Assessing morphological changes in gravel-bed rivers using LiDAR data and colour bathymetry

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Abstract Estimating underwater features of channel bed surfaces without the use of bathymetric sensors results in very high levels of uncertainty. A novel approach to create more accurate and detailed Digital Terrain Models (DTMs) integrates LiDAR-derived elevations of dry surfaces, water depth of wetted areas derived from aerial photos and a predictive depth–colour relationship. This method was applied in three different sub-reaches of a northeastern Italian gravel-bed river (Brenta) before and after flood events occurred in November and December 2010 (recurrence interval: 8 and 10 years). From the data collected through channel field survey, a regression model which calculates channel depths using the correct intensity of three colour bands was implemented. LiDAR and depth points were merged and interpolated into a DTM which features an average error of ±18 cm. The morphological evolution and the sediment volume change calculated through a difference of DTMs shows deposition and erosion areas, indicating a deficit which reduces as it goes downstream.

Key words fluvial erosion–deposition processes; gravel-bed river; colour bathymetry; LiDAR data; floods

INTRODUCTION

The shape and dynamics of rivers result from several natural (e.g. climatic and hydrologic variations) and anthropogenic factors (e.g. water capture or control works) and can act at the basin scale or directly through in-channel interventions. Natural phenomena, especially large floods, may play a significant role in influencing channel stability and modifications. Nevertheless, human-induced changes are often much greater than those that could be expected from evolutionary dynamics of natural channels.

During the last few centuries, Italian gravel-bed rivers have suffered an increasing human pressure which has caused several morphological adjustments in the entire fluvial environment (Surian *et al*., 2009; Comiti *et al*., 2011) and significant variations in discharge regime, sediment budget and natural dynamics of riparian vegetation. The Brenta River basin, situated in the northeastern Italian Alps, has experienced multiple intense human impacts starting with deforestation and reforestation phases, followed by interventions for hydroelectric power generation and irrigation purposes, which have altered the catchment and the river channel.

In order to better analyse the magnitude of different morphological adjustments, precise quantitative approaches are needed. The development of several representation technologies, which derive their DTM models from precise acquisition data instruments (i.e. LiDAR), has allowed large areas to be characterized at finer resolutions in a very short time. Consequently the role of DTM uncertainty has become crucial, as it can strongly affect volume estimations. Determination of the sediment transport rate and sediment budget is fundamental to quantify geomorphological changes as a consequence of variations in discharge regime. Fluctuation of the frequency and magnitude of flood events greater than bankfull (RI > 1.5–2 years) can produce substantial modifications of the active channel and the extent of islands (Comiti *et al*., 2011; Moretto *et al*., 2011). The morphological approach, based on surface variation over time, offers important support for estimating sediment budgets (Ashmore & Church, 1998). The evaluation of morphological changes with Difference of DTMs methodology (DoD) is affected by multiple sources of errors and the results are often subject to significant uncertainties (Wheaton, 2008; Wheaton *et al*., 2010).

The weakness of this approach is the correct representation of the bottom of wetted channels, because the water column absorbs the signal of the sensors (active or passive) (Marcus & Fonstad,

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2008). Recently-developed bathymetric LiDAR sensors (ALB) still have high costs and relatively low resolution and data quality (Hilldale & Raff, 2008). Different methods to produce bathymetric data have recently been proposed. They are based on passive sensors (aerial photos) and the technique of ortho-restitution (Rinner, 1969; Fryer, 1983), or on the calibration of a depth–spectral-variation relationship of images defined according to the Beer-Lambert law (e.g. Winterbottom & Gilvear, 1997; Carbonneau *et al*., 2003; Marcus *et al*., 2003; Legleiter, 2011).

The present work proposes the implementation of a new methodology for the production of high resolution DTMs of gravel-bed rivers starting from LiDAR surveys and aerial images. The final aim consists of evaluating morphological changes, the erosion and deposition distribution patterns and the net sediment rate which occurred in the Brenta River as consequence of the flood events of November and December 2010. The specific objectives are: (i) to determine an empirical relationship between the channel depth and the intensity of colour; (ii) to define factors that increase the errors and the uncertainty of the final DoD; (iii) to produce a Hybrid DTM (HDTM) at high resolution and low uncertainty; and (iv) identification of distributed erosion and deposition patterns at the sub-reach level.

