Satellite derived data to support flood modelling

An application to the Po River

MILOS DINIC

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“Scientists use satellites to track weather, map ice sheet melting, detect diseases, show ecosystem change... the list goes on and on. I think nearly every scientific field benefit or could benefit from satellite imagery analysis.”

- Sarah Parcak
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Abstract

Satellite derived data has become an essential input in hydraulic modelling. Digital Elevation Models (DEMs) derived from different sources through remote sensing techniques have become a powerful tool for poorly gauged regions. This paper analyses the capabilities of a DEMS derived from Shuttle Radar Topography Mission (SRTM) and a Light Detection and Ranging (LiDAR) and compares their accuracy against each other in a 1D hydraulic model. The study tests two different methods for inferring the river bathymetry under the water surface level for the SRTM derived DEM in order to enhance its performance, the study further analyze the reliability of remotely sensed altimetry data derived from different satellite missions (TOPEX and ENVISAT) and its suitability to complement spaceborne topographic data in hydraulic modelling.
Summary

Digital Elevation Models (DEMs) global availability generated a growing tendency in implementation of remotely sensed data into hydraulic modeling. Light Detection and ranging (LiDAR) and the Shuttle Radar Topographic Mission (SRTM) are some of the most commonly used sources of data in flood modeling. The DEMs are characterized by different precision and accuracy based on their resolution and satellite capabilities. LiDAR is able to produce high-resolution DEMs at a high cost, while SRTM, with a lower cost, is rather limited.

This study evaluated the impact of accuracy and precision in a one-dimensional model for a high flow event. The simulations presented a fair performance for the SRTM based model (MAE: 0.76 m) in comparison of the high performance of the LiDAR based model (MAE: 0.19 m).

As for low flows with the complementary implementation of radar altimetry data (RALTS) provided by different satellite missions. This, in order to asses remotely-sensed water elevation data integration to traditional hydrometric data, which can improve the reliability of the hydraulic model. Satellite data is characterized by lower frequencies of measurement, making the accuracy of remotely-sensed water surface water levels limited. Therefore, a combination of in-situ and remotely sensed water levels was implemented to observe the similarities and limitations of its performance in modelling of a low flow regime. A similar result in accuracy in comparison with the high flow modelling was obtained and a clear agreement between the RALTS data and the in-situ data. (LiDAR VS1 MAE: 1.03, VS2 MAE: 1.05 and Boretto MAE: 0.92; SRTM VS1 MAE:1.88, VS2 MAE: 1.75and Boretto MAE:5.1).

SRTM DEMs lacks the capability of measuring the river bathymetry below the lowest observed water surfaces, thus reducing its value for estimating the river discharge. This study evaluates the possibilities of mitigating this limitation testing two different procedures Channel Bank (CB) and Slope Break (SB) for estimating the river bathymetry under the water surface level, which later on was implemented for high and low flow modelling. A very slight increase in accuracy for high flows for both methods in comparison with the original SRTM-based model were found (CB MAE: 0.70, SB
MAE:0.73), nevertheless, for low flow modelling a higher increase in accuracy in both methods was clearly present comparing to the existing gauging stations. However, this improvement in accuracy was not observable in the comparison to the RALTS data set, which may derive from the lower frequency of data collection by the satellite missions. (CB VS1: 0.5, VS2: 1.2 and Boretto: 2.03; (SB VS1:0.61, VS2: 0.61 and Boretto: 0.71).

Results show that both CB and SB approaches enhance the performance of the SRTM-based model in the modelling of low and average flow regimes, as well a better understanding of the limitations of the RALT data measurements.
Sammanfattning

En av växande trender inom hydraulisk modellering är användning av topografiska satellitdata DEM (Digital Elevation Models). Två, idag vanligaste, källor för satellitdata dom appliceras i hydraulisk modellering är LiDAR (Light Detection And Ranging) och SRTM (Shuttle Radar Topographic Mission). Av de två LiDAR är den källan till DEM som genererar mer högkvalitativ upplösning än SRTM men kostnaden för inhämtningen är lägre hos SRTM än LiDAR.

Först, den här studien fokuserar på hur endimensionell hydrauliska modell baserad på topografiska data från SRTM och LiDAR presterar vid höga flöden. Prestationen jämförs med värden uppmätta på plats vid översvämningshändelse i oktober 2000. Resultatet, i form av det genomsnittliga absoluta avvikelse, för de simulerade och uppmätta värden är 0.19 m för LiDAR och 0.79 m för SRTM.

Sedan användes samma hydrauliska modeller för simuleringar av låga flöden och resultaten av dessa simuleringar jämfördes med inhämtad vattennivådata från två stycken satelliter (VS1 och VS2). Som komplement till inhämtade värden från satellitdata, användes även värden uppmätta vid markstationen Boretto. Det absoluta genomsnittliga avvikelse (AGV) för SRTM och LiDAR baserade modeller och VS1 och VS2 var snarlika medan stor skillnad märktes vid markstationen Boretto. För SRTM var AGV 1.88 m och 1.75 m för VS1 respektive VS2 och 5.1 m för markstationen Boretto, för LiDAR var avvikelse 1.03 m och 1.05 m för VS1 respektive VS2 och 0.92 m vid Boretto.

SRTM saknar förmåga att penetrera genom vattenytan vilket resulterar stora osäkerheter kring bottens utformning. För att kompensera för begränsningen, två olika metoder att beräkna och utforma bottenytan under vatten användes, Channel Bank (CB) and Slope Break (SB) metoder. Med hjälp av dessa metoder ny bottentytta har utformats på två olika sätt, genom att sänka botten yta jämt över hela sträckan med ett genomsnittligt värde och att sänka botten yta med olika beräknade nummer på 62 ställen. Resultaten visade endast smärre förbättringar för LiDAR modellen för både höga och låga flöden.
För SRTM modellen den stora skillnaden kunde upptäckas när låga flöden simulerades medan för höga presterade modellen med mindre förbättring.

Resultaten visar att LiDAR baserad modell presterar bättre är SRTM baserad på grund av dennes högre precision vid inhämtningen av data. Hur som helst så är det värt att nämna att modellen baserad på SRTM DEM förbättrade sin prestation med metoder att beräkna bottens utformning under vatten ytan.
Introduction

In this part the background for this study will be presented and how this study takes the
research further will be described.

Background and previous studies

The use of remote sensing has become an important tool for different hydrological and
hydraulic applications, especially in areas where the data collection can be proven
costly or hard to achieve due to accessibility to the study area. Furthermore, the
maintenance of hydro-meteorological stations has become increasingly expensive and
there is an absence of stream related data in different regions of the world, which
impairs the capacity for modelling large river systems. (Hossain and Katiyar, 2006)

For hydraulic modelling of flood events, one of the most important and growing
resources is the use of digital elevation models (DEM) derived by remote sensing. A
shift from the traditional surveying methods to remote sensing techniques has proven to
be an advantage in terms of processing, costs and accuracy of the data. One of the
biggest breakthroughs came with the implementation of remote sensing techniques for
wide-areas topographic mapping, including the use of Shuttle Radar Topography
Mission (SRTM) and later on the use of airborne laser altimetry (LiDAR), which makes
it possible to obtain high end spatial resolutions from 2 to 5 meters in comparison to
traditional surveying methods (Bates, 2012).

