Coupling MODIS and Radar Altimetry Data for Discharge Estimation in Poorly Gauged River Basins

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Abstract

The capability of coupling measurements of river velocity derived from Moderate Resolution Imaging Spectroradiometer (MODIS) and water levels derived from ENVISAT Advanced Radar Altimeter (RA-2) for river discharge estimation is thoroughly investigated. The method is applied even considering the possible unavailability of the river cross-section survey by using the entropy theory for reconstructing the bathymetry. The discharge estimation accuracy is validated using *in-situ* measurements along the Po River (Northern Italy) where daily observations are available for the period 2005-2010.

The agreement with the observed discharge is fairly satisfactory with coefficient of correlation of 0.91 and relative root mean square error of ~ 37% on average. Therefore, the coupling of the two sensors provides, with a good level of accuracy, the hydraulic quantities to use for discharge estimation. These results are particularly significant for the forthcoming European Space Agency Sentinel-3 mission, in which a visible-near infrared multispectral sensor and an altimeter will be onboard the same satellite platform providing significant improvements in terms of vertical accuracy and spatial-temporal resolution.

Key Words: MODIS, radar altimetry, remote sensing, discharge, flow velocity, Po River.

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1. Introduction

Over the past two decades the availability of remote sensing data has steadily increased and the number of studies demonstrating the potential of satellite in hydrology has grown rapidly (Alsdorf et al., 2007; Bjerklie et al., 2003; Smith and Pavelsky, 2008). In particular, the recent advances in radar altimetry technology by TOPEX/Poseidon (TP), European Remote-Sensing Satellite 2 (ERS-2) and the Environmental Satellite (ENVISAT) mission offered important information for water levels monitoring of large rivers, lakes and floodplains (Koblinsky et al., 1993; Birkett, 1998; De Oliveira Campos et al., 2001; Frappart et al., 2006; Leon et al., 2006; Zakharova et al., 2006; Santos da Silva et al., 2010; Getirana et al., 2009; Birkinshaw et al., 2010; Michailovsky et al., 2013; Getirana et al., 2013). For large rivers in continental environment, as the Amazon, the radar altimetry reaches an accuracy of 30 cm in terms of root mean square error, *RMSE*, as shown by Frappart et al. (2006) and Santos da Silva et al. (2010) who analyzed data from the Advanced Radar Altimeter (RA-2) onboard ENVISAT. With the future SWOT (Surface Water Ocean Topography) mission the remote water level identification will reach an accuracy up to 10 cm also for smaller rivers (width of ~ 100 m) (Durand et al., 2010; Biancamaria et al., 2010; Fu et al., 2012; Yoon et al., 2013).

For very large river basins (>10,000 km^2) microwave sensors have been already used for improving discharge monitoring activities (Brakenridge et al., 2007; Temimi et al., 2007, 2011). For example, Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) data have been used by Brakenridge et al. (2007) for the ñGlobal Flood Detection Systemò, in order to globally infer floods also for ungauged and inaccessible rivers (http://old.gdacs.org/flooddetection/overview.aspx). The technique is based on the changes in brightness temperature between wet measurement pixels (*M*) centered over rivers and dry calibration pixels (*C*) that are not affected by the river. River flooding is detected by comparing the signal from the wet pixel and the one from the calibration pixel. Khan et al. (2012) used this technique for the calibration of a distributed hydrological model with satisfactory results showing that remote sensing data from microwave sensors could be used to supplement stream gauges in large sparsely gauged or ungauged basins. The same technique, applied to optical Moderate Resolution Imaging Spectroradiometer (MODIS) data, was also used for river discharge estimation in a preliminary study by Brakenridge and Anderson (2006). Specifically, the different behavior of water and land in the Near Infrared (NIR) portion of the electromagnetic spectrum is exploited by computing the ratio of the MODIS channel 2 reflectance values between two pixels located within and outside the river. The values of the ratio increase with the presence of water and, hence, with discharge.