GENERAL SETTING OF THE STUDY AREA

The Brenta River, one of the principal Italian streams, is located in the southeastern Alps covering a drainage basin of approximately 1567 km^2 and length 174 km. For more detailed information we refer to Rigon *et al*. (2012). The study reach (19.2 km), located between Bassano del Grappa and Carturo (Fig. 1), has the morphological structure of this piedmont area and the channel is braided and tends to shift; the active channel width ranges between 300 and 800 m and the average slope is 0.0036.

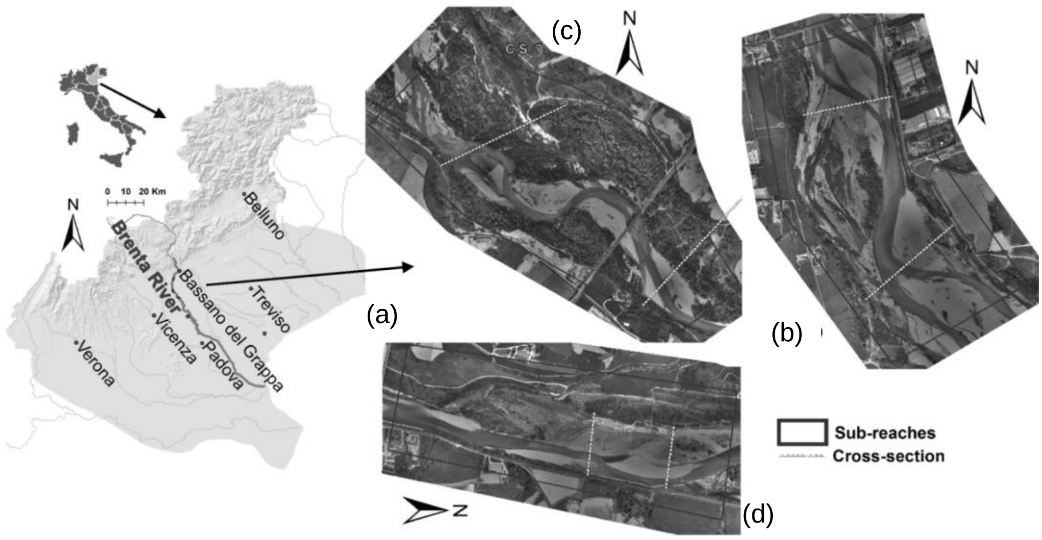

Fig. 1 General view of the Brenta study reach (a), and sub-reaches: Fontaniva (b), Friola (c), and Nove (d).

Human impacts on this river were very intense; dams, gravel mining and torrent control works have caused severe effects, especially during the second half of the 20th century, influencing and producing alterations in sediment flux (Lenzi *et al.*, 2003; Lenzi, 2006; Rigon *et al*., 2008; Conesa-Garcia & Lenzi, 2010). As result of these impacts, the average river-bed width has reduced from 442 m at the beginning of the 19th century to 212 m in 2010, and the channel incision has ranged from 2 to 8 m, especially due to the effects of gravel mining that only ceased during the 1990s. In recent times, a new equilibrium and/or widening phase seems to be taking place (the channel enlarged to 253 m in 2011) driving the river channel towards a more natural evolution.

Three sub-reaches 1.5 km long and 5 km apart from each other were selected and named according to the names of the nearby villages: Nove, Friola and Fontaniva (Fig. 1). Two severe flood events occurred in November and December 2010 (Fig. 2). The first flood, caused by prolonged and extended rainfall, which reached 300 mm with local maxima over 500 mm, lasted from 31 October to 2 November 2010, featuring a recurrence interval (RI) of about 8 years. The Brenta River registered very high hydrometric levels, among the highest ever recorded, and numerous instability events occurred, such as landslides, bank erosion processes and flooding outside the banks. The second flood, caused by intensive precipitation between 21 and 26 December 2010, primarily in the pre-alpine and piedmont areas, reached a recurrence interval (RI) of about 10 years. The rainfall exceeded 150 mm with local maxima of 300–400 mm, and the river registered (at Barzizza station) greater hydrometric levels relative to the first flood event, probably due to the higher soil saturation at basin scale and particularly because the Corlo Reservoir was already filled by the previous flooding.