The different resolutions, vertical precisions and accuracy of a DEM depend on the
different types of equipment and methods used to obtain the topographic data. This
difference in quality of the DEMs will result in different model output performances
when used in hydraulic modelling (Md Ali et al., 2014a).

Different studies have been performed in order to evaluate the impact of the accuracy
and precision of the different topographical data on their application in hydraulic
modelling using both 1-D and 2-D models for flooding. (Md Ali et al., 2014b) (A. Koch
and C. Heipke, 2001)
Schumann et al. (2008) compared water stages at different types of DEMs (derived from LiDAR, SRTM and topographic contours) with different resolutions using a calibrated flood model in HEC-RAS 1-D simulating flood propagation in the Alzette River in Luxembourg. The results showed a good performance of SRTM with an acceptable RMSE (1.07 m) in comparison to its more accurate counterpart LiDAR, which, as expected, had the lowest RSME (0.35 m). This study showed that SRTM can be a valuable source of information for initial studies in flooding in large homogenous flood plains, saving resources as for the information being of public domain.

DEM resolution, vertical precision and accuracy differ due to the types of equipment and methods implemented to obtain the data. There are three different types of errors that are found in DEMs data sets: Blunders, which are a type of vertical errors caused by careless observations, erroneous correlations and misreading of the contours; Systematic errors, which derive from the procedures or systems used in the capture and extraction of data and follow a pattern; and random errors (A. Koch and C. Heipke, 2001).

Studies performed by Ludwig and Schneider (2006) investigated the general accuracy of SRTM X-SAR elevation data and its value for applications in hydraulic modelling. The results of their studies found out those SRTM data sets have a high vertical accuracy, yet after removing surface objects a higher systematic error in the SRTM DEMs which was partially hidden by vegetation and other surface objects. In roughed terrain, the elevations errors increased considerably due to the effects of radar shadow. The overall quality of SRTM DEMs in an overall quality proved sufficient for hydrological modelling with very little impact on the model results.

As lack of topographical data represents an issue, the lack of measurements of water levels represents a challenge for calibrating hydraulic models. Remote sensed data for estimating water elevations and flooded areas has recently become an increasingly employed tool in hydraulic modelling. The advances in radar altimetry (RALT) lead to an increase in the use of these sensors for inland water bodies. Studies have focused on the combination of RALT levels with field measurements of discharge data in order to estimate rating curves in places where the satellite tracks intersect the river reach, which is in literature is referred as a virtual station (VS) (Domeneghetti et al., 2014a).
(Biancamaria et al., 2011) used Topex/Poseidon satellite altimetry measurements of water levels of the Ganges and Brahmaputra river combined with in-situ measurements inside Bangladesh to extend the expand the operational forecasts for flood events the with a very small RMSE for period of times of up to 5 days (0.4 m) providing useful information for operational application, thus demonstrating that VS derived from satellite altimetry data can have a high potential to improve forecast of flood events.

Domenghetti et al. (2014) compared a calibration of a quasi-two-dimensional hydraulic model of a lower part of the Po River using different configurations of data as for in-situ observed data, remote sensing data provided by ERS-2 and ENVISAT satellites and a combination of both. The results of the study showed that satellite data can describe hydrometric regimes of river reaches that are at least 400 m wide with effectiveness. It demonstrated that despite the accuracy of satellite data cannot be highly accurate; a large data set can integrate the in-situ measurements enhancing the calibration capacity of hydrodynamic numerical models.

One of the biggest limitations of using DEM in hydraulic modelling is the absence of information on the submerged river portions. River bathymetry cannot be inferred directly from satellite instruments due to the inability to penetrate the water surface. Different procedures to estimate the river bathymetry under the water surface level have been discussed in literature. Mersel et al. (2013) explored the Linear and Slope-Break(SB) method to identify optimal locations where the water surface elevation \( (h) \) can be extrapolated. They concluded that the linear method has high uncertainty, while the Slope-Break method holds better results.

In another study, Domeneghetti (2016) analyzed how 1-D numerical model performance can be enhanced by using the Channel Bank-full (CB) depth and Slope-Break(SB) approaches to improve the description off cross sections in SRTM-based models. He concluded that both approaches enhance the performance, in which Slope-Break showed high efficiency.

A combination of the different DEMs and the RALTs data set in order to have a bigger picture of application of satellite based data as a whole in hydraulic modelling its
needed to further investigate the possibilities of performing flood predictions without the use of in-situ data and understand the limitations of satellite data.

**Aim and objectives of the thesis**

The study combines available space borne data, both topographical and hydrological, to analyze their performance in flood modelling for both high flow and low flow scenarios and in combination with in-situ measurements. In particular, this study investigates the performance of remotely sensed data for hydraulic flood modelling by considering the following:

I. Evaluate the performance of integrated space borne DEMs (SRTM) in flood modelling for the central reach of the River Po, between Cremona and Borgoforte, in comparison with LiDAR-derived topographical data.

II. Study the effectiveness of RALT data from Virtual Stations between Cremona and Borgoforte combining them with observed water levels in the gauge station at Boretto, for the calibration of the flood model using the previously mentioned space borne DEMs.

III. Test the two different approaches (Channel Bankfull (CB) depth and Slope-Break(SB)) proposed by Domeneghetti (2013) to improve the description of the SRTM derived cross section geometry below water surface.
Study Area and Collected Data

In this section, methodology of the performed study will be presented which includes approach and data used in order to achieve results and answer the research questions. Also, the study area where the research question is applied will be presented.

Study area

From the northern-eastern Alps in the west to Adriatic Sea in the east stretches a 650 km long river named Po. Po river is one of the biggest rivers in Europe and the biggest one in Italy with basin area of 71 000 km² and total of 140 tributaries. River’s large floodplain plays a very vital role in Italy’s agricultural sector so knowledge on river’s hydrological characteristics is essential from economical point of view. Also because of river’s large extent and its importance, there are many inhabitants who resident there which makes the rivers behavior important from social stand point (Domeneghetti et al., 2014a)

The study area adopted in this research includes the middle-lower portion of the Po River, from the city of Cremona, on the upstream side, to city of Borgoforte which will be the downstream boundary (Figure 1). The extent of the delineated section is 98 km with the width of the main channel varying between 200-500 m. Along the same reach the two lateral banks varying in width between 0.2 – 5 m and the bed slope of the river reach is 0.2 m · km. (Mazzoleni et al., 2015)
The reason behind chosen river reach is based on availability of the data needed to perform purposed modelling and analysis to reach the aim and objectives for this study. All the data will be described further down in this report.
Space born data

Data gathered by the satellites will be presented here.