Two recent studies (Tarpanelli et al., 2013a; 2013b) have investigated the use of sensors like radar altimetry and MODIS for the discharge evaluation in the Po River (~70,000 km^2) in northern Italy. In particular, Tarpanelli et al. (2013a) applied a simple flood routing model for the estimation of discharge in two river sections along the Po using water level observations by satellite radar altimetry. The knowledge of discharge at an upstream river section is needed in order to apply the procedure. Tarpanelli et al. (2013b) showed that MODIS can give satisfactory estimates of velocity and discharge and that the method can be extended for ungauged river sites. However, the discharge is evaluated considering the water level measured in the gauged stations, where the cross-sections survey is available. Therefore, in both approaches in situ observations (upstream discharge or water level) were used with the purpose of discharge estimation from remote sensing. Additionally, both the procedures need the cross-section geometry to be applied..

On this basis, we present a study in which for the first time two satellite sensors working in two different spectral regions and with a different technology are coupled for providing discharge estimation in ungauged section without the knowledge of bathymetry of the cross-sections. Generally speaking, the discharge is given by the product of the river velocity and the flow area that can be derived as a function of the water level when the river section geometry is known. Differently from Tarpanelli et al. (2013a; 2013b), both these hydraulic quantities were derived, in this work, by satellite measurements. The mean flow velocity was calculated considering the MODIS sensor (Tarpanelli et al., 2013b), while the water levels, used for the flow area computation, was inferred from the

ENVISAT altimeter data. Moreover, if the river section geometry is unknown, the entropy method proposed by Moramarco et al. (2013) may be used for reconstructing the cross-section flow area from the flow velocity (estimated by MODIS). This approach may be conveniently applied in poorly gauged or ungauged river where *in-situ* data are scarce, inaccessible or absent.

The Po River (in Northern Italy), where daily *in-situ* water level and discharge observations are available, is used in this work as a case study. *In-situ* and satellite-derived discharge data are compared in order to assess the reliability of the proposed procedure.

2. METHODOLOGY

2.1 Water level derived by radar altimeter data

In order to evaluate the accuracy of altimetry data a preliminary analysis was carried out by comparing the satellite water level observations with *in-situ* water level measurements. ENVISAT RA-2 provides a water level time series at the virtual station (VS), i.e. the location where the satellite track intersects the river reach, with 35-day time interval, while (*in-situ*) discharge and water level data are available at daily temporal scale. Therefore, for the data comparison, the water levels measured *in-situ* are selected in temporal correspondence of the acquisition dates of the satellite sensor overpasses. The comparison between the water level time series, observed at a gauged station and derived by altimetry, was carried out removing the temporal average values computed considering both the whole time series (Tourian et al., 2013).

2.2 Flow velocity estimation by using MODIS data

For a detailed description of the approach we refer the reader to Tarpanelli et al. (2013b). In what follows, only a brief synthesis is reported. Following the studies of Brakenridge and Anderson (2006) and Brakenridge et al. (2007), we exploit the different behavior of water and land in the Near Infrared (NIR) portion of the electromagnetic spectrum (MODIS channel 2). Specifically, in the NIR region, the reflectance values of the water pixel are lower than the ones of the common land pixel and whenever the water surface level increases (i.e. during flood events) affecting a wider portion of the pixel, a further reduction of the reflectance value of the investigated area has to be expected. These reflectance measurements are affected by significant noise induced by atmospheric factors. Over a large area this noise may be minimized by calculating the ratio between the surface reflectance of a land pixel (*C*) and a water river pixel (*M*). The ratio is sensitive to the increased water level within the river as well as to the presence of wet areas in the analysed pixel and, hence, of discharge (i.e. flow velocity). The procedure used in this study can be summarized in the following five steps:

1. from each MODIS image we selected the box centered in the investigated area, that is the VS, for which the water levels derived by radar altimetry are available;

2. the pixels affected by cloud cover and/or snow are identified both by using a fixed threshold on reflectance values of the first channel, R_1 (R_1>0.2) and a visual inspection and then excluded from the analysis;

3. the position of pixels *C* and *M* is chosen following the guidelines described in Tarpanelli et al. (2013b) for ungauged sites and the ratio between the temporal series of the reflectance values of the second channel R_2 corresponding to the two pixels is calculated;

4. since the trend of the ratio *C/M* appears quite noisy due to the high variability of the surface reflectance values, the exponential smoothing filter (Albergel et al., 2008; Wagner et al., 1999) is applied to reduce this effect, obtaining *C/M**.

The regional relationship

$$v = 0.56 \cdot C / M^* - 0.03 \quad (1)$$

proposed by Tarpanelli et al. (2013b) between the reflectances ratio *C/M** and the mean flow velocity, *v*, derived by using MODIS data at four river reaches along the Po River is here used for obtaining the velocity at the VS after that the ratio *C/M** is estimated.

