approximation of the channel shape also provides better results than the trapeze approximation during calibration of the Manning friction coefficient. For the Rating Curve method a selection of reaches without big tributaries allows to avoid a backwater effect, while the selection of reaches with narrow floodplain avoids non-uniform flow situations. In both these conditions, the rating curve is unique for all hydrological phases. In more complex conditions (for example for seasonally frozen rivers) the H-Q relation can shift due to increasing channel resistance exercised by ice (Zakharova et al., 2020). The overspill of water to the floodplain (non-uniform flow) results in a decreasing proportion of the total discharge passing through the river cross-section. In these conditions in the beginning of the flood for the same water stage the discharge is lower than during the flood fall (Zakharova et al., 2020).

### 5.3. Uncertainty due to flow law parameters' error

Many studies conducted in the framework of SWOT mission preparation demonstrated that different approaches relying on physical flow laws provide good estimates of discharge dynamics, but may have large biases (Gleason and Duran, 2020). These methods are sensitive to the a priori guess of unknown equations' parameters and the more prior data about the river we have (*in situ* Q, bathymetry, friction estimate), the more accurate the discharge estimate will be (Durand et al., 2016, Gleason and Durand, 2020). In this study, targeting to obtain the best possible for rivers of middle-size Q accuracy, we use the best prior information (i.e. *in situ* Q) allowing us first, to evaluate the bathymetry term ( $D_0$ ) via RC method inversion and then, explicitly calibrate the friction terms. Friction (conductance) and bathymetric parameters in both Manning and Bjerklie methods are inversely related to each other. With the known bathymetry the calibration does not represent a difficulty. However, when the channel depth is unknown an ensemble calibration of two terms results in their equifinality and an *a priori* guess on channel bathymetry simplifies the calibration task (Yoon et al., 2016). A multiple cross-section approach for optimization of these two terms may solve this issue for many river reaches (Scherer et al., 2024). However, Scherer et al. state that in certain VS configurations, the appeal to expert knowledge is still required. Parameterisation of the depth was considered important for the discharge estimation algorithms developed by the SWOT science team and this parameter was introduced into the global river database (SWORD) (Altenau et al., 2021). The SWORD channel depth was obtained from inversion of the Bjerklie equation and historical discharge observations (Andreadis et al., 2013). With our  $D_0$  values inverted from the rating curves (6.8 m, 5.2 m, 6.9 m and 4.0 m for B156Goar, A156Mainz, A156Worms and A136, respectively) the good accuracy for the Q time series is achieved. These  $D_0$  values differ from the values reported in the SWORD database for studied locations by 15%–28%. Differences of this order may introduce significant biases in discharge estimation based on the SWORD  $D_0$  parameterization (Zakharova et al., 2020). So, revising and updating the global database with results obtained by research groups in different regions of the World may be useful.

Another flow law parameter, the friction force may vary over time. An introduction of variable  $n$  in the Manning equation may considerably improve the discharge estimates (see Fig. 6a). Calibrated for different

ranges of WL the Manning friction coefficient values for a given VS coincides well at middle and high flow conditions for Mainz and Worms reaches (Fig. 9). The  $n$  values are quite dispersed in range of low levels for the reaches with complex configuration of VSs (i.e. B156Goar and A156Worms). We suppose that this may be related to ability of different L2 products and WLTS generation algorithms for retrieving accurately the water level during low flow conditions (see Fig. 2).

### 5.4. Effect of river morphology on the discharge retrieving accuracy

For our study four river reaches with different track/channel orientation and river valley and channel geomorphology are selected. Joining together uncertainties from different datasets used, different methods and their modifications, we examine an overall effect of altimetry-derived variables on the discharge accuracy in different configurations of virtual stations. Uncertainties are lowest for the Mainz section of the studied river reach (Fig. 10), where satellite track – channel orientation is near  $90^\circ$ , the cross-section is the largest among three reaches (~450 m) and the river banks are flat. The presence of two big islands and, consequently, of two large channels within the virtual station A156Mainz does not deteriorate the discharge retrieval accuracy. Almost the same high accuracy in the discharge estimation is obtained at the location of the VS B145Goar. Narrow river valley and channel width (500 m and 300 m respectively) surrounded by high hills, are not critical factors for SAR altimetry-based discharge estimation. At this location the track – channel crossing angle is  $70^\circ$ . However, the orientation of the altimeter track parallel to the river causes higher errors in the water height estimates in VS A156Worms, and is therefore unfavorable for Q processing. At this location we note the lowest accuracy of the rating curve fitting and, consequently, the lowest accuracy of Q estimates with the RC method. Moreover, both the Bjerklie and Manning methods at this station work better with generalised parameters. The specific calibration of Bjerklies' exponents and the use of variable Manning friction coefficient do not ameliorate Q estimates for 3 of the 5 datasets demonstrating the weakness of the altimetry data and WLTS generation methods for this VS configuration. It is worth noting that in parallel track-channel configuration for medium and small size rivers with channel width  $<1$  km, a  $\pm 1$  km cross-track oscillation of Sentinel-3 measurements results in situations when the water target is in off-nadir position. An ability of altimetry signal processing algorithms to handle the off-nadir measurements correctly (i.e. handle the outliers) may be crucial for the water level and discharge estimation accuracy in such cases. The Fully-Focused SAR processing of along-track altimeter data in SAR mode and its extension to handle off-nadir measurements (Chen et al., 2025) has high potential.