SRTM data

The Shuttle Radar Topography Mission (SRTM) is an international project to acquire radar data to create a global set of land elevations. The first mission was flown by the Endeavour in year 2000 in a mission commanded by NASA. The shuttle used single-pass interferometry using 2 different set of antennas using the difference between them to calculate the Earth’s surface elevation. The elevation models produced by the mission are derived in tiles covering five degrees of latitude and five of longitude. (US Geological Survey, 2015)

Globally, three arc-seconds (90 m along the equator resolution) are available for mostly all parts of the globe. The derived DEMs have a reported error less than 16 m. The existing no-data have been filled by the production of vector contours and points, and the re-interpolation of these derived contours back into a raster DEM by researchers at the CIAT Agroecosystems Resilience project. SRTM DEM with 90 m resolution will be used in this project (figure 2) (CGIAR Consortium for Spatial Information, 2017).

![Figure 2 SRTM DEM](image-url)
LiDAR data

Light Detection and Ranging uses a light in form of a pulsed laser to measure different distance ranges from the Earth’s surface. Combined with other airborne data, they can generate complex and detailed three-dimensional information of the surface characteristics. The most common way of collection LiDAR data is by Airplane helicopters in large areas (US Department of Commerce, 2017).

The LiDAR used in this study (figure 3) was collected by the Italian authority of the Po River’s basin with a resolution of 2 m acquired in 2005 from the middle-lower portion of the river and its mayor tributaries, the elevation was obtained by different airborne-techniques (Autorità di bacino distrettuale del fiume Po, 2016).

Figure 3 LiDAR DEM
Hydrological data

Virtual Stations (VS)

RALT water levels were measured at the points in which the satellite tracks intersect with the river reach, thus estimating the rating curves at these points. Different sources will be used in the study.

The (Institute of Geodesy (GIS) University Stuttgart, 2016), within the Faculty of Aerospace Engineering and Geodesy, provided information of altimetry data from the year 1992 to 2015 using satellite information from the satellites Topex (NASA) and ENVISAT (ESA) missions for Virtual Station 1 (VS1).

The Database for Hydrological Time Series of Inland Waters (DAHITI) from the Munich Technical University (TUM) provides real time water level series at different points of the Po River using a multi-mission altimeter data from Topex (NASA), Jason-1 (NASA) and other satellites, which will be found at the Virtual Station 2 (VS2) (Schwatke et al., 2015).

Figure 4 shows the location of the river reach boundary condition (Cremona and Borgoforte) and the location of the two virtual stations.
Gauge station in Boretto and Cremona

In addition to the virtual stations, one gauged station at Boretto (figure 4) is available. Data from this station is used to calibrate model for low flows and it is gathered between year 2002-2010. For high flows, the hydrograph from flood event in year 2000 at station of Cremona will be used. The data was provided by the regional agency for the prevention, environment and energy of Emilia-Romagna (ARPAE, 2016).

Methods

Comparison of space borne topographic data sets

Longitudinal Profiles

The elevations of the different DEM sources were extracted from the study area to analyze the influence of spatial resolution. First, the difference between the LiDAR and SRTM data sets were compared through extracting the elevations following:

1. 62 ground points (in each selected cross section) along river reach longitudinal profile of the study stretch for the lowest elevations.
2. 62 ground points (in each selected cross section) along the dike systems on both sides of the river embankments for the highest elevations.

The difference in elevation was assessed by means of the mean absolute error (MAE):

$$MAE = \frac{1}{P} \sum_{p=1}^{P} |L_p - S_p|$$  \hspace{1cm} Eq.1

Where P is the number of points along the profile, $L_p$ is the elevations extracted from the LiDAR data set at each point $p$, and $S_p$ is elevations extracted from the SRTM data set.
Cross Sections

Along the study stretch 62 cross sections were extracted from both data. For each of the cross sections, the elevation was extracted every 2 meters to plot the cross sections profiles and observed the difference by means of the mean absolute error (MAE). Positioning and the length of the cross sections (figure 5) are based on the AIPO ground survey.

![Figure 5 Positioning of the cross sections](image)

Numerical Modelling

We are implementing a 1-dimensional modelling using the software package HEC-RAS in which the different cross sections extracted from the remote sensing data will be input along with the boundary conditions. HEC-RAS was developed at the Hydrologic Engineering Center (HEC), which is a division within the Institute of Water Resources in the U.S. Army Corps of Engineers. The first version of the software was released in July of 1995. (Hydrologic Engineering Center, 2016)
HEC-RAS 1-dimensional modelling for a steady flow is based on solving the one-dimensional energy equations from Saint Venant (Eq. 2 and Eq. 3). This component of the modelling system focuses on calculating the water surface profiles for a steady gradually varied flow. The energy losses are evaluated by the friction depending on Manning’s coefficient $n$ and contraction/expansion dependent on the change of velocity heads. (Hydrologic Engineering Center, 2016)

\[
\frac{\partial A}{\partial t} + \frac{\partial (Au)}{\partial x} = 0 \quad \text{Eq. 2}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial \zeta}{\partial x} = -\frac{P}{A} \quad \text{Eq. 3}
\]

In order to analyses the performance of performance of the satellite borne data, two different scenarions of calibration where implemented:

1. High Flows
2. Low Flows

Model Calibration using high flows

For the high flow condition scenario, two hydraulic models were set up: one with the Lidar extracted cross sections and one with SRTM extracted cross sections. The hydrological information used to calibrate the model is based on ground observation from the October 2000 flood event. The models were run in unsteady flow conditions. The estimated peak flow of the event in Cremona is approximately 11871 m$^3$/s, and the observed hydrograph in Cremona was as upstream boundary condition (from October 13th 2000 to October 22th 2000), see figure 6 For the downstream condition a friction slope of 0.0185% was calculated, based on mean slope of the last 1000m of the river stretch for the LiDAR model and 0.0165% for the SRTM based model.
To assess the sensitivity of the model to the parameters used, the Manning $n$ roughness coefficients for all the simulations were sampled uniformly from 0.02 to 0.06 m$^{1/3}$ s for the river channel, and between 0.06 to 0.14 m$^{1/3}$s for the floodplains, by steps of 0.005 m$^{1/3}$s based on the commonly used tables for Manning’s coefficient values used in previous studies in the same area. (Brandimarte and Di Baldassarre, 2012)

The model was then calibrated, by varying Manning’s $n$ roughness coefficients, against the high water marks (i.e. post-event measured maximum water levels) surveyed after the October 2000 flood event (Coratza, 2005). The performance of the hydraulic model was then assessed by comparing the observed average high water marks in the different 62 cross sections to the simulated ones by means of the mean absolute error (MAE):

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |O_i - S_i| \quad \text{Eq. 4}$$

Where $n$ is the number of the cross section, $O_i$ is the observed water level at the cross section $i$, and $S_i$ is the simulated water lever at the cross section $i$.