2.3 River discharge estimation integrating MODIS and altimetry data

The discharge is assessed by multiplying the mean flow velocity by the flow area calculated as a function of the water level. If the cross section survey is known, we may use the MODIS ratio, *C/M**, to derive the mean flow velocity from the regional relationship, and the water level, *h*, derived from the altimetry data for the evaluation of the flow area, *A*, from the *A(h)* relationship.

2.4 River cross-section estimation

If the river cross-section is unknown, the entropy-approach as proposed by Moramarco et al. (2013) is applied. This method allows determining the flow depth distribution in a natural channel and it is used here for the cross-sectional estimation of the flow area. For each measurement the method requires the surface velocity, the maximum flow depth and the channel width. In detail, the flow depth distribution, *d*, along the horizontal distance *x* from the vertical *y*-axis (*x*=0), where the maximum surface velocity across the river, v_{maxS}, occurs, is given by

$$d(x) = \frac{D}{W} \ln\left[\frac{e^W - 1}{v_{\max S}} v_s(x) + 1 \right] \quad (1)$$

where *W* is a parameter, *D* is the maximum flow depth and v_s is the surface water velocity for each vertical that is calculated as a function of v_{maxS} assuming an elliptical or parabolic profile (Moramarco et al., 2011).

In Moramarco et al. (2013), the ratio between the mean and the maximum flow depth, H_m/D is assumed given by:

$$\frac{H_m}{D} = \left(\frac{e^W}{e^W - 1} - \frac{1}{W} \right) \quad (2)$$

H_m can be also obtained integrating the Equation (1) across the whole flow area:

$$H_m = \frac{1}{L} \int_0^L \frac{D}{W} \ln\left[\frac{e^W - 1}{v_{\max S}} v_s(x) + 1 \right] dx \quad (3)$$

where L is the channel width. Therefore, coupling Eqs. (2) and (3) allows to compute (numerically) the parameter W.

Since the satellites provide the water surface elevation, h, from altimeter and mean flow velocity, v, from MODIS, the entropic method needs further assumptions.

The flow depth, D, is computed as h-z_0, where z_0 is the elevation of the channel bottom level. v_{maxS} is inferred from the mean flow velocity as $v_{maxS}=v/\Phi$ (Chiu, 1989). Φ is a parameter found to be constant for a given river and ranging between 0.5-0.7 in different regions (Moramarco et al., 2004; Moramarco et al., 2011; Ammari and Remini, 2010). Nevertheless, in most cases presented in literature a value around 0.67 can be efficiently employed in ungauged river site.

The channel width, L, is assumed here as a constant and corresponds to the bankfull discharge. In this analysis the information coming from Google Earth Ê is considered. The approach is found able to accurately model the surveyed flow area and assess the corresponding discharge by coupling the flow depth distribution and the surface flow velocity.

2.5 Performance scores

The accuracy of the water level and discharge estimates is determined by using different performance measures: coefficient of correlation, r, root mean square error, *RMSE* and Nash-Sutcliffe efficiency coefficient, *NS* (Nash and Sutcliffe, 1970), the mean absolute error, *MAE* and (for discharge) the relative root mean square error, *RRMSE*, defined as follows:

$$RRMSE=\frac{RMSE}{\overline{Q}_{obs}}\cdot 100 \qquad (2)$$

where $\overline{Q}_{obs}$ is the mean value of the observed discharge. *RRMSE* ranges from 0 to Đ, where 0 is the perfect match between the model and observations.

3. STUDY AREA AND *IN-SITU* DATASET

The study area is the Po River, in Northern Italy, located in the center of a large flat alluvial plain, the Pianura Padana (i.e. the Po river Valley). For this study, only the gauged station of Pontelagoscuro, subtending a drainage area equal to 70,091 km^2, is used (see Figure 1). The geometric characteristics of the gauging station are derived through a ground survey carried out by the Interregional Agency of the River Po in 2005. In particular, the bankfull width and depth are equal to 302 m and 18.73 m, respectively. The Pontelagoscuro station is used for the comparison of the simulated discharges. However, the analysis is carried out considering the VS where the altimetry satellite track overpasses the river and the characteristics of the section are 378 m and 13.20 m for the bankfull width and depth, respectively.

