Article

River Discharge Estimation by Using Altimetry Data and Simplified Flood Routing Modeling

Angelica Tarpanelli *, Silvia Barbetta, Luca Brocca and Tommaso Moramarco

Research Institute for Geo-Hydrological Protection, National Research Council, Via Madonna Alta 126, I-06128 Perugia, Italy; E-Mails: silvia.barbetta@irpi.cnr.it (S.B.); luca.brocca@irpi.cnr.it (L.B.); tommaso.moramarco@irpi.cnr.it (T.M.)

* Author to whom correspondence should be addressed; E-Mail: angelica.tarpanelli@irpi.cnr.it; Tel.: +39-075-5014-426; Fax: +39-075-5014-420.

Abstract: A methodology to estimate the discharge along rivers, even poorly gauged ones, taking advantage of water level measurements derived from satellite altimetry is proposed. The procedure is based on the application of the Rating Curve Model (RCM), a simple method allowing for the estimation of the flow conditions in a river section using only water levels recorded at that site and the discharges observed at another upstream section. The European Remote-Sensing Satellite 2, ERS-2, and the Environmental Satellite, ENVISAT, altimetry data are used to provide time series of water levels needed for the application of RCM. In order to evaluate the usefulness of the approach, the results are compared with the ones obtained by applying an empirical formula that allows discharge estimation from remotely sensed hydraulic information.

To test the proposed procedure, the 236 km-reach of the Po River is investigated, for which five *in situ* stations and four satellite tracks are available. Results show that RCM is able to appropriately represent the discharge, and its performance is better than the empirical formula, although this latter does not require upstream hydrometric data. Given its simple formal structure, the proposed approach can be conveniently utilized in ungauged sites where only the survey of the cross-section is needed.

Keywords: altimetry data; remote sensing; river discharge; Rating Curve Model; Po River

1. Introduction

River discharge is the variable of interest for many scientific and operational applications related to water resources management and flood risk mitigation. Unfortunately, it is not a direct measure, and it is normally expressed in terms of water level variations using mathematical formulas or calibrated relationships, referred to as rating curves. A rating curve is established by simultaneous measurements of velocity and water levels, and a curve is fitted through the measured hydraulic variables [1]. Traditionally, monitoring of river flow velocity is carried out for low-medium water level conditions, because sampling velocity pointing in the wetted flow area during severe flood events is not only difficult, but even dangerous [2]. Therefore, the highest values of discharge are obtained by extending the rating curve through extrapolation that could be affected by significant uncertainties [3].

In addition to these inherent issues, the need to develop new procedures for river discharge estimation based on remote sensing technology is also motivated by: (1) the recent decrease in the hydraulic monitoring network observed all over the world [4–6], (2) the inaccessibility of many remote areas and (3) the difficulties for data sharing among developing countries [7]. In this context, although not specifically dedicated for inland waters, radar altimetry represents an interesting alternative to record the *in situ* water level measurements in the continental environment. Indeed, satellite altimetry has been developed and optimized for open ocean and, only later, the capability of measuring water level change of continental surface reservoirs, such as inland seas and lakes, has been demonstrated [8–10].

Radar altimetry measures the distance between satellite and instantaneous water surface. The differences between the satellite altitude, relative to a reference ellipsoid determined through precise orbit computation, and the distance from the satellite to the water provides a measurement of the water level above the datum. In order to obtain the height of the water, various corrections have to be added, such as the time delay related to the propagation of the pulse through the atmosphere (dry and wet tropospheric correction) and the ionosphere (ionospheric correction) and the correction for solid tidal effects on the Earth (the solid tide correction) [11,12].

Due to the size of the footprint, the radar altimetry technology has been widely applied to large rivers, such as the Amazon River [13–19], on which many altimeter sensors onboard of Geodetic Satellite (GeoSat) [13], TOPEX/POSEIDON (T/P) [14,15,18], ERS-2 and ENVISAT [19] have been tested. Few studies dedicated to a thorough assessment of the radar altimetry over rivers, such as Ob, Mekong, Negro, Gange and Brahmaputra, even without comparisons with *in situ* gauges, have been published [7,20–25].

The accuracy of altimeter water level time series over river and floodplains has been discussed in several previously published papers (*i.e.*, [14,15,26]). Starting from one of the first studies of Koblinsky *et al.* [13], who estimated the accuracy of the altimetry on board GeoSat of about 70 cm (in terms of root mean square error, RMSE, between satellite and *in situ* measurements), much progress has been achieved. Indeed, lower RMSEs are obtained with radar altimetry from T/P: for example, 60 cm in Paraguay and in Amazon basins, as reported by Birkett [14], or 45 cm in the Amazon basin, as demonstrated by De Oliveira Campos *et al.* [15]. The use of ERS-2 and ENVISAT altimeters furnished a further improvement in the water level estimation. For example, Frappart *et al.* [16] and Santos da Silva *et al.* [19] obtained an RMSE of about 30 cm by using radar altimetry on board ENVISAT in the Amazon basin. Despite these studies seeming to be encouraging, the comparative accuracy

between altimetry and *in situ* measurements may also be very high, on the order of 2 m [19,24], and this can be ascribed to the location of the satellite track with respect to the gauged site. Indeed, the location of the *in situ* station does not correspond with the virtual station (VS), *i.e.*, the location where the radar satellite track intersects the river reach [5]. This drawback is significant when the satellite altimetry data are combined with *in situ* measured discharge data for estimating the rating curve. The problem is relocating the observation of water levels derived by altimetry radar at the gauged river site or the *in situ* discharge at the VS. If a relationship between the water level observations derived by radar altimetry and the ones measured *in situ* is identified, the *in situ* rating curve may be applied to the altimetry-derived water levels, provided that no lateral flow is present between the gauged site and VS and that the river cross-section geometry is quite similar. Otherwise, a specific rating curve at the VS can be directly developed, relating altimetry water levels to observed discharge at the gauged station (e.g., [18,20]). For discharge (or flow velocity) estimation where no *in situ* data are available at the VS, Bjerklie *et al.* [27] proposed different equations involving various combinations of potentially remotely observable variables. The main difficulty to apply these empirical equations is to relate the level of the water surface, provided by the satellite altimetry, to the average water depth. This issue can be easily solved when the geometry of the cross-section is available close to the VS. If the cross-section bathymetry is unknown, different solutions have been developed in the literature. For example, Birkinshaw *et al.* [25] found the water level corresponding to zero flow, inverting the empirical formula of Bjerklie *et al.* [27] and assigning a discharge value obtained from another measured location on the same river on the basis of the catchment areas. In order to apply these empirical formulas relating the river discharge and different hydraulic variables, the involved coefficients have to be estimated *a priori* on the basis of a robust database of channel hydraulic information and discharge measurements [25,27]. Alternatively, Getirana *et al.* [22] used modeled discharge from a distributed rainfall-runoff model to estimate the river bed depth and the discharge at the same time.