Model calibration with low flows

For the low flow condition scenario, the two set up hydraulic models were used. The hydrological information used to calibrate the model is here based on both ground observation in Boretto gauge station (water levels from 2009 to 2016) and remote
sensed information, water levels derived by the two virtual station (VS1 from 2009 to 2015; VS2 from 2009 to September 2015).

Refereed as Virtual Station 1 (VS1), altimetry data are from year 2009 to 2015 using satellite information from the satellites Topex (NASA) and ENVISAT (ESA) missions. (Institute of Geodesy (GIS) University Stuttgart, 2016); whereas VS 2 water level data are derived from data from Topex (NASA), Jason-1 (NASA) and other satellites ( Jan 2009 to September 2015) (Schwatke et al., 2015). Water levels gathered from the virtual stations is illustrated in figure 5.

Figure 7 shows the water level observed at Boretto gauge station.
We use the mean absolute error (MAE) to quantify the performance of each hydraulic model by means of comparing the different water levels in in-situ and remotely-sensed data. The gauging station at Cremona with the daily flow values from January 2009 to December 2016 (see figure 8) was used as upstream border condition, while the friction slope of 0.0185\% for the LiDAR and 0.0165\% for the SRTM based models was used as downstream boundary condition.

It is worth noting that the location of the satellite tracks of each virtual station does not exactly coincide with the gauged station in Boretto. Nevertheless, given that the main scope of our investigation is to assess the performance of remotely-sensed water levels for the calibration of hydraulic models, the satellite data series of the virtual stations are considered to be error-free and the uncertainties regarding the water levels are neglected.
River Bathymetry Estimation with Channel Bankfull- Depth Approach for SRTM

One of the most discussed topics in the field of fluvial geomorphology is the identification of empirical relationships between the different hydromorphic variables. (Such as river depth, river width, and river flow velocity)

The CB approach investigates the possible relationship between the draining area A (km²) and the Channel Bankfull depth \( d_{bf} \) (m) at given point along a river reach in order to enhance the characteristics of the river geometry in hydraulic modelling, which was tested in different geographic and geomorphic settings where more in-situ observations and data were available by Neal et al., (2012).

A theoretical A-\( d_{bf} \) relationship is established based on the existing topographical surveys available at the river cross section, which will establish a linear function to predict the main channel depth at any given ungauged river section based on this relationship. With a given draining area \( A \), which were previously extracted from the geospatial resources available from the Po Basin, using GIS tool, in order to be able to predict the channel bank-full dept \( d_{bf} \), where traditional surveys are limited using the linear function based on the known depths from the gauged cross sections. This method is implemented to the available SRTM DEM to create a new model geometry based on CB modified SRTM cross sections in order to evaluate its performance and compare it with the unmodified SRTM and LiDAR model by means of the MAE.

River Bathymetry Estimation with Slope Break Approach for SRTM

By examining the more detailed topographic data, Mersel at al. (2013) developed a way to approximate river bathymetry for the river topography derived from remote sensed data by using two water surface (h) and flow width (w) relationships. Linear and Slope break method. The later one was proven to be more accurate the linear one because it comprises two linear h-w relationships; one for the low flows and one for the high flows.

The computation, for finding the slope break, begins with an extraction of h-w pairs, at a certain cross section, every 0.5 m. linear relationship between those pairs are
established by calculating the derivatives of those pairs. Further, the mean derivate dh/dw is calculated by using first four initial points and thereafter the derivative will be calculated for each h-w pair until the difference between the initial mean derivate and the new calculated derivate is more than 40%. At that point the slope break is found. For all the w-h pairs under the slope break point the new mean derivate is computed and the new water elevation z_{min} is estimated by using this new mean derivate and interpolate new values until w=0 (figure 9).

Previous studies have shown that, in order to be reliable, the results must be based on at least 5 pairs under the slope break. If there are 4 or less w-h pairs the new z_{min} will not be calculated.

The Slope break approach was applied to the SRTM topographic data and its 62 cross section, one at the time to find the breakpoint and estimate the lowering to be applied to each cross section. A MATLAB code elaborated by Elin Anderson and Sofia Hietala (2018) during their BSc work was is used for calculation of those values.
Uncertainties and assumptions

Modelling natural environment is not an easy task to do because of its complex structure. According to Di Baldassarre (2012), to provide a model which will be able to generate as realistic scenario as possible it is important to simplify it just enough to include all that is needed but not to simple so that the important data are neglected. In order to do so and to define model’s boundaries, assumptions are needed. In following text assumptions made for this particular aim are listed.

- Channel geometry is fixed during the inundation event, no erosion is taking into consideration
- No sediment transport is included in modelling
- No civil structures will be taken into consideration since the effect of those on the flows can be neglected.
- No tributaries will be added into the model because the flow from those has to small impact on the flow from the main river
- Constant roughness coefficient for the whole floodplain outside the main channel
- Satellite data is considered to be error free and water uncertainties are neglected.

All above mentioned assumptions may present a source of results uncertainty to a certain degree but is considered to be too small to be included into created models.
Results

In this part of the thesis the results of comparison between SRTM and LiDAR DEM will be presented along with results from simulations with SRTM and LiDAR based models. Simulated results are compared between the models and against the ground and satellite surveyed data.

Comparison of space borne topographic data sets

In following text, the results for extraction of topographic data from the space borne DEM will be presented. Further the LiDAR and SRTM topographic data will be compared with respect to longitudinal profiles of the main channel and the left and right banks. Topographic data of the extracted cross section with the previous mentioned methods will be presented and compared as well.

Longitudinal Profiles

Extracted longitudinal profiles of the river bed and the dike systems are presented in figure 10. Clear differences between the one extracted from SRTM and the one from LiDAR may be seen. River bed extracted from the SRTM DEM has generally higher elevation value than the one from LiDAR and the differences seem to be increasing at the lower elevations. The river bed extracted from LiDAR shows variation in elevation along the whole river reach while the one from the SRTM doesn’t variate that much which generates more of plane river bed elevation.