More than five years of daily data of water level, h, from February 2005 to August 2010, are selected for Pontelagoscuro station. The river discharge, Q, at the selected gauging station is derived through a rating curve obtained by the contemporary water level and velocity measurements, occasionally collected for different discharge conditions. The mean flow velocity is computed as the ratio between Q and the river section area A, where A is calculated as a function of the water level, $A = f(h)$.

4. REMOTE SENSING DATASET

As regards the altimetry data, we used River - Lake Hydrology (RLH) products provided by de Montfort University, UK, on behalf of ESA (http://earth.esa.int/riverandlake). We consider the track 315, henceforth named as virtual station (VS), as the location where data derived from ENVISAT are available (Figure 1).

MODIS channel 1 (0.620-0.670 µm ï Red) and channel 2 (0.841-0.876 µm ï Near Infrared) at 250 m of spatial resolution were extracted from MODIS Level 1B (MYD02QKM) datasets, acquired by the sensor aboard Aqua satellite in the same period (February 2005 - August 2010). The images from MODIS are available every day, whereas the altimetry data are provided every 35 days.

5. RESULTS AND DISCUSSION

5.1 Comparison of *in-situ* and altimetry water level

The altimetry data from VS are compared with the *in-situ* water level, removing the average values of both the time series (Figure 2). As the section of Pontelagoscuro is located about 30 km downstream the VS and the time delay between the virtual and the *in-situ* station is less than one day, the observed and altimetry water levels can be considered simultaneous. The altimetry data are in good agreement with the observed data with a coefficient of correlation of 0.88 and the *NS* equal to 0.78. The estimated *RMSE* is equal to 0.70 m, consistently with previous studies. For example, Birkinshaw et al. (2010) found *RMSE* values in the range 0.44-0.65 m along the Mekong river (Malaysia), whereas Bercher and Kosuth (2012) found an average *RMSE* value of about 0.73 m on 27 VSs considering ENVISAT satellite data in Amazon basin.

5.2 Evaluation of mean flow velocity for the VS

All the images of MODIS onboard Aqua acquired in the period 2005-2010 over Northern Italy are firstly processed obtaining surface reflectance values (R_1 and R_2). Successively, for each image, a box with dimensions of 29x33 pixels centred at the VS is extracted (the dashed box in Figure 1) obtaining globally 4764 sub-scenes (2382 for R_1 and 2382 for R_2), almost one per day. After the cloud detection, the number of R_2 images selected is 1121, equal to 47% of the total (2382), representing a huge and robust sample of data.

To identify the best locations for the pixels *C* and *M*, we follow the approach described in Tarpanelli et al. (2013b) for which the urban areas (or areas with temporal coefficients of variation, *CV*, less than 0.4) and the meanders are considered as the best locations for the position of the pixels *C* and *M*, respectively. Following the above guidelines, the pixel *C* is taken in the upper part of the box, where the *CV* is low (*CV* = 0.37) and an urban area is present, and *M* is located very near the river as shown in Figure 3a. Successively, the ratio *C*/*M* is calculated considering the temporal series of the selected pixels. In order to reduce the effects of the short term and observation noises, the exponential smoothing filter is applied choosing *T*-value equal to 20 days (comparable to the revisit time of the Aqua satellite equal to 16 days). As a result, once *C/M** time series is identified, the mean flow velocity can be estimated, by applying the regional relationship (Eq. (1)). Figure 3b shows the comparison between the *C/M** and the *v* time series, normalized to identify approximately the same range of variability. The *C/M** index closely follows the seasonal pattern of *v* with higher values in the winter season and lower in summer. Interestingly, MODIS-derived data are also able to identify the difference in the *v* values among the different years. In fact, in the period 2005-2007 the *C/M** values were considerably lower than in 2009 and 2010, in good accordance with the *in-situ* observations. Nonetheless, the discrepancies, as for instance, in the second half of 2007, between the two time series highlight the residual noise not accounted for in the developed procedure.