The high accuracy of altimetry data provided by the latest spatial missions and the convincing results obtained in the previous applications suggest that these data may also be employed for hydrological model calibration [22,23,28–30]. Using hydrological models calibrated with *in situ* data in other sites in the basin, Leon *et al.* [17] and Getirana *et al.* [22] developed methods to derive rating curves at VS locations based on altimetry levels and modeled discharges. In particular, Getirana *et al.* [22] analyzed four years of ENVISAT altimetry time series in the Branco River, showing that it is possible to obtain accurate estimates of the rating curve in sections of a width from 120 m up to 1,130 m, with RMSE ranging from 9.9% to 26.9%.

Based on the above insights, this work proposes a simple methodology to estimate the discharge along rivers, even those poorly gauged, taking advantage of water level measurements derived from satellite altimetry and of the application of the Rating Curve Model (RCM) [31,32]. RCM is a simple method allowing for the estimation of the flow conditions in a river section using only stages recorded at that site and the discharges observed at another upstream (or downstream) section, taking into account the significant lateral inflow contributions. In order to be applied, the proposed approach for discharge assessment at a VS requires that a hydrometric station, where both water level and discharge measurements are available, is located some distance upstream (or downstream) and that the geometry of the river close to the VS is known [33].

A long branch of the Po River, in northern Italy, is selected as a case study. It represents one of the up-to-date stream gauged networks in Italy, and so far, studies that use satellite altimetry data do not exist. Five gauged stations, with daily observations of water levels, located along the selected reach and water level time series (35-day time step) at four VSs, are available, derived from ERS-2 and ENVISAT tracks from May 1995 to August 2010.

2. Methodology

Two different analyses are carried out. At first, the water levels derived by altimetry and *in situ* data are compared. In the second step, RCM is applied in order to estimate the discharge by using altimetry data.

A comparison between the discharges estimated by RCM and by the empirical equation proposed by Bjerklie *et al.* [27] is done to assess the possible benefit provided by the RCM approach.

2.1. Comparison between Satellite and in Situ Water Level Data

The validation of the altimetry data is performed by comparing them with the ground-based water level data from gauged stations. At first, a preliminary analysis is carried out by investigating the coefficients of correlation calculated between the satellite data and the *in situ* measurements.

Considering the temporal resolution of the altimetry sensor and the distance between the gauged stations and the satellite track, *i.e.*, the VS, which may be far, time series of water levels at the gauged station are simulated by using a linear regression between satellite observations and the available water level dataset recorded at a gauged site, shifted by the water travel time between the VS and the gauged site. This allows, on the one hand, transferring of the information coming from the satellite observations at the gauged station, and on the other hand, inferring of how much the altimetry observations may be representative of the recorded stages. The root mean square error, RMSE, and the Nash-Sutcliffe efficiency coefficient [34], NS, are considered as reference measures to estimate the discrepancy between the simulated satellite observations and the observed *in situ* series.

2.2. Discharge Estimate by Using RCM and Altimetry Data

2.2.1. RCM Model

The Rating Curve Model (RCM) is a simple approach for discharge assessment at local sites where only the stage is monitored, while the river flow and the stage are known at another river section some distance away. Therefore, RCM allows rating curve estimation at hydrometric sites where flow velocity measurements cannot be carried out or are available only for low stage values. RCM was originally developed for downstream discharge estimation when the flow hydrograph is recorded at an upstream site [31,32]. The model does not solve a set of routing equations, but it identifies a simple relationship between the hydraulic conditions at two river sections, also accounting for significant lateral inflows along the selected river reach:

$$Q_d(t) = \alpha \frac{A_d(t)}{A_u(t-T_L)} Q_u(t-T_L) + \beta = \alpha X + \beta \tag{1}$$

where Q_u and Q_d are the upstream and downstream discharges, respectively, A_u and A_d represent the effective upstream and downstream flow area, respectively, T_L is the wave travel time and α and β are the model parameters. Equation (1) simulates the discharge hydrograph in the downstream section allowing one to derive the rating curve as a result of different flood events.

The effective flow area is that part of the wetted section that conveys the water flow, and in principle, it can be different from the surveyed one, due both to the morphological characteristics and the interaction with hydraulic structures. The wave travel time is assumed as the time shift necessary to overlap the rising limb and the peak region of the two dimensionless stage hydrographs [32]. When the downstream water level data are available with a time resolution that does not allow describing of the flood hydrograph evolution (*i.e.*, daily data as it occurs with satellite altimetry data). T_L can be derived through the mean upstream peak flow velocity, $\overline{v_u} = Q_u/A_u$ [31]. In particular, T_L is computed as:

$$T_L = \frac{L}{c} \tag{2}$$

where L is the reach length and c is the celerity, computed as:

$$c = \frac{5}{3}\overline{v_u} \tag{3}$$

When RCM is applied to simulate continuous flood events, the model parameters, α and β, can be derived through Equation (1) expressed for the baseflow and the peak flow conditions, as reported in Moramarco *et al.* [32] and Barbetta *et al.* [33]. In this way, for each investigated flood event, a value of α and β is assessed. However, by comparing the term, $X = \left[\frac{A_d(t)}{A_u(t-T_L)}\right]Q_u(t - T_L)$, against the downstream observed discharge, Q_d, for different observed floods, a linear relationship can be identified [32,35]. It is shown that α and β thus assessed may represent an inherent property of the investigated channel reach. Indeed, once their value is used in Equation (1), errors in peak discharge and time to peak are found, of a few percentage points [33,36]. It is worth noting that RCM, besides being applied if the upstream site is of interest for the discharge estimation, is able to simulate the presence of a flood loop, due to unsteady flow effects [33].