## 6. Conclusion and outlook

With conventional altimeters which provided the measurements in low resolution mode, an accuracy  $<10\%$  was traditionally achieved only for large rivers, with high seasonal magnitude of water level and discharge and large channel width, such as the Amazon River. For medium size rivers, previously, the achieved accuracy was only 30%–50% (see the review Table in Zakharova et al. (2020)). Only recently, the study of Scherer et al. (2024) demonstrated that with a large number of satellite altimetry and optical observations as well as complex methods of data treatment and optimisation, the accuracy of the satellite discharge estimations for rivers with flow  $<100$  km<sup>3</sup>/y can reach 6–70% (12% in median). In this study we have shown that the accuracy of SAR altimetry-derived discharge estimates for the Rhine and Po Rivers with flow of 50 km<sup>3</sup>/year, having sufficient a priori information enabling good constraints to be applied using simple either statistical or physical algorithms, can attain 4–16% accuracy (expressed as NRMSE) in agreement with Scherer et al. (2024). The statistical algorithm based on  $H_{\text{alti}} - Q$  Rating Curves remains the most accurate among the three tested methods. However, we find that the RC method is more sensitive

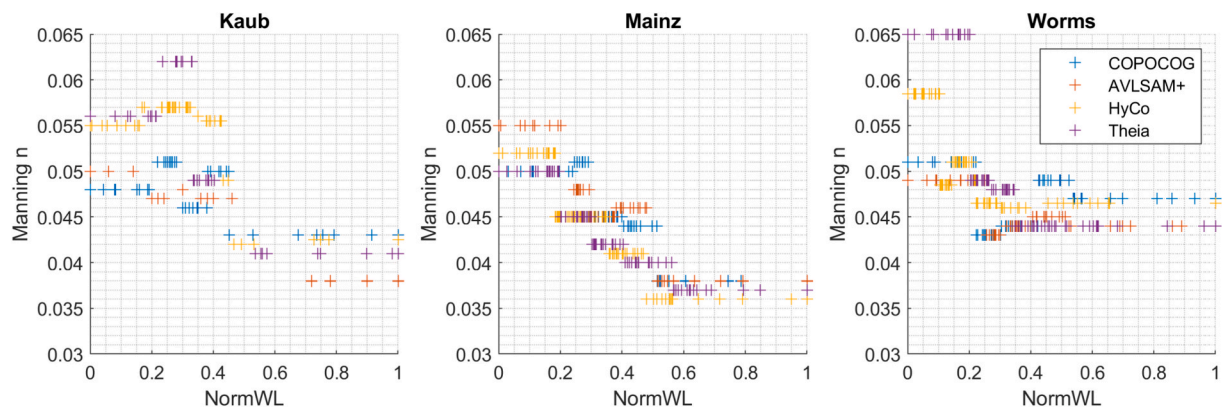


Fig. 9. Example of relation between Manning friction coefficient and water level (normalised between 0 and 1) for the Rhine R. VSs.

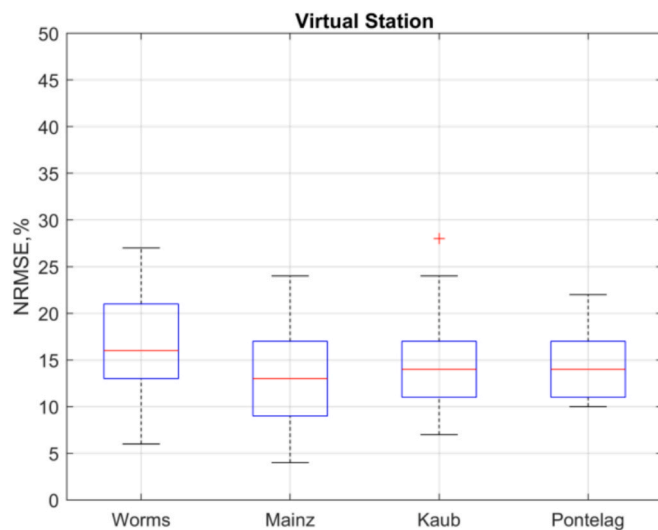


Fig. 10. Accuracy of the discharge retrievals expressed as NRMSE for the studied four virtual stations.

to the accuracy of the water level retrievals than the methods based on physical laws. This implies that the selection of advanced water level processing chains is crucial for the generation of accurate discharge time series with the RC method. The study shows that both the enhanced 50 m along-track resolution and adapted to the inland waters L1B-L2 processing of altimetry measurements are highly beneficial for accuracy of WL and Q estimates, especially in complex configurations of virtual station (for example, in parallel channel-track orientation).