5.3 Evaluation of mean flow area by using entropic approach

The mean flow velocity derived by MODIS is here used for estimating the maximum surface velocity. Generally, the ratio between the mean and the maximum velocity for different flow regimes is found constant and for the Po River is equal to 0.668 (Moramarco et al., 2011). As above specified, a value of 0.67 might be assumed if no measurements are available in the study area. Assuming the surface velocity distribution as an elliptical profile, the maximum surface flow velocity for each vertical is calculated and used in the entropy flow depth distribution. As regards the entropy parameter, *W*, which is an indicator of ratio between the mean and maximum flow depth, it is calculated coupling equations 2 and 3. For the Po River the value of *W* is found more than twice the ones obtained by Moramarco et al. (2013) for narrower rivers (e.g. Tiber River, from 30 to 70 m) compared to the Po River (~300 m). Specifically, the width of the Po River at the VS has been extracted by Google Earth Ê and is equal to 352 m.

For the estimation of maximum flow depth, we assumed the bottom level at the centre of the cross section to be known. From the water level derived by satellite altimetry, Eq.(1) is used for estimating the flow depth distribution. Concerning the calculation of the cross section flow area A, this is addressed by integrating Eq.(1) along the river cross section. Therefore, for each measurement of velocity and water level, an estimation of flow area is provided.

The flow area calculated following the entropy approach is very well predicted (the *RMSE* value is 43 m^2, whereas the RRMSE is about 3%). This result confirms the reliability of the assumption for considering the central point as the point where the maximum depth occurs.

5.4 River discharge estimation by coupling altimetry and MODIS data

In Tarpanelli et al. (2013b) the discharge is inferred as the product of the velocity derived by *C/M** according to the regional relationship and the flow area estimated considering the water levels measured *in-situ*. In this analysis, for the estimation of the river discharge two cases are analyzed: 1) the cross section geometry is available from *in-situ* survey, 2) the cross section geometry is reconstructed through the entropy approach. In both cases, the flow area is estimated considering the water level derived from satellite altimetry. Similarly to the water levels, the simulated discharges are also compared to the ones observed in the nearest *in-situ* gauged station of Pontelagoscuro, in the same day of observation.

In the case of known bathymetry, the comparison between the observed and simulated discharges reported in Figure 4 shows a slight overestimate for low flows and an underestimate for high flows. The latter result is expected as MODIS is unable to detect the reflectance value during high flows or flood event because of the high probability of cloud cover (Khan et al., 2012). However, the performance of the proposed approach is quite good with coefficient of correlation equal to 0.91 and *RMSE* and *RRMSE* equal to 423 m^3s^{-1} and 36%, respectively (see Table 1). The analysis is carried out also choosing other locations for *M* and *C* (not shown for brevity) and very similar results are obtained.

In the second case, in which the cross section geometry is reconstructed through the entropy approach, the results in terms of discharge worsened remaining very close to those obtained by considering the geometry of the actual cross-section (see Table 1). The coefficient of correlation remains high and equal to 0.91, whereas the *RMSE* increases and the Nash Sutcliffe decreases. The error on the discharge of about 38% is a good result considering that only a ground point (the middle point elevation of the cross-section) was used in the analysis.

In order to evaluate the different error sources for assessing the discharge, a further analysis, exploiting satellite data in a separate way, is carried out. In particular, the discharge is evaluated with two different approaches: 1) by the product of the MODIS-derived velocity and the ñobservedò flow area, namely Q_{MODIS} and 2) by the product of the ñobservedò mean flow velocity and the flow area determined considering the satellite altimetry-derived water level, namely Q_{ALT}. The discharge observed at Pontelagoscuro gauged station is assumed as a benchmark. The ñobservedò flow area and ñobservedò mean flow velocity are computed at the gauged station, whereas the satellite data (velocity and water level) refer to the VS. In both cases, the actual cross sections are considered in the analysis. As shown in Table 1, the maximum source of error is due to the velocity derived by MODIS with the RRMSE equal to 43%. Although the error on the velocity is quite high, in the final evaluation of the discharge this aspect is compensated by the good performance of the altimetry that provides lower error (RRMSE = 22%). Indeed, the river discharge obtained through MODIS and altimetry data, Q_{MODIS} (blue line in Figure 5a), is strongly affected by the error on the velocity derived by MODIS, leading an overestimation for low flow, as for example in the 2006 and 2007, and an underestimation for high flow, as shown for the peak discharge in 2008 and 2010 (see also Figure 5b). On the contrary the use of altimetry with the ñobservedò cross section and the ñobservedò mean flow velocity gives very good results as shown by the red circle lying above the bisector in Figure 5b. As an explanation, it should be stressed that one possible residual source of error could be related to the MODIS data reprojection operation. This procedure needs when spatially co-located series of data have to be analyzed. When data are acquired at very high zenithal angle, the actual spatial resolution is higher than the nominal one (i.e. 1km at Nadir for MODIS), so that during the reprojection of these data a smoothing of the detected reflectance value may be possible. It is expected that further studies on the topic for deriving mean flow velocity from MODIS and the future Sentinel-3 mission, in which a visible-near infrared multispectral sensor (i.e. the Ocean and Land Colour Instrument, OLCI) and an altimeter (i.e. the Sentinel-3 Ku/C Radar Altimeter, SRAL) may contribute to the improvement of the proposed procedure. Indeed, the two sensors will provide data with both better vertical accuracy (total range error up to 3 cm) and higher spatial (inter-track separation at the equator of 52 km) and temporal resolution (27 days for SRAL with 2 satellites); besides, being onboard the same satellite platform, the issue of having simultaneous measurements will be solved.