2.2.2. RCM Application with Altimetry Satellite Data

The discharge assessment at the river site of interest through RCM by using altimetry satellite data can be carried out if an upstream gauged site, for which a rating curve is available, is present, and topographical surveys are executed at both end sections for A_u (gauged site) and A_d (track of satellite) assessment.

In the present study, it is assumed that no level-discharge records are available at the downstream river site (ungauged site) where the discharge assessment is of interest, and hence, α and β are not calibrated and assumed equal to 1 and 0, respectively [24]. In this context, the downstream section is represented by the VS, where only the water levels derived by the radar altimetry are measured. The validation of the results is carried out by establishing a direct relationship between satellite altimetry-derived discharge at the VSs and observed discharge at the nearest gauged station(s).

2.3. Comparison between RCM and the Empirical Equation

Bjerklie *et al.* [27] proposed an empirical equation, here in after, BJ03, applied with satellite data in order to infer the discharge by using geometric and hydraulic features of the river cross-section, such as water-surface width, surface slope and average depth. The hydraulic variables can be measured separately through remote sensing and used, successively, for discharge estimation. The BJ03 derives from the resistance equation formulated by Chezy and Manning [1], which relates discharge to width, depth and slope as a power function. In particular, the following formulation is used:

$$Q = c_1 W^a Y^b S^d \tag{4}$$

where Q (m³/s) is the discharge, W (m) is the water-surface width, Y (m) is the average depth and S (-) is the water surface slope. $c1$, a, b and d are coefficients calibrated and validated by using a dataset of 1,012 discharge measurements in 102 rivers in the United States and New Zealand, including four measurements from the Amazon River at Obidos. In this study, the parameters proposed by Bjerklie *et al.* [27] are used, *i.e.*, $c1 = 7.22$, $a = 1.02$, $b = 1.74$ and $d = 0.35$.

The comparison between the two approaches, RCM and BJ03, is carried out considering the VSs where the altimetry data are available.

The accuracy of the discharge estimates is determined by using four performance measures: RMSE and NS, the relative root mean square error, RRMSE, and the relative error, RE, these two latter defined as follows:

$$RRMSE = \frac{RMSE}{\overline{Q}_{obs}} \cdot 100 \tag{5}$$

$$RE = \frac{\sum_1^n Q_{sim} - \sum_1^n Q_{obs}}{\sum_1^n Q_{obs}} \cdot 100 \tag{6}$$

where n is the length of the time series of discharge, Q_{sim} and Q_{obs} are the simulated and observed discharges and $\overline{Q}_{obs}$ is the mean value of the observed discharge. RRMSE and RE range from 0 to ∞, where 0 is the perfect match between the model and observations.

3. Study Area and *in Situ* Dataset

In order to test the proposed methodology for river discharge estimation by satellite altimetry data, the Po River in northern Italy is selected as a case study. It is located in the center of a large flat alluvial plain, the Pianura Padana (Po Valley), and this avoids some issue tied to the presence of mountains that may affect the altimeter echoes. For this study, five gauged river stations along the river, continuously monitoring the water level, are used: Piacenza (basin area equal to 42,030 km²), Cremona (50,726 km²), Borgoforte (62,450 km²), Sermide (68,724 km²) and Pontelagoscuro (70,091 km²) (Figure 1). The geometric characteristics of the five analyzed river stations are deduced by a ground survey carried out by the Interregional Agency of the Po River in 2005 and shown in Table 1. The riverbed consists of a stable main channel with a width varying from 200 to 300 m and

two lateral banks (the overall width varies from 400 to 4 km) confined by two artificial levees. The bankfull river depth ranges from about 10 to 18 m. The 236 km river reach bounded by the hydrometric stations of Piacenza and Pontelagoscuro is characterized by the low slope of the river bed bottom and by a significant intermediate drainage area equal to about 40% of the basin, subtended by the downstream station.

Figure 1. Geographical location of the study area. Spatial distribution of *in situ* and virtual stations used in the study. Diagonal tracks correspond to ERS-2 and ENVISAT satellite overpasses.
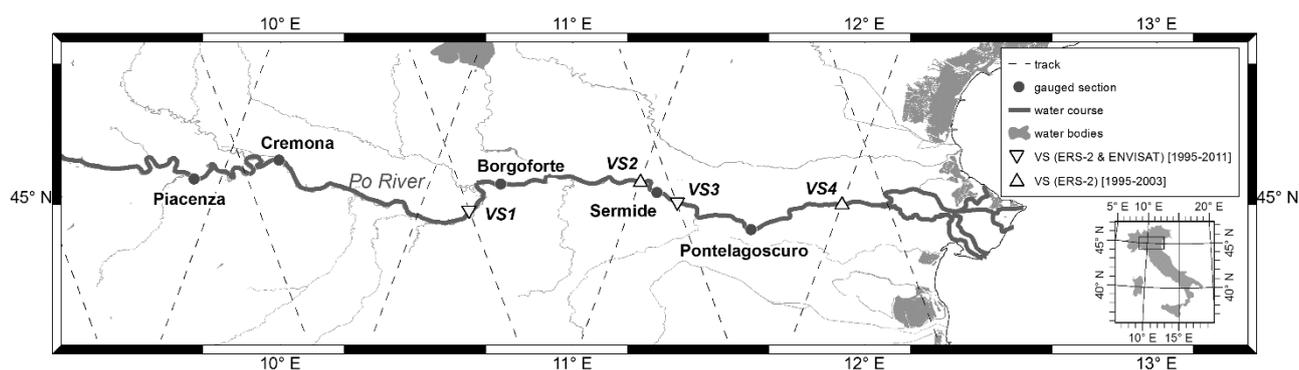
The stage and discharge recorded *in situ* have been provided by the Interregional Agency of the Po River. In particular, daily data of water level, *h*, for all the stations are selected from May 1995, to August 2010. It must be noted that the knowledge of river discharge, *Q*, at the selected gauged stations is derived by rating curves obtained by local recorded water levels and velocity measurements, *v*, occasionally collected for different flow conditions. For each gauged site, at least 25 pairs of *h-v* values are available, thus allowing one to obtain a reliable stage-discharge relationship. We denote, henceforth, the discharge derived through the rating curve as "observed discharge".