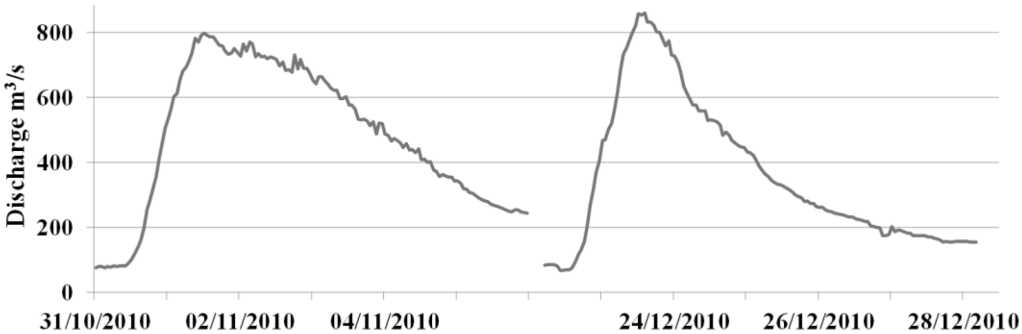

Fig. 2 Hydrographs of the flood events of November and December 2010 (Barzizza station).

MATERIALS AND METHODS

The methodology for creating an accurate HDTM consists of the calibration of a regression model between a de-trended Z coordinate, assessed by Differential Global Positioning System (hitherto DGPS), and red, green and blue (hitherto RGB) band values of aerial photos taken contemporaneous to the LiDAR survey. The Z coordinates were de-trended in order to indirectly compare different water depths derived by the Z DGPS coordinate. The method consists of five main steps, described below.

LiDAR data and field survey

Two LiDAR surveys were commissioned: 23 August 2010 by Blom GCR SpA through a OPTECH ALTM Gemini sensor, and 24 April 2011 by OGS company through a RIEGL LMS-Q560 sensor (fly height ~850 m). The average vertical error of LiDAR points, is ±0.20 m. The LiDAR survey was accompanied by analysis of a series of photographs (RGB aerial photos) with 0.15-m pixel resolution. The survey was carried out during the best weather conditions and low hydraulic channel levels. In-channel DGPS surveys were performed, taking different depth levels and different colour scales of the river bed. Overall, 882 points in 2010 and 1526 points in 2011 were taken. Finally, two cross-sections for each sub-reach were surveyed through DGPS (DGPS vertical error ±0.025 m).

Dataset preparation

Raw ground LiDAR data were filtered using automatic methods (TerraScan, Microstation Application®), with manual checks in critical areas. The aerial photos were georeferenced and corrected by applying a brightness analysis using the appropriate tool within the semi-automatic framework (TerraPhoto, Microstation application®). The corrected photos were joined (ESRI® ArcGIS 10) and the pixel size was transformed from 0.15 m to 0.5 m. Wetted areas were digitized through a manual photo-interpretation process. Along the polygon defining the active channel, elevation points were extracted from LiDAR, spaced about 10 m from each other and the channel slope trend was built up (kriging interpolation) so as to obtain the points on the wet areas with water level (Zwl). Colour band intensity and Zwl were added to the points acquired in the wetted areas (DGPS wet-area survey) obtaining a shape file of points containing five fields (in addition to the coordinates x and y): intensity of the three colour bands, red (R), green (G), blue (B), elevation of the channel bed (Zbd) and Zwl. Finally we calculated the channel depth (Dph = Zwl – Zbd).

Bathymetric model determination

Of the total available DGPS points, 80% were processed with statistical regression techniques (R® software) using two methods, the first being the traditional regression method based on statistical significance testing of variables (p-value < 0.05; Ricci, 2006) and the second being based on AICc index (Burnham & Anderson, 2002). This system estimates all significant models, forming a ranking based on the AICc value (the lower the value, the better the model) and starting from a physically plausible model. The two best models were tested in an Excel environment with the remaining 20% of test points. The model featuring the lower error was used to build the "raw de-trended bathymetric raster".