In the dike system profiles, the SRTM follows a more similar pattern to the LiDAR, which can be stated that a higher elevation the SRTM is able to show more clearly the variations of the terrain as of contrary to the . (see figure 10b & 10c). In figure 10b and 7c there is clearly shown that the elevation values from the LiDAR extracted profiles are higher the one from SRTM. As mentioned earlier the elevation values for river bed profile are higher for SRTM extracted the for LiDAR extracted profile.
Differences between SRTM and LiDAR extracted profiles of river bed and levee systems are quantified by mean absolute error method and presented in table 1. As it can be seen in the table the mean absolute error does not differ that much between different profiles. In figure 11, the relationship between SRTM and LiDAR is illustrated.
Figure 11 Scatterplots of the SRTM and LiDAR for a) river bed, b) left levee, c) right levee.
Table 1 Average MAE at the different profile from the comparison of LiDAR and SRTM

<table>
<thead>
<tr>
<th>Longitudinal Profile</th>
<th>Average MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>River bed</td>
<td>3.909527</td>
</tr>
<tr>
<td>Left Levee</td>
<td>4.141444</td>
</tr>
<tr>
<td>Right Levee</td>
<td>3.909527</td>
</tr>
</tbody>
</table>

Cross Sections
A comparison of the extracted cross sections demonstrated a lower MAE in comparison to the longitudinal profiles. The SRTM extracted cross sections does not reach the river bed due to that the laser/radar waves used in the remote sensing technique are not capable of penetrating the water surface which limits the capture of the river bed elevations, thus increasing the error in the profiles, which will be analyzed further on the modeling section. The location of small tributaries and vegetation could have affected the accuracy of the SRTM data set in comparison to the LiDAR, nevertheless most of the extracted cross sections presented similar terrain patterns in both data sets.

The highest variations were present in some of the downstream profiles, which can be correlated to SRTM having a less accurate resolution in lower elevation areas and flat floodplains, weather the cross sections with lowest variation are located upstream. This may be connected to results in previous chapter in which it is shown bigger difference between the two methods in the lower parts of the river reach. In figure 12 the comparison of the cross sections is illustrated. In figure 12a, the cross section with the lowest MAE is presented and as previous mentioned and shown in the figure 12, the cross section 27C is the cross section at the upstream part of the river. In 12b one of the cross sections from the downstream part are presented and it is clear that the MAE is much higher in comparison with the cross section 27C. To further understand the differences of how the resolutions of the different DEM resolution different studies have been performed (Md Ali et al, 2014.)
Model calibration: high flow scenario

Model Calibration

You need to recall here what the boundary conditions for the high flow are, what model parameters you varied, what the range was and what the values against which you calculate the MAE are.

Figure 11 shows the model results in terms of the Mean Absolut Error by the two different HEC-RAS models in simulating the 2000 flood event. In figure 13a and 13b the ranges of mean absolute error for SRTM based model while c and d illustrate the same range for LiDAR based model. Changing Manning’s coefficient for the channel showing to notable affect range of MAE (figure 13a and 13c) in both SRTM and LiDAR based models. In cases of variating Manning’s coefficient for the flood plain (figures 13b and 13d) the range of error does not variate in any bigger visible way.
Figure 13 Effects of different Manning’s coefficient on the mean absolute error. a) SRTM channel, b) SRTM floodplain, c) LiDAR channel, d) LiDAR floodplain
To best illustrate the range of all tested Manning’s coefficient the calibration contour map is made, see figure 14. The results of the calibration showed the LIDAR as the best-fit model with general good performances and range of variations of 0.19 to 2.9 m. One of the main differences in both SRTM and LiDAR models is the difference in value in the best performing Manning’s n roughness coefficients, as the ones in LIDAR are more centered in higher ranges at $n_{\text{channel}} = 0.05$ to 0.055 and $n_{\text{floodplain}} = 0.085$ to 0.095. The model based on the SRTM Dem also performed with a shorter range of MAE from 0.76 to 2.79, while the best performing Manning’s n roughness coefficient were located in lower ranges at $n_{\text{channel}} = 0.03$ to 0.034 and $n_{\text{floodplain}} = 0.06$ to 0.065. The results shown the difference in performance of both DEM sources due to the variation in their resolution. The Manning’s coefficient for the best performing models with both methods are shown in the table 2.
Figure 14 Contour maps in which mean absolute error is shown for different combinations of Manning's coefficient. 

a) LiDAR, b) SRTM

Table 2 Best performing Manning’s Coefficients for high flow simulations

<table>
<thead>
<tr>
<th>Model</th>
<th>Calibrated Manning’s n</th>
<th>MAE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel</td>
<td>Floodplain</td>
</tr>
<tr>
<td>LiDAR</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>SRTM</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Figure 13 shows the water surface profile of the best performing set of Manning parameters against the observed water marks for the two geometries: the LIDAR data set shows a lowest MAE of 0.19 m, while the corresponding model for the SRTM shows a slightly higher variation and MAE of 0.76m.

The results of this first analysis indicates that the reduction of resolution of the LIDAR DEM to the SRTM DEM does affect slightly the model performance as well as a less consistency in the best performing Manning’s n roughness coefficients

Results on how the best performing models works taking high flows in consideration is illustrated in figure 15. Looking at a it is clearly seen that the line representing simulated values almost perfectly follows the observed water marks during the event. Illustration on picture b shows how the SRTM based model answers to the values from the flood event and the biggest differences are to be seen in more upstream parts of the river reach. However, at the downstream part which is in the lower altitudes of the river, model follows almost identical line as the observed water marks.
Figure 15 Illustration of best performing model considering high water marks. a) LiDAR, b) SRTM
Model calibration: low flow scenario (space borne and gauged data)

The exercise was performed referring to remotely-sensed water surface elevations retrieved by the different satellite missions for the two considered virtual stations for both experiment configurations with additional comparison to the water elevation at the gauging station in Boretto.

LIDAR Model

For the LIDAR model the virtual station time series were used for the comparison of the model predictions with the best 20 performing pairs of Manning’s roughness coefficient of the high flows scenario. The lowest MAE is 1.03 and 1.05 for respectively VS1 and VS2. Corresponding in both cases to an $n_{\text{channel}} = 0.07$ and $n_{\text{floodplain}} = 0.05$, with a quite accurate performance as presented in figure 16.

The simulated values for the water elevation along the river stretch present a slightly higher marks in comparison of both virtual stations, nevertheless they follow a very similar pattern in the graph behavior as seen in the times series shown in Figure 17.
Figure 16 Scatter plots for model validation at a) VS1 and b) VS2 performed referring to the LIDAR Configuration

Figure 17 Water Level Time Series at virtual stations a) VS1 and b) VS2
The simulated water levels in low flows were compared also to the observed water levels recorded at Boretto gauging station: the calibration results are comparable to the results obtained during calibration against VS1 and VS2 values, thus showing a better in the upper middle section of the stretch with a MAE= 0.92 m with a higher amount of data compared based on the 20 best performing Manning’s n numbers from the high flow scenario.

The scattered plot and time series follow a similar pattern very similar to the virtual stations as shown in the Figures 18a) and 18b). , which for a practical point of view makes the RALT data suitable for reproducing average flow regime associated with medium and low flows conditions.

![Scattered plot and time series](image18)

*Figure 18 Boretto Gauging Station a) Scattered plot b) Water Surface Time Series*
SRTM Model

For the low flow scenario, 20 best performing models were used, with a range of Manning’s coefficient for the channel between $0.03 \text{ m}^{1/3}/\text{s}$ and $0.035 \text{ m}^{1/3}/\text{s}$, for the floodplain, the range was between $0.06 \text{ m}^{1/3}/\text{s}$ and $0.105\text{m}^{1/3}/\text{s}$. Results generated by simulations were compared to water levels recorded by 2 space borne stations VS 1 and VS 2 and also against the values given by gauge station in Boretto.