As regards the flow regime, the values of maximum, mean and minimum discharge of the period 1995–2010 are reported in Table 1 for each gauged site.

Table 1. Characteristics of the gauged stations of the Po River: basin area (A_b), river width (*w*) and river depth (*d*), for bankfull discharge, maximum discharge (Q_{max}), minimum discharge (Q_{min}) and mean discharge (Q_m).

Gauged Station	A_b (km^2)	w (m)	D (m)	Q_{max} (m^3·s^{-1})	Q_{min} (m^3·s^{-1})	Q_m (m^3·s^{-1})
Piacenza	42,030	213	18.01	12,800	125	958
Cremona	50,726	278	12.86	13,750	200	1,115
Borgoforte	62,450	266	10.47	12,047	209	1,373
Sermide	68,724	493	11.19	10,100	123	1,358
Pontelagoscuro	70,091	302	18.73	10,300	156	1,501

4. Radar Altimeter Dataset

At present, various databases are available, enabling the retrieval of water level altimetry time series for large basins, such as Hydroweb [37], the Global Reservoir and Lake Elevation Database [38] and the retracked T/P database within the Contribution of Satellite Altimetry to Hydrology (CASH) project [39].

The altimetry data used in this study came from the database of the processing of ERS-2 and ENVISAT at de Montfort University, UK, on behalf of European Space Agency, ESA [12]. Two types of products are available: (1) the River-Lake Hydrology (RLH) product, intended for hydrologists with no special knowledge of radar altimetry, grouped by the river/lake crossing point (one product per crossing point); (2) the river-lake altimetry (RLA) product, designed for radar-altimetry experts, grouped by satellite orbital revolution. In this work, RLH products are used. The location of the available altimetry data on the Po River is provided in Figure 1 for both ERS-2 (1995–2003) and ENVISAT (2002–2011). The overlap between ERS-2 and ENVISAT allows the data to be adjusted to a common track. Therefore, in total, there are four VSs: four for ERS-2 and two for ENVISAT (overlapping ERS-2 VS1 and VS3) (see Table 2). At each VS, the water level is retrieved every 35 days, but the crossing day differs for each location.

5. Results and Discussion

In this section, first, the comparison between satellite and *in situ* water level measurements is analyzed, identifying the correlation and the discrepancies among them. Second, the river discharge is estimated through the use of the RCM and BJ03 approaches.

5.1. Comparison between ERS-2 and ENVISAT Data with in Situ *Water Level Data*

As the first step, both the water level measurements from gauged stations and satellite sensors are referred to the same ellipsoid in order to allow data comparison. As expected, the VSs do not correspond with the gauged stations (see Figure 1 and Table 2). For example, Piacenza and Cremona stations are distant from the nearest VS, 124 km and 77 km, respectively. On the other hand, Sermide station is located between VS2 and VS3, and it is quite near to them (less than 11 km). Figure 2 shows the daily water level time series derived by *in situ* stations and the 35-day water level time series derived by the radar altimetry. As can be seen, the altimetry data are consistent with *in situ* measurements, being lower (higher) than the water level recorded at the upstream (downstream) gauged stations. It is worth noting that the ERS-2 data belonging to the VS2 agree very well with the Sermide gauged station, because the mean slope of the river bed between the two sections is very low (0.02%).

Table 2. Distance in km between *in situ* gauged stations and virtual stations, VSs. Negative (positive) distances indicate that the track crosses the river upstream (downstream) from the gauged stations.

Virtual Stations	Gauged Stations				
	Piacenza	Cremona	Borgoforte	Sermide	Pontelagoscuro
VS1	124	77	−20	−77	−112
VS2	190	144	47	−11	−46
VS3	207	160	63	6	−29
VS4	264	217	120	63	28

The correlations between the water levels recorded in all the gauged stations and provided at the VSs from altimetry data are reported in Table 3. In particular, the water levels measured *in situ* are

selected during the acquisition dates of the satellite sensor overpasses plus (or minus) the wave travel time, T_L, calculated as in Equations (2) and (3), if the VS is upstream (downstream) of the gauged station. The lowest correlation values are obtained when VS4 is considered, and this has to be ascribed to the effect of the mouth of the Po River (see Figure 2). As can be seen in Figure 3, where a scatter plot of the water levels derived from each *in situ* gauged station and each virtual station is depicted, overall, VS2 and VS3 show a good linear relation with *in situ* observations (R = 0.79–0.92, Table 1), with the exception of a few data points. Therefore, only these two VSs are selected in the following analyses. Indeed, as regards the VS1, the correlations are quite low for all the gauged stations, ranging from 0.35 to 0.44. For VS1, the actual causes for the obtained inaccuracy are not known and will be the object of future investigations.

Figure 2. Water level time series of available *in situ* and virtual stations.
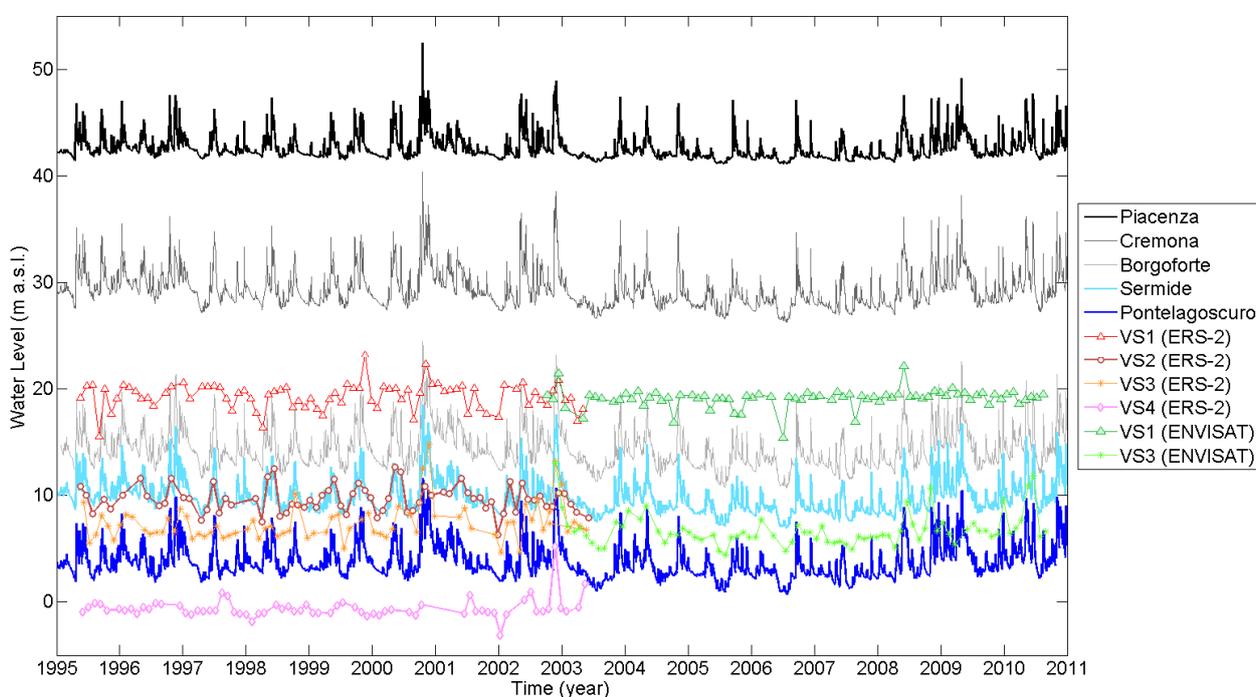