Hybrid DTM creation and validation

Subsequently, the best bathymetric model was applied to the georeferenced photos (raster calculator) to determine the "raw channel depth" (RDPH model). The RDPH model was than transformed into points and was filtered in order to delete wrong or suspicious points, mainly due to light reflections, turbulence, and elements (woods or sediments) above the water surface. The proposed methodology, used to highlight possible wrong points, is provided by an analysis of slope changes in neighboring pixels. In this sense, through a semi-automatic method which forecasts the creation of a "curvature raster" (ArcGIS tool®), points featuring curvature values outside the range $-600 < x < 700$ were removed. In addition, outlier points (>95%) were deleted. On the corrected points (by DPH model), the corresponding Zwl was added to obtain, for each point, the estimated elevation of river bed (Zbd model = DPH model + Zwl). A hybrid DTM (HDTM) with 0.5 m cell size (natural neighbour interpolator) was built-up. The final step was the validation of the HDTM models which was carried out by comparison with DGPS cross-section surveys. The accuracy of the hybrid DTMs was estimated separately for wet areas and dry areas.

RESULTS

The statistical regressions performed with the two different approaches (traditional regression and AICc) produced two bathymetric models for each inter-flood period. The average errors, detected in the two models by comparing the test points of 2010 (±0.26 m), have highlighted negligible differences which can be included within the estimation errors. Therefore we preferred to use the model resulting from the traditional method and featuring a simple structure with fewer factors:

$$DPH_{10} = 15.31 + 0.07513R - 0.1869G - 0.01475B - 0.0004582RB + + 0.001056G^2 + 0.0003352B^2 - 0.000002142G^3 \quad (1)$$

where DPH_{10} is the estimated water depth (increased by a fictitious elevation of 10 m to make positive all the values of calibration estimated indirectly), and R, G and B are the red, green and blue bands, respectively. The regression model presents a value of R-squared equal to 46.3%.

However, for 2011 the two different methodologies of statistical regression have generated the same model:

$$DPH_{10} = 9.393 + 0.03508R - 0.06376G - 0.1377B + 0.002257RG - 0.001096RB + 0.002303GB - 0.0007273R^2 - 0.002956G^2 + 0.0009993B^2 + 0.000002837G^3 - 0.00000685B^3 \quad (2)$$

In this case, R-squared is equal to 39% whereas the average error, resulting from the test points, accounts for ±0.19 m. Both models proved to be statistically significant (p-value < 0.05), and it is noteworthy that all the three colour bands contribute significantly to depth estimation.

In Fig. 3 an output deriving from model application (2) at the Friola sub-reach is presented. From a visual inspection, it appears that depth variations are generally respected and colour modifications at the channel bottom do not seem to influence the water depth strongly. In this sub-reach, maximum estimated depths reach 2 m.