The best Manning’s coefficient combination is for the VS 2 and Boretto station, $0.03 \text{ m}^{1/3}/\text{s}$ and $0.06 \text{ m}^{1/3}/\text{s}$ with MAE 1.73 and 5.75 m respectively while the lowest MAE for the VS 1 is with combination of the $0.03 \text{ m}^{1/3}/\text{s}$ and $0.105 \text{ m}^{1/3}/\text{s}$ with the MAE of 1.88 m. The results of the best performing model in low flows are illustrated in figure 19.
The results presented above (figure 19) present how the model respond in comparison with the measured values and looking at all of the 3 graphs there can be seen difference on how model reacts to higher and lower flows. At higher flow peaks the simulated values matches it while at the lower flows the gap between simulated and observed values are getting bigger.
River Bathymetry Estimation: SRTM modification

In this chapter the results of river bathymetry estimation are presented. Estimation is done based on two different methods, Channel Bankfull (CB) depth approach and Slope Break (SB) method. Results presented in following chapter will be used for sensitivity analysis on SRTM based model further in the work.

River Bathymetry Estimation with Channel Bankfull- Depth Approach for SRTM

Table 3 states the hydrological and morphological characteristics for the existing eight gauged stations managed by the Regional Agency for the prevention, environment and energy from the Emilia-Romagna (ARPA, 2016). From this data it was possible to derive a linear relationship found in Figure 20 that establishes the dependence of the main channel depth with their respective contributing areas of the different surveyed cross sections of the river stretch.

Table 3 The different characteristics of the gauged stations considered for the application of the linear relationship in the CB approach

<table>
<thead>
<tr>
<th>Gauged Stations</th>
<th>Contributing Area (km²)</th>
<th>Bankfull Depth dbf (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.te Becca</td>
<td>37223</td>
<td>7.77</td>
</tr>
<tr>
<td>P.te Spessa</td>
<td>37372</td>
<td>7.58</td>
</tr>
<tr>
<td>Piacenza</td>
<td>42030</td>
<td>10.95</td>
</tr>
<tr>
<td>Cremona</td>
<td>50726</td>
<td>9.95</td>
</tr>
<tr>
<td>Casalmaggiore</td>
<td>53460</td>
<td>9.67</td>
</tr>
<tr>
<td>Boretto</td>
<td>55183</td>
<td>11.46</td>
</tr>
<tr>
<td>Borgoforte</td>
<td>62450</td>
<td>11.67</td>
</tr>
<tr>
<td>Pontelagoscuro</td>
<td>70091</td>
<td>13.4</td>
</tr>
</tbody>
</table>

The study area was divided in three different sections, based on the location of the mayor secondary tributaries distributed along the study stretch. A) From Cremona to Casalmaggiore where the creek Parma confluences with the river Po B) From
Casalmaggiore to Boretto, where a derivate channel is constructed and C) From Boretto to Borgoforte, where the creek of Oglio is located.

Corresponding to these stretches, Table 4 states the estimated Channel Bankfull Depths (m) estimated from the A-dbf relationship from which the linear function stated was derived in Figure 20, providing with the lowering value h_{low-CB}, which is applied to the SRTM-derived cross sections from the linear function and later established and average lowering based on the three established sections. (Equation 5).

\[ d_{bf} = 0.0001 \times A + 2.7465 \]  
Eq.5

<table>
<thead>
<tr>
<th>River Stretch</th>
<th>Channel Bankfull Depth (m)</th>
<th>Lowering Value ( h_{low-CB} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cremona-Casalmaggiore</td>
<td>9.81</td>
<td>6.15</td>
</tr>
<tr>
<td>Casalmaggiore-Boretto</td>
<td>10.565</td>
<td>2.69</td>
</tr>
<tr>
<td>Boretto-Borgoforte</td>
<td>11.565</td>
<td>6.28</td>
</tr>
<tr>
<td>Total Average</td>
<td></td>
<td>5.04</td>
</tr>
</tbody>
</table>
The resulting elevations for the channel depth from the topographic surveys and the ones of the CB approach are compared in Figure 21. In this comparison we can observe a considerable similarity among the two different elevation series. (MAE: 2.02)

Figure 21 Comparison of River Bed Elevations retrieved at each cross section from the topographic surveys and from the SRTM sections modified with the CB approach

In figure 22 example is shown on the general approach for configuration of the river bathymetry, in which the lowest elevation values changes to new calculated values giving the bottom new elevation.

Figure 22 Cross Section S26C with original SRTM elevation and modified with CB-approach

Figure 23 presents a comparison of the surveyed, SRTM and SRTM-CB modified elevation with single and average lowering along the 61 sections. The differences in the lowering method shows how much the SRTM changes using the CB- approach. Using an individual lowering for each of the river stretches results in a more variable bed
elevation with high and lower points which don’t comply with the river slope, on the other side using an average lowering generates a river bed with a slope and level following a similar pattern as the LiDAR.

![Graph showing different bed elevations of the river stretch](image)

*Figure 23 Different bed elevations of the river stretch*

**Simulations Results for the CB approach model**

The comparison of simulated water elevations and the observed water elevations by the CB-model for high flows refer to the calibration period for the high flow event is presented in the longitudinal profile in Figure 24a using the individual lowering for each of the stretches. The best performing was very similar to those given by the SRTM (MAE: 0.724). The contour map shown in Figure 24b shows how the distribution of the Manning’s n roughness coefficient correlation with the MAE, which in, contrast to the standard SRTM model, presents higher manning’s numbers for lower errors.
In order to analyse the sensitivity of the CB approach and improve its performance, a second model using only an average lowering (\( h_{\text{low-ch}}=5.04 \)) for all river cross sections was implemented, which presented a slightly better accuracy (MAE= 0.704 m) and slightly lower Manning values (\( n_{\text{channel}}= 0.055 \text{ m}^{1/3}/\text{s} \), \( n_{\text{floodplain}}=0.06 \text{ m}^{1/3}/\text{s} \)), see Figure 25.

Figure 24 a) Longitudinal profile of high water marks in a CB approach  b) Contour map showing MAE distributing for Manning numbers for High Flow Calibration
The CB model based on average lowering in low flow simulation was performed and checked against the virtual stations and gauged station, revealing an improvement in the performance in comparison to the standard SRTM model. The biggest improvement was present in the virtual stations (VS1 MAE= 0.57 m, VS2 MAE=1.05 m), while at the gauged station was slightly improved. (Boretto MAE=2.03 m). This improvement can be observed in the scattered plots in Figure 26.