Table 3. Coefficient of correlation between water levels recorded at the *in situ* gauged station and provided at the virtual stations (VSs) by the satellite altimeter. The gauged sections closest to each VSs are highlighted in bold.

Satellite	Data Availability	Gauged Stations				
		Piacenza	Cremona	Borgoforte	Sermide	Pontelagoscuro
VS1 (ERS-2 and ENVISAT)	1995–2010	0.37	0.38	**0.42**	0.42	0.43
VS1 (ERS-2)	1995–2003	0.35	0.37	**0.43**	0.42	0.44
VS1 (ENVISAT)	2002–2010	0.40	0.39	**0.40**	0.41	0.42
VS2 (ERS-2)	1995–2003	0.79	0.83	0.83	**0.79**	0.82
VS3 (ERS-2 and ENVISAT)	1995–2010	0.81	0.85	0.90	**0.89**	0.91
VS3 (ERS-2)	1995–2003	0.75	0.81	0.87	**0.86**	0.89
VS3 (ENVISAT)	2002–2010	0.89	0.90	0.92	**0.92**	0.92
VS4 (ERS-2)	1995–2003	0.31	0.32	0.31	0.35	**0.30**

In order to evaluate the quantitative accuracy of the satellite data, the water levels derived by satellite altimetry are simulated by using linear regression between satellite observations and *in situ* measurements; these latter are considered a benchmark (see Table 4). The RMSE values obtained with the VS3 (ERS-2 and ENVISAT series) are similar to the ones obtained with the VS2 (ERS-2 series), but if considered separately, ERS-2 provides higher errors, equal to 0.87 m and 0.85 m for Sermide and Pontelagoscuro, respectively. If ENVISAT data are used, lower RMSE values are obtained for both gauged stations, confirming the statement of Frappart *et al.* [16], who also found that ENVISAT is more accurate than ERS-2. This is ascribed to a combination of factors. The first factor is the surrounding topography. ENVISAT has the ability to dynamically switch modes when it determines that it is struggling to maintain lock (capture the entire waveform). This means that when the surrounding terrain becomes rough, it can switch from 320 MHz to 80 MHz, and even down to 20 MHz, whilst still retaining information (providing a range window of 64 m, 256 m and 1,024 m, respectively, compared to ERS-2's 128 m). Therefore, when the terrain becomes less variable, ENVISAT is able to move back up the modes and obtain more waveforms than possible if the lock were lost (such as with ERS-2 and its mask based approach) in the best resolution possible. The second factor is the bin representation. The number of bins for ENVISAT is twice ERS-2 (128 compared to 64). Moreover, the bin width for the ERS-2 altimeter is about 1.82 m wide, whereas for 320 MHz ENVISAT, it is about 47 cm. Therefore, even with retracking when results are obtained from ENVISAT at 320 MHz, they are likely to be more accurate than those from ERS-2.

The estimated accuracy is consistent with previous studies, as, for example, by Birkinshaw *et al.* [24], who found errors in the term of RMSE in the range 0.46–0.76 m for ERS-2 and 0.44–0.65 m for ENVISAT. The RMSE values obtained for the Po River are slightly higher, but this is expected, as the river channel is much narrower than the Mekong.