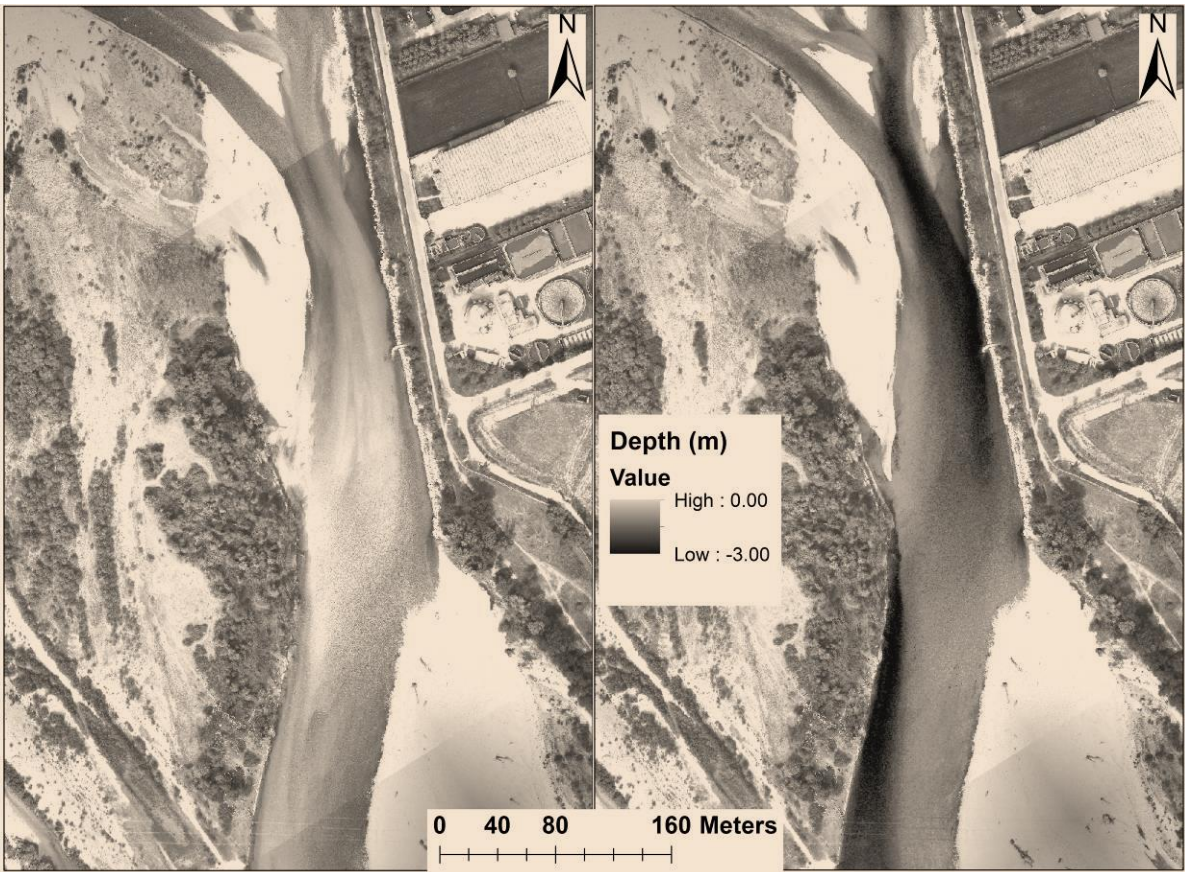

Fig. 3 Model application (2) at Friola sub-reach (2011). The darker lateral zones on the left side are due to the presence of *Periphyton* at the bottom.

After filtering out evidently wrong depth points, the points derived from the model application on wet areas were integrated with dry areas surveyed with the LiDAR flight. The hybrid points cloud featured an average density equal to 2.5 points/m^2 both for 2010 and 2011; therefore, the final HDTMs were generated using a 0.5 m × 0.5 m cell size. An example of HDTM (Friola 2011) is reported in Fig. 4. It is interesting to note the alternation of bed-forms (riffle and pool) within the wet channel estimated through bathymetric process. Overall, three HDTMs were produced for 2010 and another three for 2011 (Nove, Friola and Fontaniva sub-reach).

The data validation (Table 1) was carried out separately for both the wet and dry areas, obtaining an average uncertainty value for each HDTM, which includes DGPS error and the separation in each origin typology (LiDAR or colour bathymetry). The average uncertainty associated with wet areas ranges from a minimum of ±0.19 m (Friola 2011) to a maximum of ±0.26 m, whereas in dry areas average uncertainty ranges from a minimum of ±0.14 m (Nove,