6. CONCLUSIONS

A study addressed to evaluate the potential of satellite data for estimation of the discharge in poorly gauged river sites is presented in this paper. Specifically, the discharge is assessed as the product of the flow velocity derived from MODIS and the flow area, calculated as a function of the water levels derived from the radar altimeter onboard ENVISAT satellite.

The obtained good results (relative root mean square error of about 37% and a correlation of 0.91 with in-situ measurements) demonstrate the potential of coupling the two satellite sensors to calculate the discharge. The procedure can be applied also when the river section geometry is unknown by using the entropy approach proposed by Moramarco et al. (2013) for estimating the river bathymetry from the flow velocity estimated by MODIS. However, the latter method needs the knowledge of at least one point of the bed level.

These aspects may be of particular interest in view of the next satellite mission Sentinel-3 for which the Ocean and Land Colour Instrument (OLCI) and the Sentinel-3 Ku/C Radar Altimeter (SRAL) will be onboard the same satellite thus solving the issue of having simultaneous measurements, with improvements in terms of both vertical accuracy and spatial and temporal resolution.

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TABLES

Table 1 Comparison between the discharges calculated by using the actual and reconstructed cross section and the ones observed at Pontelagoscuro gauged section (*RMSE* = root mean square error; *NS* = Nash Sutcliffe efficiency; *RRMSE* = relative root mean square error; *MAE* = mean absolute error). For symbol, please see text.

DISCHARGE	**RMSE (m^3s^{-1})**	**NS (-)**	**RRMSE (%)**	**MAE (m^3s^{-1})**
Q_{MODIS} **(Actual geometry)**	506	0.65	43	447
Q_{ALT} **(Actual geometry)**	259	0.90	22	165
$Q_{MODIS+ALT}$ **(Actual geometry)**	415	0.75	36	346
$Q_{MODIS+ALT+ENTR}$ **(Reconstructed geometry)**	448	0.72	38	363