Figure 3. Scatter plot of the water level for *in situ* and virtual stations.
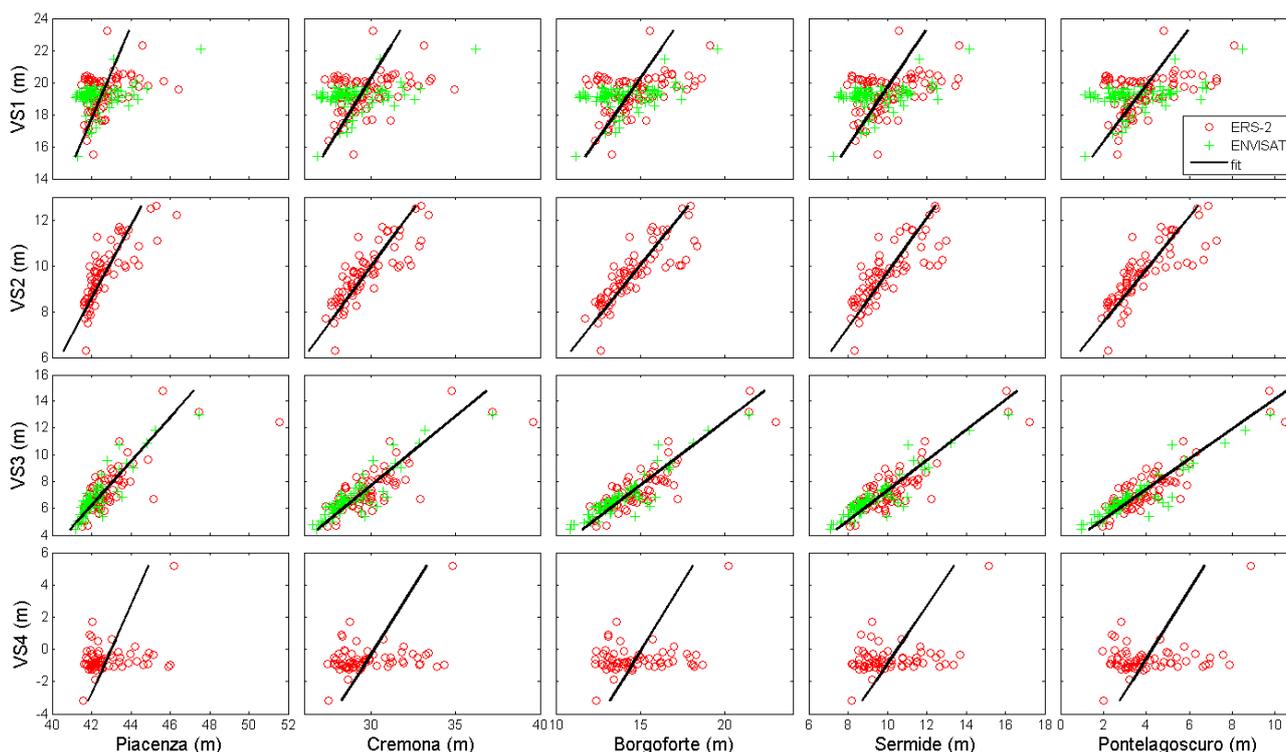
The same conclusions can be drawn by examining the NS coefficient values that are found higher for ENVISAT (0.85 for both the stations) than for ERS-2 (0.73 and 0.78 for Sermide and Pontelagoscuro, respectively) for the VS3. Moreover, the NS coefficients for VS3 (ERS-2 and ENVISAT) are much higher than the ones for VS2, despite RMSE being the same. This is ascribed to the variance of the altimetry series belonging to VS2 that is equal to 0.98 m and 1.04 m for Sermide and Pontelagoscuro, respectively, whereas for the VS3, it is found to be almost twice (in the range 1.99–2.39 m).

Table 4. Root mean square error (RMSE) and Nash Sutcliffe coefficient (NS) between the water levels measured at the *in situ* stations of Sermide and Pontelagoscuro and the water levels simulated by using regression relationships between satellite observations for VS2 and VS3 and *in situ* measurements.

Satellite	Number of Altimetry Measurements	Sermide		Pontelagoscuro	
		RMSE (m)	NS	RMSE (m)	NS
VS2 (ERS-2)	72	0.80	0.63	0.75	0.67
VS3 (ERS-2 and ENVISAT)	148	0.76	0.79	0.69	0.82
VS3 (ERS-2)	72	0.87	0.73	0.75	0.78
VS3 (ENVISAT)	76	0.59	0.85	0.61	0.85

5.2. Discharge Estimation for Ungauged Sites

The accuracy of RCM to estimate discharge by using satellite data is carried out by comparison with the observed discharge at the closest gauged stations. To this end, we analyze two river reaches: Piacenza-VS2 and Piacenza-VS3. The gauged stations of Sermide and Pontelagoscuro are used as benchmarks, assuming that the contribution of the intermediate drainage area is negligible (see Table 1).

The hydraulic quantities involved in Equation (4), *i.e.*, the water surface width, the average depth and the slope, are applied to the VS2 and VS3, thereby providing a fair comparison of the two approaches.

5.2.1. RCM Application: Piacenza-VS2 River Reach

The analysis is performed by assuming the section geometry available at both river reach ends, while the *in situ* discharge and the stage are known at the upstream site (Piacenza). The downstream water level data, VS2, are provided by the ERS-2 altimeter in the period 1999–2003 (number of altimetry measurements = 72). Assuming that the downstream station is ungauged, *i.e.*, no flow measurement is available, the parameters of RCM, α and β, are assumed equal to one and zero, respectively. T_L is assessed considering the mean flood event (~3,500 m$^3 \cdot$s^{-1}) observed in the upstream station in the entire period by using Equations (2) and (3). The T_L value is found equal to 26 h. The results are displayed in Figure 4, and the performance measures are reported in Table 5. The pairs (Q_{obs}, Q_{RCM}) overlap the bisector line for both the gauged stations, demonstrating the good agreement of the discharge derived by RCM with *in situ* observations, even if a slight underestimation is observed, as demonstrated by negative RE (−2.7% and −12.1% for Sermide and Pontelagoscuro,

respectively), shown in Table 5. RRMSE is equal to 29% and 27% for Sermide and Pontelagoscuro stations, respectively, and NS is 0.73 for both stations.

Figure 4. Piacenza-VS2 river reach: comparison between the discharge simulated by using the Rating Curve Model (RCM) and the Bjerklie formula and the observed *in situ* discharge for the two gauged station of Sermide (**left**) and Pontelagoscuro (**right**).
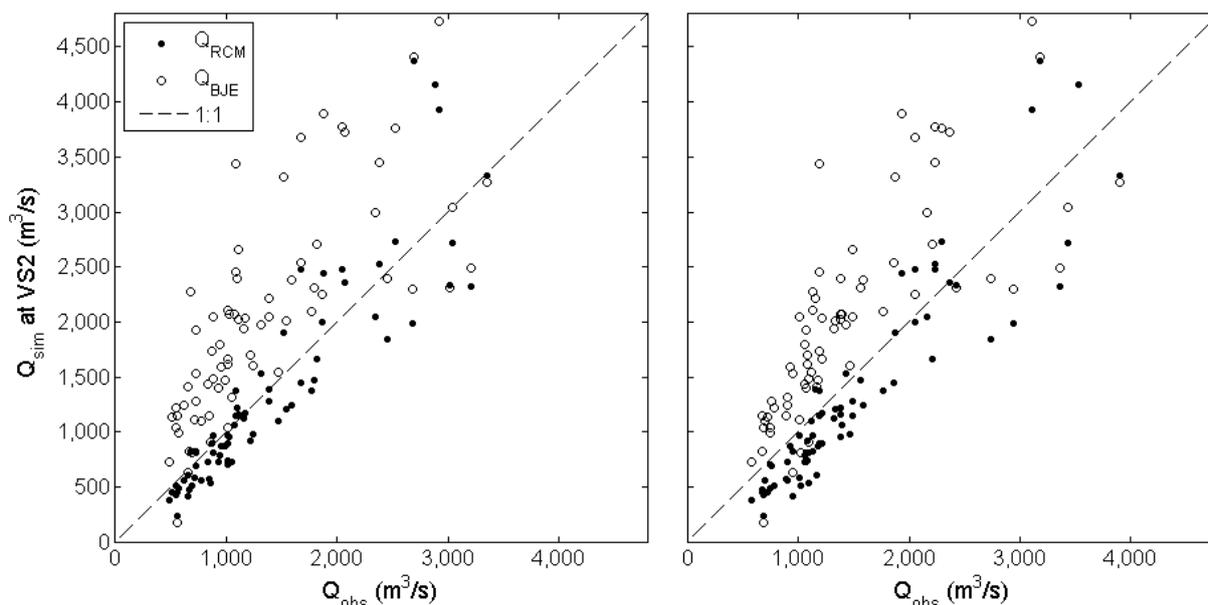