The well constrained Manning-based algorithm produces results comparable with the RC discharge estimates. Our sensitivity test shows that an accuracy of 8–22% may be achieved with the Manning-based method over 300–500 m-width river reaches even with invariable slope parameter taken from external existing datasets (for example SWORD or IRIS (Scherer et al., 2022)). For reaches with weak control of width variable on the discharge, the condition of simultaneous observations of WL and width is not critical for the Q accuracy and simple power Width –  $H_{alt}$  function can be used.

For the Rhine and Po Rivers the Bjerklie equation, which underlies the river depth inversion algorithm in the global SWORD database, provides unbiased discharge estimates of expected accuracy of 20% only after regional adjustment of the conductance and exponent parameters. It signifies that for many locations the SWORD's depth obtained from global set of these parameters may not be accurate. The depth inversions based on the altimetric Rating Curves may help to improve the global database for many locations.

The study also demonstrates that for more accurate discharge estimation the selection of appropriate configuration of virtual station (or river reach) is important. The parallel track-channel configurations should be avoided. The narrow hilly valleys, which were excluded from many studies based on conventional altimetry, are no longer an obstacle for the SAR altimetry-based discharge estimation (considering a correct DEM information in OLTC).

Using the climate projections we attempted to assess whether the accuracy of the river discharge estimates attained in this study and in the Scherer et al. (2024) is sufficient to address the climate tasks. For the intermediate Shared Socio-economic Pathway scenario (SSP2-4.5) climate models agree that in many regions of the World the river runoff is likely to change at least by  $\pm 0.06$  mm/day (or  $\pm 26$  mm/year) to the end of the XXI Century (Douveille et al., 2021). More severe scenarios predict higher changes. We estimated that considering, for example, the modern runoff of middle-size European rivers ranges from 150 mm (Elbe R.) to 550 mm (Rhine R.), the IPCC projected runoff change to 2080 will be of the order 4–15% comparing to the modern period. Formally, for most part of European middle-size rivers the accuracy of discharge retrievals attained with SAR altimetry missions for daily Q in this study would be sufficient to reliably detect these projected changes. However, regarding the medium and small-size rivers, the temporal sampling frequency of the Sentinel-3 (27 days) is insufficient for climate change related tasks. Since 2021 the Sentinel-6 mission carrying similar instrumentation to the Sentinel-3 SRAL altimeter is in orbit. In this study, with Sentinel-6 measurements we attained the 11–15% accuracy with 10-days temporal frequency. Studies have already demonstrated several altimetry-based multi-mission approaches of discharge estimation, which facilitates greatly increased temporal sampling (Tourian et al., 2016; Boergens et al., 2017; Scherer et al., 2020; Nielsen et al., 2022; Zakharova et al., 2020). An assessment of effect of these different approaches on the accuracy of final water level and consequently discharge retrievals for rivers of different scales should be envisaged in the near future. In this work we demonstrate that the high accuracy of the daily discharge retrievals can be achieved not only for big rivers, but also at least for two medium-size rivers such as Rhine and Po. So, a development of a near-operational protocol for retrieving the river discharge with accuracy acceptable for climate monitoring for a large range of global rivers is certainly theoretically achievable in the near future, especially if there were an increase in altimetry missions of sufficient absolute measurement quality. In addition, a Full Focused SAR processing applicable to measurements of Sentinel-3, CryoSat-2 (Egido and Smith, 2017; Kleinherenbrink et al., 2020) and Sentinel-6 (Amraoui et al., 2023) and allowing for higher spatial resolution in comparison to the Unfocused SAR processing used in this study, could also help improving the WL measurement quality. Moreover, expecting a similar accuracy of the SWOT satellite discharge retrievals (Frasson et al., 2021), which will be provided with 3–5 days temporal resolution in our

region of analysis, merged multi-mission satellite discharge products have a chance to fulfill an essential part of operational requirements, such as for example, decisions on planning of water supply or withdrawal.

### CRedit authorship contribution statement

**E. Zakharova:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **L. Fenoglio-Marc:** Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation. **K. Nielsen:** Validation, Methodology, Investigation, Formal analysis, Data curation. **P. Thorne:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **M. Restano:** Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **J. Benveniste:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zakharova E. reports financial support was provided by European Space Agency.

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### Data availability

Data will be made available on request.

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