FIGURES

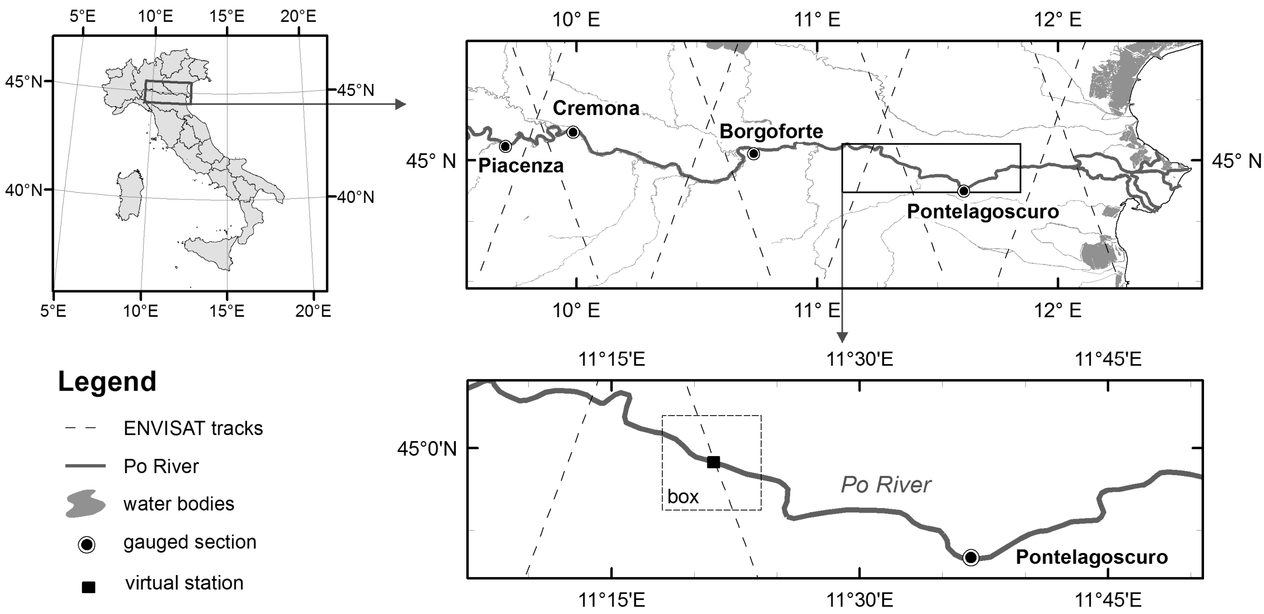

Figure 1. Location of the Po River study area. The ENVISAT satellite tracks, the Pontelagoscuro gauged section and the box used for the MODIS data analysis are also shown.

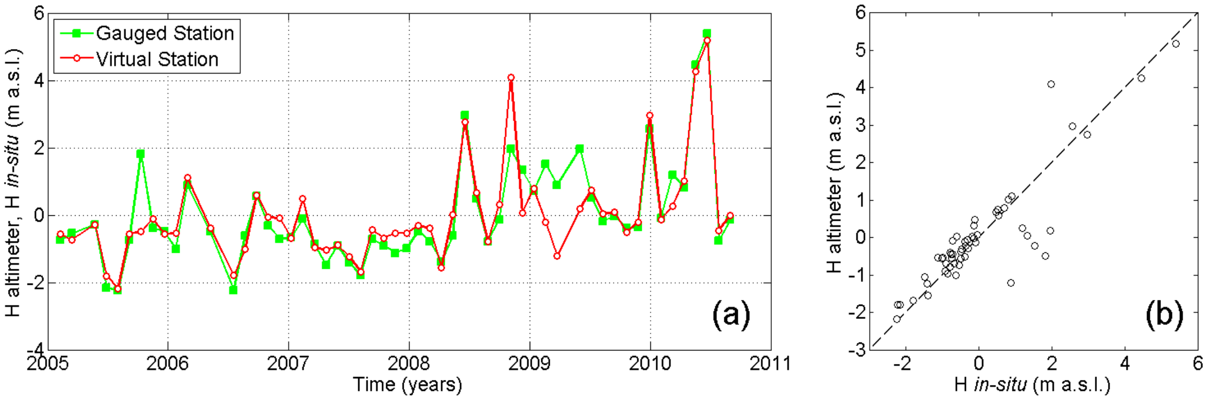

Figure 2. Comparison between the water levels recorded at the *in-situ* gauged station of Pontelagoscuro and the ones provided at the virtual station (VS) by ENVISAT RA-2.

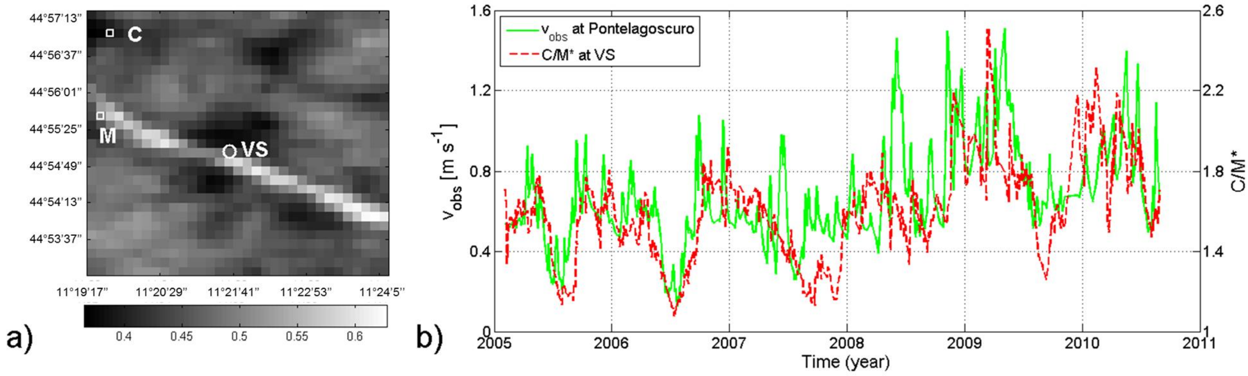

Figure 3. a) Map of temporal coefficients of variation of the reflectance values of the box VS shown in Figure 1; b) Comparison between the temporal series of mean flow velocity observed at Pontelagoscuro, v_{obs}, and of the MODIS ratio C/M*.