Table 5. VS2 and VS3: comparison between the discharge derived from RCM and the empirical equation derived by Bjerklie *et al.* (2003) and the ones observed at Sermide and Pontelagoscuro sections (RMSE = root mean square error; RRMSE = relative root mean square error; NS = Nash Sutcliffe efficiency; RE = relative error)

	Sermide							
	RCM				**BJ03**			
Satellite	RMSE $(m^3 \cdot s^{-1})$	RRMSE (%)	NS (-)	RE (%)	RMSE $(m^3 \cdot s^{-1})$	RRMSE (%)	NS (-)	RE (%)
VS2 (ERS-2)	396	29.0	0.73	−2.7	962	70.5	−0.61	52.9
VS3 (ERS-2 and ENVISAT)	453	32.6	0.85	−20.2	755	54.3	0.59	29.6
VS3 (ERS-2)	530	33.4	0.84	−17.3	892	56.2	0.54	29.2
VS3 (ENVISAT)	365	30.3	0.87	−23.9	597	49.6	0.64	30.2

	Pontelagoscuro							
	RCM				**BJ03**			
Satellite	RMSE $(m^3 \cdot s^{-1})$	RRMSE (%)	NS (-)	RE (%)	RMSE $(m^3 \cdot s^{-1})$	RRMSE (%)	NS (-)	RE (%)
VS2 (ERS-2)	405	26.9	0.73	−12.1	834	55.3	−0.14	38.3
VS3 (ERS-2 and ENVISAT)	497	33.3	0.82	−25.8	670	44.9	0.66	20.6
VS3 (ERS-2)	526	31.2	0.82	−22.3	794	47.0	0.60	21.3
VS3 (ENVISAT)	467	35.7	0.80	−30.1	527	40.3	0.74	19.8

5.2.2. RCM Application: Piacenza-VS3 River Reach

A further analysis is carried out by considering the river reach, Piacenza-VS3. The conditions are the same as the previous case, but the T_L is 28 h for a reach of 207 km. The results are shown in Figure 5 for the case in which all the available satellite data are considered, *i.e.*, ERS-2 and ENVISAT. Furthermore, in this case, RCM provides, on average, underestimated discharges, and the pairs (Q_{obs}, Q_{RCM}) are below the bisector. RMSE is higher than the one estimated for VS2 (equal to 453 $m^3 \cdot s^{-1}$ and 497 $m^3 \cdot s^{-1}$), but NS increases up to 0.85 and 0.82, for Sermide and Pontelagoscuro station, respectively (see Table 5). The discharge underestimation in the VS3 is more evident, as confirmed also by RE, which assumes higher values equal to about −20.2% and −25.8% for Sermide and Pontelagoscuro, respectively. If we consider the ERS-2 and ENVISAT time series separately, the results are slightly different. Generally, the RCM approach performs better when the satellite series from ENVISAT are used, as shown by the RMSE being higher for ERS-2 than ENVISAT for both of the gauged stations.

Figure 5. Piacenza-VS3 river reach: comparison between the discharge simulated by using RCM and the Bjerklie formula and the observed *in situ* discharge for the two gauged stations of (**left**) Sermide and (**right**) Pontelagoscuro. The inset graphs show the same data on a logarithmic scale.
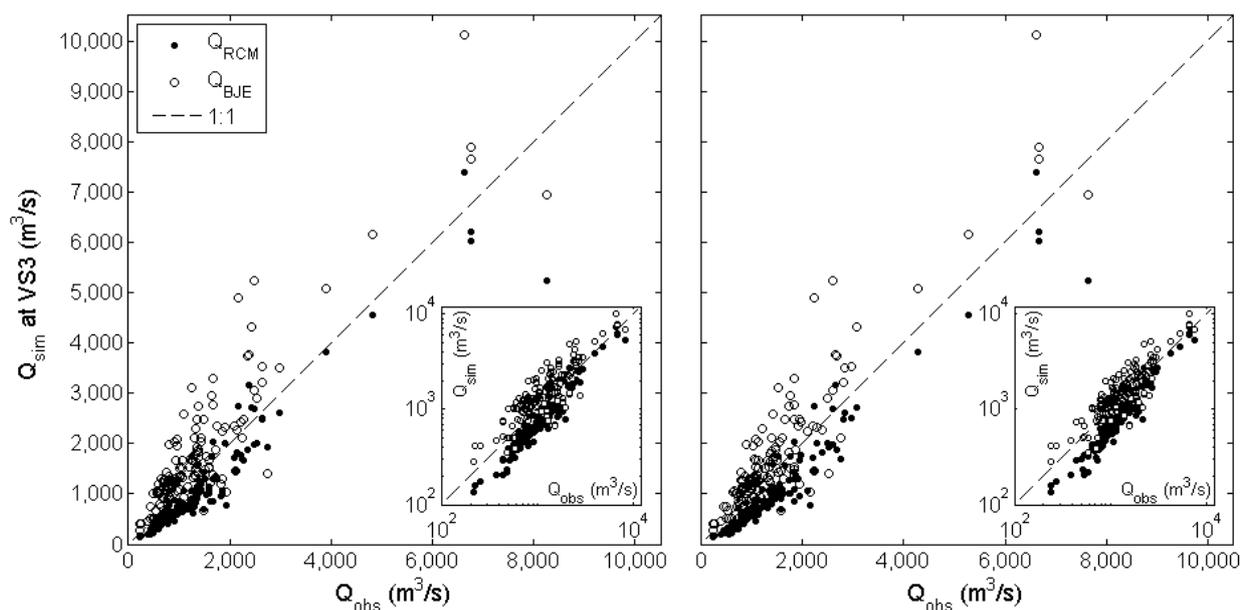
If we compare the observed and simulated discharge considering only ERS-2 altimetry data, RCM works better for VS2 (ERS-2) with RMSE, RRMSE and RE errors lower than the ones computed for VS3 (ERS-2).