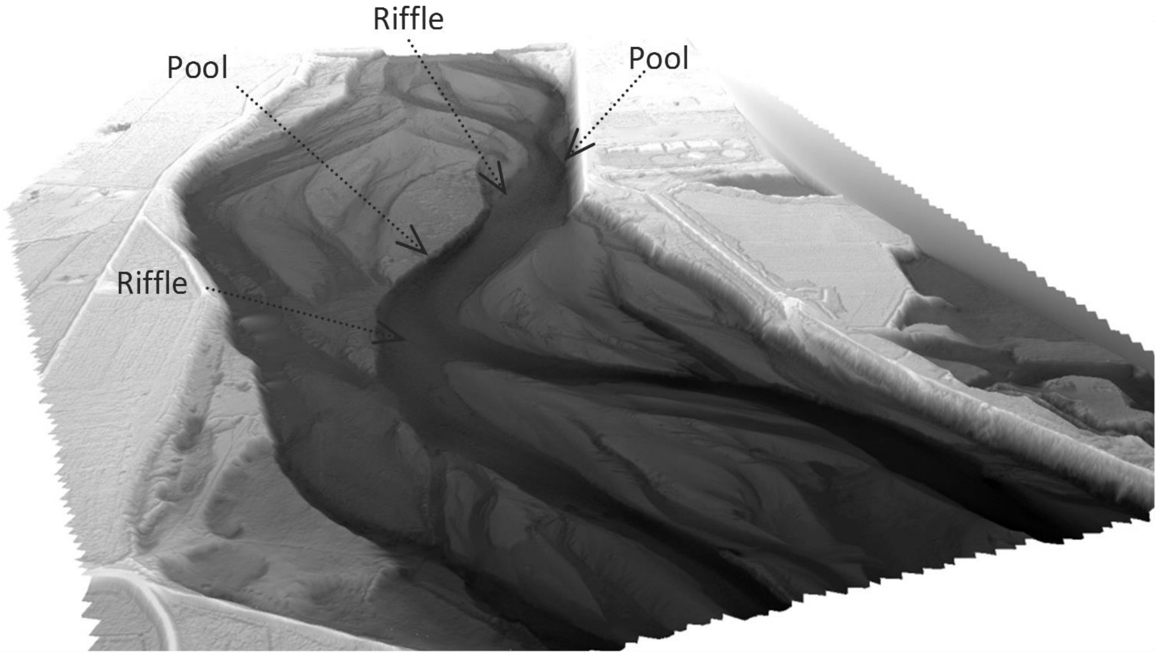

Fig. 4 Hybrid Digital Terrain Model (HDTM) of Friola 2011 sub-reach, 0.5 m × 0.5 m of cell size.

Table 1 Estimated uncertainty for HDTM and for DoD models.

		Nove		Friola		Fontaniva	
		2010	2011	2010	2011	2010	2011
HDTM area	(m^2)	566916	566916	836967	836967	627049	627049
Wet area	(m^2)	76463	76526	108265	119497	75545	97407
Wet area/HDTM area		0.13	0.13	0.13	0.14	0.12	0.16
No. DGPS point for test DTM_{BTH}		192	408	279	821	204	283
Average uncertainty DTM_{BTH} + DGPS	(m)	0.26	0.26	0.25	0.19	0.26	0.26
No. DGPS point for test DTM_{LD}		72	132	98	155	53	64
Average uncertainty DTM_{LD} + DGPS	(m)	0.14	0.15	0.24	0.15	0.26	0.16
TOTAL average uncertainty	(m)	0.16	0.16	0.24	0.16	0.26	0.17
δuDoD	(m)	0.23		0.29		0.31	

DTM_{BTH}: part of digital elevation model derived by bathymetry; DTM_{LD}: part of digital elevation model derived by light detection and ranging; DGPS: Differential Global Positioning System; δuDoD: propagated error in raster difference between 2011 and 2010.

2010) to a maximum of ±0.26 m (Fontaniva 2010). Moreover, we calculated the average weighting uncertainty (with the respective influence areas) in the HDTMs which ranges from 0.16 m to ±0.26 m. Finally, using the Brasington *et al*. (2003) approach, the average uncertainty derivable from the raster of difference (DoDs) utilized for erosion and deposition volume calculation was estimated to be in the range ±0.23 m for Nove, ±0.29 m for Friola, and ±0.31 m for Fontaniva.