Figure 25 High Water Marks of Simulated High Water marks using a CB approach with average lowering for the whole river stretch.
Figure 26 Scattered plots of the Water levels for low flows a) VS1 b) VS2 c) Boretto gauged Station
Time series of the simulated CB average lowering model values present a considerable improving as compared to the observed one at the stations, with a considerable lowering of the water levels presented by the standard SRTM model. The different time series are presented in Figure 27.

Figure 27 Time series for the different virtual stations a) V1 b) V2 and the gauging station at c) Boretto
Based on theory of slope break method described in chapter Methods, bathymetry estimation has been computed. In 59 of the 62 cross sections the $z_{\text{min}}$ was found. However, in 3 of cross sections the new lowest water elevation could not be found because number of w-h pairs were 4 or less (figure 28). As mentioned in Methods in that case the result is not reliable, and those cross sections were left with initial topography extracted from SRTM data set.

The method of applying computation results on the 59 cross section was done in that way that the lowest flat part of the cross sections was lowered at new elevation (figure 29). Further in the results it is examined how modifying the bottom with average value affects the results. Average lowering value was calculated based on all the computed values taking in to consideration the cross sections that was neglected. The mean value was calculated to 3.17m and in this case all of the 62 cross sections were modified.
Result of Slope break method approach

The results of lowering the river bed elevation by the SB method applied on all the cross sections are illustrated as longitudinal profiles (figure 30). In the figure 30, the longitudinal profiles of the SRTM based topography and on-situ surveyed based river bed profile are shown. Also, lowered river bed profiles with the slope break approach are presented in two ways. One, where the river bed is lowered at each cross section with the individually calculated value using the method described above. The second lowered profile is lowered at each cross section by the average value for all calculated values. In figure x it can be seen that the deviation between the 4 profile bed is clearly visible. The difference may be seen along the hole reach no matter the elevation Comparision on relationship between the new lowered river bed and on- situ surveyed bottom profile is presented by scatter plot in figure 30b and it confirms earlier statement about deviation between the profiles.
High flows—single lowering

Using high flow event from 2000 and the new river bottom lowered at each cross section by its own value calculated by slope break method the new calibration of the model is done, and the results are illustrated in figure 31. The top performances of the new model are in the Manning’s coefficient range of 0.045-0.06 for the main channel and 0.06-0.09 for the floodplain. In those ranges the mean absolute error get under 1.00 m. The best performing model had Manning’s coefficient of 0.055 for the main channel and 0.06 for the flood plain giving lowest mean absolute error of 0.85m.
Figure 31. Contour map illustrating mean absolute error for different set of Manning's coefficient with SB lowering

In figure 32 the best performing model with lowered river bottom is illustrated. Again, as it can be seen in the most downstream part of the river reach the model and the measured values are almost at identical values while the difference is clearer at the upstream part.

Figure 32 Illustration of difference between high water marks and simulated elevation values for SB Lowering
**Low flows-lowering with single lowering**

The new SB modified model with lowered river bottom has been run with low flows and compared to the values achieved by the two virtual stations and the Boretto gauged station. The results are presented as a time series graph (figure 33) and show how simulated flows are against the observed values. Looking at VS 1 and VS 2 results the simulated curve follows the observed curve even though it is higher than the observed one. However, the simulated flow in figure 33c is clearly higher than the observed one, matching only at the higher flow peaks. The quantify the illustration, mean absolute error and the best performing Manning’s coefficient are presented in the table 5.
Figure 33 Comparison of the water elevations between simulated values with low flows and observed values. a) VS1, b) VS2, c) Boretto station

Table 5 Best performing Manning’s Coefficients with Individual Lowering

<table>
<thead>
<tr>
<th>Station</th>
<th>Calibrated Manning’s n</th>
<th>MAE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>roughness coefficient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Channel</td>
<td>Floodplain</td>
</tr>
<tr>
<td>VS1</td>
<td>0.045</td>
<td>0.06</td>
</tr>
<tr>
<td>VS2</td>
<td>0.035</td>
<td>0.06</td>
</tr>
<tr>
<td>Boretto</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>

High flows-lowering with average value

In order to provide more data and perspective on the results the model was run with lowered river bottom at each cross section by the average value. Manning’s coefficient was set to the best performing as mentioned earlier. The result of the high flow simulation is presented in figure 34 below. In the lower parts of the river stream, model’s output and the measured water levels overlap each other while at the higher elevation the difference is visible. Mean absolute error for the new model was calculated to 0.73m.
Low flows-lowering with average value

Applying the lowered bottom with the average value of 3.17 m the model was run with the low flows to examine if the result may differ from the results where bottom is lower with the individual calculated values. The results of the performance are shown in fig 35. in which the simulated curves follow the observed ones even though simulated one are bit higher then observed in cases of VS1 and VS2. This time, the model performance and the flow values at the Boretto station are close to each other making the good fit between curves. However, that result is achieved by trying to variate the Manning’s coefficient which is presented together with the VS1 and VS2 combinations in the table 6.

<table>
<thead>
<tr>
<th>Station</th>
<th>Calibrated Manning’s n</th>
<th>MAE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel</td>
<td>Floodplain</td>
</tr>
<tr>
<td>VS1</td>
<td>0.045</td>
<td>0.06</td>
</tr>
<tr>
<td>VS2</td>
<td>0.035</td>
<td>0.06</td>
</tr>
<tr>
<td>Boretto</td>
<td>0.02</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 6 Best performing Manning’s Coefficients with Average Lowering
Figure 35 Comparison of the water elevations between simulated values with low flows and average lowered bottom and observed values. a) VS1, b) VS2, c) Boreto station.

To be able to understand the differences of model performance, illustration on how simulated results relates to the observed and measured ones is done on figure 36, the
The figure shows the behaviour of the SRTM geometry with no lowering, single value lowering and average lowering. Looking at a) in which model performance with high flows are presented, in all 3 SRTM geometries simulated values are placed on the normal line at the lower elevations while at higher elevation the values deviate from the line. At figure 32 b and c where the results at VS1 and VS2 are presented there is a pattern shown in which simulated values last most further away from the normal line while the simulated values with individually lowered river bed comes next and lastly the simulated values with average lowering of the river bed lays closest to the line. Boretto station, at figure d), results show that simulations without and with individual lowering ends up far away from the normal line while model with average lowered bottom perform close to the observed values.
Figure 36 Scatter plots for relationship between best outcomes for low flow simulation in cases of no lowering, lowering with individual values, and lowering with average values. a) high flows, b) VS1, c) VS2 and d) Boretto.
Discussion

This section is subdivided into 3 parts. First, the comparison of the quality and suitability of the different DEMs used in the study. Then, the results of modelling of high flows for each of the different DEMs and the two lowering methods for the SRTM. Followed by the modelling of low flows.