The use of constant and uncalibrated values for the parameters, α and β, produces both the underestimation of RCM discharge and the scattering of the pairs (Q_{obs}, Q_{RCM}) in Figure 5. Indeed, the underestimation may be also ascribed to the overestimation of the upstream effective flow area (Piacenza section) where the water levels affect the floodplains and the flow area is likely overestimated [40]. Moreover, the scattering also depends on the flow area at the VS that is computed

through a single cross-section survey available in the area of the satellite track. Therefore, the possible changes in the cross-section geometry are not taken into account.

Generally, RCM provides satisfactory results, confirming the potential usefulness of the method to be used with satellite data for the estimation of the discharge. Moreover, these errors are consistent with the ones of the study carried out by Getirana *et al.* [22], who obtained RE ranging from 8.4% to 19.7% by using a rainfall-runoff model for the discharge estimation in the Branco River in the Amazon basin.

5.2.3. Application of Empirical Equation Derived by Bjerklie *et al.* [27]

For the application of the empirical equation, BJ03, the slope, S, is calculated considering the average value of the altimetry levels at both sections, VS2 and VS3, and the distance between them (17 km), and it is equal to 0.00014. For the other two quantities, W and Y, the values are based on the section survey that is assumed to be known. In particular, the top width, W, is estimated considering the level of bankfull, equal to 400 and 377 m for VS2 and VS3, respectively. For the calculation of depth, Y, we subtract from the water level elevation derived from radar altimetry the elevation of the cross-section bottom, z_0. The latter is computed referring to the equivalent rectangular section at the bankfull level, and hence, it is estimated considering the bankfull cross-section area divided by the corresponding width of the section, W.

In Figures 4 and 5, the discharges obtained through the use of BJ03 are shown and compared with the observations. As can be seen in Table 5, differently from RCM, the application of BJ03 for VS2 does not provide satisfactory results. RMSE (962 $m^3 \cdot s^{-1}$ and 834 $m^3 \cdot s^{-1}$ for Sermide and Pontelagoscuro, respectively) and the RRMSE values (70.5% and 55.3%) are quite high, whereas negative NS values are obtained. This result is due to an important overestimation of BJ03, clearly visible in Figure 4.

Furthermore, by considering the VS3 (ERS-2 and ENVISAT), errors are found to be higher than the ones referring to RCM, above all for the Sermide section, with RMSE, RRMSE and NS equal to 755 $m^3 \cdot s^{-1}$, 54.3% and 0.59, respectively. For Pontelagoscuro section, the performance measures are slightly better, with RMSE, RRMSE and NS values of 670 $m^3 \cdot s^{-1}$, 45% and 0.66, respectively. Additionally, in this case, altimetry data from ENVISAT are better than ERS-2 ones, as shown in Table 5. Moreover, the discharges estimated by BJ03 are overestimated, as confirmed by RE that is positive for both the VSs ranging from 20% for VS3 (ENVISAT) at Pontelagoscuro to 53% at VS2 (ERS-2). Better results were obtained by Birkinshaw *et al.* [25], applying the same empirical equation in the Mekong and Ob rivers, with NS values ranging between 0.86 and 0.90. However, the strong seasonality of the rivers investigated by Birkinshaw *et al.* [25] surely enhance the obtained NS values [41]. Moreover, in Birkinshaw et al. [25] measurements were taken along a 50 km reach of river to account for short-scale variability of natural river morphology, rather than at a specific location. This aspect might be another reason for the lower NS values here obtained.

It is worth noting that RCM takes into account the discharge recorded at the upstream section, whereas BJ03 does not consider this input data. Furthermore, also, the application of the BJ03 in Italy should be preceded by a calibration of the coefficients by using the *in situ* measurements.

6. Conclusions

In this study, river discharge is estimated for two gauged sites on the Po River by using altimetry data from ERS-2 and ENVISAT satellites. The comparison between the satellite and *in situ* water level measurements has shown that the accuracy of the altimetry data depends on the satellite sensor. ERS-2 is found to be less accurate than ENVISAT, as shown at the VS3, where comparison with the observed water levels provides errors of about 60 cm and 81 cm for ENVISAT and ERS-2, respectively (see Table 4). An issue to address is how to filter out inaccurate radar altimetry data (e.g., at VS1) without considering the ground data.

The study uses two methods for the discharge estimation in the ungauged river site, where only the geometry of the cross-sections is required. The proposed simplified routing model, named RCM, applied with altimetry data, is able to estimate the discharge in a river site narrower than the one usually considered for altimetry applications [25]. Despite that a slight underestimation can be observed in both gauged stations (see Figures 4 and 5), Sermide and Pontelagoscuro, a low RRMSE nearly equal to 30% is obtained (see Table 5).

Moreover, the RCM method outperformed the empirical formula proposed by Bjerklie *et al.* [27], which, however, does not use the knowledge of discharge at an upstream river section. If the data of velocity and water level for different flow conditions would have been available for the investigated river reaches, it is expected that Bjerklie's equation would have provided better performance by an appropriate calibration of parameters.

The obtained results suggest that the radar altimetry observations can be used to estimate discharge at ungauged river sites. An open issue that has still to be addressed is related to the assessment of the cross-section geometry [42] and, specifically, the estimation of the elevation of the cross-section bottom [43].

Future investigations will be performed to integrate altimetry-derived water levels and velocity data derived by Moderate Resolution Imaging Spectroradiometer, MODIS [44] for further improvement of discharge estimation in ungauged river sites.

Acknowledgments

Conflict of Interest

The authors declare no conflict of interest.

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