DISCUSSION

Potential and limitations of the proposed method

The suggested methodology, used to produce high-resolution DTMs, requires only a DGPS survey in the wetted areas, contemporary to aerial image acquisition which is necessary for the calibration of the bathymetric model. In fact, its calibration does not need direct field surveys of water depth over the selected DGPS points. Water depth is indirectly estimated through the creation of a water level raster which subtracts the corresponding DGPS elevation points. Estimated depths, associated with the corresponding RGB values, are used for the statistical calibration of the regression model. Another novel characteristic of the presented method is represented by the polynomial model testing and the use of all its significant factors. The statistical analysis has shown that all the three bands (red, green and blue) and also some of the other constituent factors (interactions among bands and square and cubic terms) are significant (p-value < 0.05). The *ad hoc* calibration for each study year was necessary for the different water stages during the LiDAR survey. Figure 5 shows that the optimal application range of the estimated bathymetric models ranges between 0.2 m and 1.1 m for both 2010 and 2011. The variability increase in the first 20 cm of depth, due to severe colour variations at the bottom (*Periphyton*, exposed pebbles, woody debris, etc.), was eliminated by substituting those areas with LiDAR points which are capable of penetrating this surface water layer. Outliers due to debris, reflections and turbulence in the deepest zones were intercepted by the curvature assessment and eliminated through the establishment of upper and lower implausible limits in the bathymetric raster.

Shadows represent a disturbing factor which is difficult to correct and remove. However, in the study sites the presence of shadow was minimal thanks to image acquisition during midday hours. A further limitation is represented by water depth greater than 1.10 m, where the model tends to underestimate the water depth. This may be partly due to the limited availability of calibration points in the deeper areas of flow (due to safety reasons).

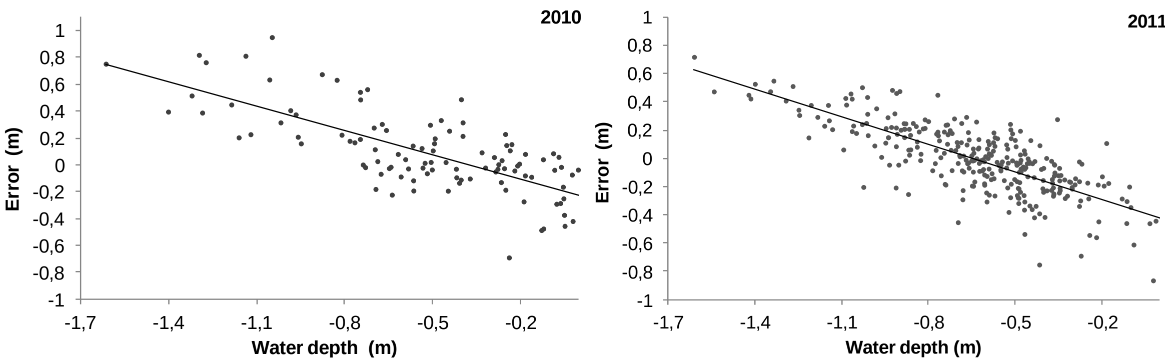

Fig. 5 Error evaluation of model in relation to depth (DGPS test points).

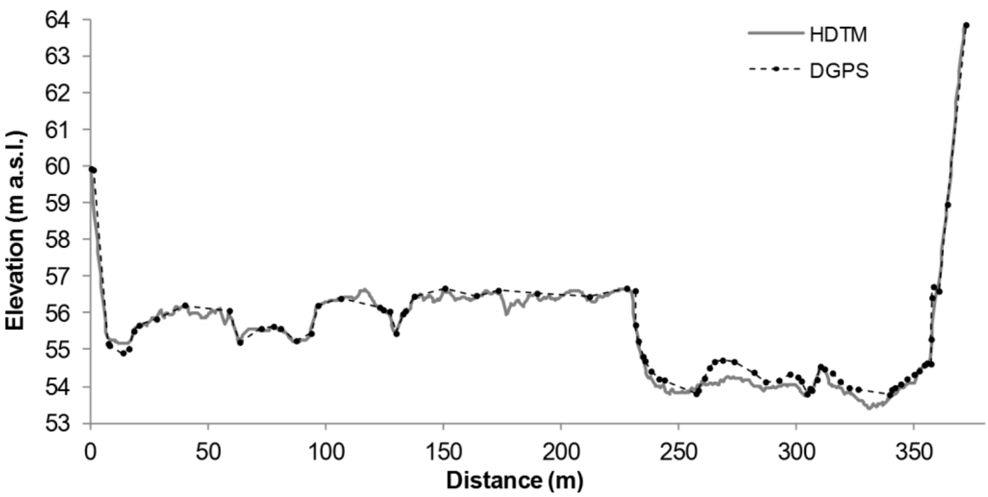

Fig. 6 Comparison between DGPS and HDTM in Friola 2011.