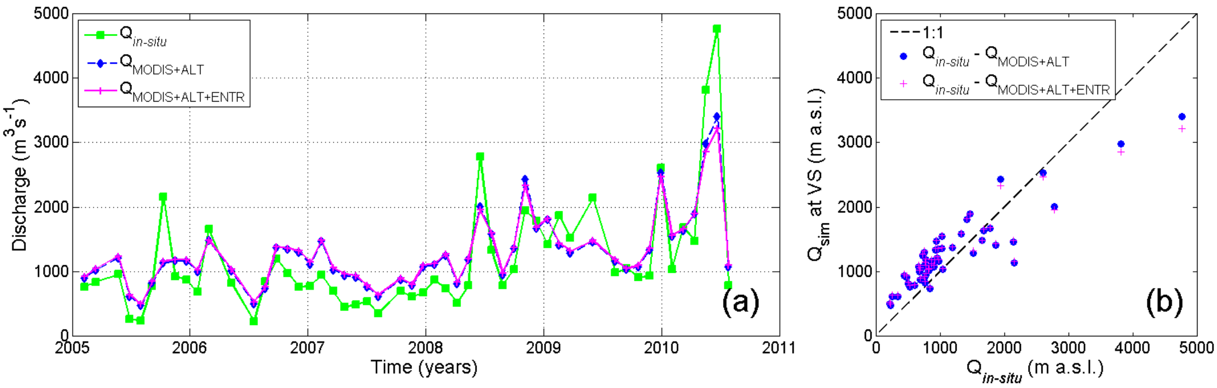

Figure 4. Comparison in terms of the temporal series a) and the scatter plot b) between the discharge observed at Pontelagoscuro gauged station, $Q_{in\text{-}situ}$, and the one simulated at the virtual station VS, Q_{sim}, by considering the actual section geometry, $Q_{MODIS+ALT}$, and the one derived by the entropy approach $Q_{MODIS+ALT+ENTR}$.

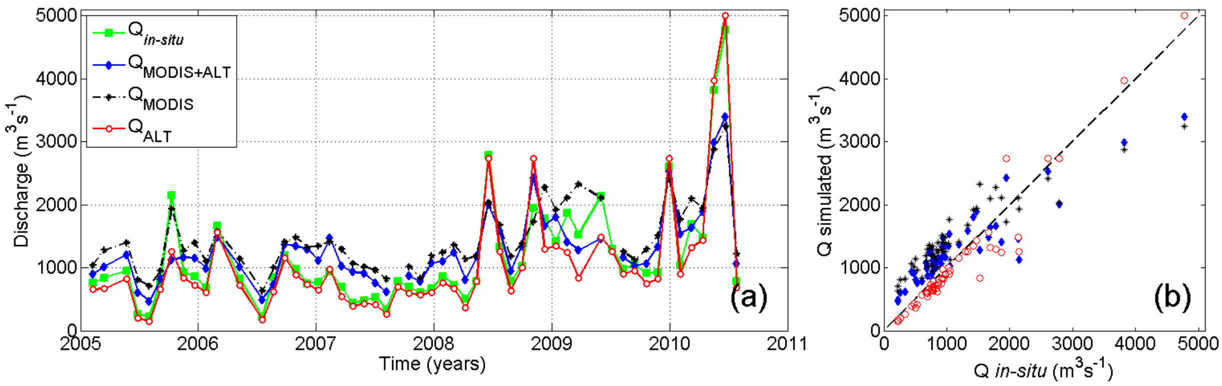

Figure 5. Comparison in terms of the temporal series a) and the scatter plot b) between the discharge observed at Pontelagoscuro gauged station, $Q_{in\text{-}situ}$, and the ones simulated at the virtual station VS, by considering the actual section geometry, $Q_{MODIS+ALT}$, Q_{MODIS} and Q_{ALT}. For symbol see text.