Digital Elevation Models

Due to its high resolution (2 m), the LiDAR represents the highest performing DEM; therefore the SRTM DEM was compared to understand its differences. The difference in resolution can clearly be demonstrated by the different profiles along the reach of the study. The terrain can be considered well defined under the LiDAR DEM due to its higher accuracy (2m resolution). The differences in the vertical accuracies may be partly due to the lack of information in flat areas in the case of SRTM.

Previous studies (Schumann et al., 2008) have stated that accuracy of the SRTM values depend in many factors, directly or indirectly related to the location of the globe from which it was extracted. Therefore, it is appropriate to state that the data extracted from the SRTM should be confined to the specific area of the study. Along the reach, the error between both DEMs varies around 4. This is mainly derived from the middle section of the reach, where the SRTM presents a less varying and more flattened profile in comparison to the LiDAR, due to a non-considerable change in slope which cannot be appreciated in the low resolution of the SRTM. This same difference in accuracy can be confirmed with the profiles of the Levee system along the river reach, in which was also variation around 4 m.

For extracting of the cross sections, the mainly difference between both DEMs was the limitations on the SRTM to capture the river bed, as it was stated before, due to the limitations of the satellite equipment to penetrate the river surface. Nevertheless, in different cross sections the similarities were higher in profiles were possibly due to the fact that the water surface had a lower elevation.
High Flows Simulations

Table 7 represents the overall errors of the different calibrated models compared to the high water marks. As expected, the LiDAR gives the best performance compared to the surveyed high water marks of less than 0.2 m within the proximity. Mean absolute error for SRTM based model with and without modification of the river bed is at least 0.5 m higher then MAE for LiDAR based model. The results are in agreement with previous studies.

Table 7. The different models simulating high flows with their respective Manning’s n best performing values.

<table>
<thead>
<tr>
<th>Model</th>
<th>Manning’s n Coefficient</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel</td>
<td>Floodplain</td>
</tr>
<tr>
<td>LiDAR</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>SRTM</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>SRTM - CB</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>SRTM – CB Average</td>
<td>0.055</td>
<td>0.06</td>
</tr>
<tr>
<td>SRTM- SB</td>
<td>0.055</td>
<td>0.06</td>
</tr>
<tr>
<td>SRTM - SB Average</td>
<td>0.05</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The lowering methods in comparison to the unmodified SRTM DEM had a slight improvement, nevertheless the Manning’s n coefficient of the lowered models came closer to the ones used in the LiDAR simulations, showing that higher manning’s numbers on the channel are correlated to a better performing model. As it can be seen in table 7 there are bigger variations in Manning’s n for the channel than for the floodplain, which indicates that the Manning’s n for the channel has bigger influence in outcome of the flood modelling then the one for the floodplain.

The errors presented in Table 7, clearly highlight a good performance of the different calibrated models for high flows with slightly overestimated water levels.
Low Flows Simulations based on Radar Altimetry Data and in-situ Observations

Due to the limitations of the satellite capturing capabilities, the average flow conditions in the river are the most frequently sensed, which reduces the opportunity to compare in total all the lowest and highest discharged captured by the gauging station.

Taking into consideration these limitations of the RALTs data it possible to state a good agreement between the performance of the virtual stations and the simulated data, which pin points the opportunity to achieve reasonable results by using remotely sensed data only based on model performance on virtual stations information. Considering the results of calibrations for the LiDAR model, it is clear that this type of DEM is the type of data which ensures the best performance, with the highest model efficiency for both in-situ observations and radar altimetry data as shown in Table 8.

<table>
<thead>
<tr>
<th>Model</th>
<th>Manning’s n Coefficient</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel</td>
<td>Floodplain</td>
</tr>
<tr>
<td>LiDAR</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>SRTM</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>SRTM – CB</td>
<td>0.075</td>
<td>0.055</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRTM- SB</td>
<td>0.06</td>
<td>0.045</td>
</tr>
<tr>
<td>SRTM - SB</td>
<td>0.06</td>
<td>0.045</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The standard SRTM-based model presents a good performance on both virtual stations, however its performance defers highly at the gauging station which can be derived from the comparisons of very low flows in which the SRTM presents a higher uncertainty for its resolution capabilities. The lowering methods based SRTM models present a notable
improvement at both virtual stations and, compering to results of the LiDAR based model at the same stations, achieved better results meaning the mean absolute error were lower. These improvements can be seen more clearly in its comparison with the gauging stations observations, which covers a bigger and more variating range of flows.

The CB-model exhibits a satisfying improvement in the river simulation along the stations for low flows with a significant decrease at the error in comparison to the in-situ observations at the gauging stations at Boretto. One drawback presented from these method is associating the lowering to specific set of cross sections, which results in higher different along the sections selected which affected the model performance (instability of the low flow simulation for individual lowering). Generalizing an average lowering may be seen as an advantageous alternative, yet referring to an average may cause larger error and uncertainty in other modelling conditions.

However, the results on low flows are based on simulation with 20 best performing combinations of Manning’s n from the simulations with high flows. As mentioned earlier changing of Manning’s n for the channel may cause big variations in result outcome so, it is worth taking in to consideration that the model may perform better with the set of Manning’s n that are not being used in simulations for the low flows.
Conclusion

Our analysis investigates the performance of remotely-sensed altimetry provided by the different space missions combined with the remotely sensed altimetry (LiDAR and SRTM) for the calibration of 1D dimensional model in a section of the Po River. We implemented the models for a 98 km reach, for which both satellite and in-situ water levels data are available. The study evaluates the performance of the 1d models calibrating a high flow event with the friction coefficient describing the roughness conditions along the main channel and its flood plains.

The results of the study highlight the difference in performance of the higher resolution LiDAR DEM in comparison to a SRTM DEM and two different approaches to enhance it by lowering the river depth. As expected, the LiDAR performance presented a higher efficiency, yet the improvement of the SRTM DEM by using the two different approaches of lowering did not increase significantly its performance of the high water marks in comparison to the SRTM original performance. However, the calibrated Manning’s coefficients resulted from the modified SRTM models reached an agreement with the ones used in the LiDAR, which may present a correlation of the lowering the cross sections to higher Manning’s coefficients for better performance, which can be analysed more deeply.

On the other hand, calibration through low flows resulted in a significant increase in the performance of the SRTM modified approaches in comparison to the unmodified SRTM. The improvement on the space born topographic data results shows the potential of freely available SRTM when modified according to the proposed approaches for modelling lower flow regimes.

Based on the results, the satellite data can effectively describe the hydrometric behaviour of the river reach compared to the gauged station. However, the accuracy of a single satellite data is limited; a larger satellite dataset may effectively complement the traditional observations in order to enhance the calibration. The limitation of the satellite data sets can be observed when comparing the performance of the modified SRTM models, as they may not capture all the flow variations along the time like a
traditional gauging stations, therefore the performance of the modified SRTM models was clearly observed in the reduction of the error at the Boretto station of the simulated water levels. On this basis, we can conclude that satellite data do not seem to be totally capable of substituting in-situ observations of water levels, at least for the scope of this study.
References