Comparing a DGPS profile and a profile derived from final HDTM (Fig. 6, Friola 2011), we can observe that, overall, the ground points are fairly well replicated. Consequently, it can be considered a satisfactory representation in the homogeneous study of morphological variations.

Morphological changes after November–December 2010 floods

The DoD models of the three sub-reaches have highlighted a predominance of erosion processes as a consequence of the impacts of the flood events of November–December 2010. Also, there is a transition from erosional to depositional overall tendency from the upper to downstream reaches (Friola to Fontaniva; Table 2). The difference between erosion and deposition rates is greatest in the uppermost reach, Nove, and more balanced with progressive deposition patterns in downstream reaches. The marked predominance of erosion in the first sub-reach could be due to the higher physical constraints which do not permit the channel to migrate. In fact, human interventions aimed at protecting the nearby areas against hazardous floods (e.g. embankments, groins, and rip raps) could have reduced the active channel width, producing incision tendencies, as partially confirmed by the multi-temporal analysis undertaken by Moretto *et al.* (2011). The concentrated bank erosion could be enhanced by both alteration of sediment flux, due to the low connectivity with the upstream drainage basin already identified by Surian *et al.* (2007), and scarce presence of vegetation growing on the banks. In contrast, in the Fontaniva sub-reach, the greater amounts of deposition led to a more equilibrated condition between erosion and deposition volumes. This could be due to the higher uniformity of the reach and also to the higher degree of migration freedom featured by the river channel as result of the generally lower human pressure in this section. In fact, gravel mining activities were not intensive in this sub-reach, and sufficient volumes of coarse sediment are available through bank erosion from the upper part of the reach. Moreover, the presence of vegetation and islands and the “deposition enhancement” caused by an artificially reduced bed slope, could have accounted for its substantial stability and less potential erosion (Moretto *et al.*, 2012). In this sense, a braided morphological structure and stable tendency are conserved in the short- and medium-term dynamics of this sub-reach (Moretto *et al.*, 2011).

Table 2 Deposition, erosion and net volume (deposition volume – erosion volume) without uncertainty analysis and with standard uncertainty of three sub-reaches.

DoD	Sub-reach surface (m^2)	DoD changes: Deposition (m^3)	Erosion (m^3)	Net (m^3)	Difference from original: Deposition (%)	Erosion (%)	Total (%)
No uncertainty analysis							
Nove	566916	17315	114428	–97113	NA	NA	NA
Friola	836967	97039	169226	–72187	NA	NA	NA
Fontaniva	627049	95376	110994	–15618	NA	NA	NA
Standard uncertainty							
Nove	566916	9263	57831	–48568	–46.5	–49.4	–49.9
Friola	836967	53359	113404	–60045	–45.0	–32.9	–16.8
Fontaniva	627049	55494	74062	–18568	–41.8	–33.2	18.8

Standard uncertainty: 23 cm for Nove, 29 cm for Friola and 31 cm for Fontaniva (δu_{DoD} of Table 1).

FINAL REMARKS

The proposed methodology allows the production of high-resolution DTMs of wetted areas with an associated uncertainty that is comparable to LiDAR data. The bathymetric model calibration requires only a DGPS survey in the wet areas contemporaneous to aerial image acquisition. Statistical analyses have demonstrated that all the three colour bands (R, G, B) significantly relate to water depth. Error sources (reflections, turbulences, severe colour variations at the bottom, shadows. suspended transport, exposed sediment) were mostly intercepted through curvature assessment and eliminated thanks to the establishment of implausible upper and lower limits in the bathymetric raster. The validation of Hybrid Digital Terrain Models (HDTM) is satisfactory and enables evaluation of morphological variations. The raster of difference (DoDs) highlights the consequences of the flood events of November–December 2010 (RI = 8 and 10 years), indicating a predominance of erosive processes, which are more marked in the upstream sub-reach (Nove), becoming more equilibrated downstream where progressive deposition occurs.

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