HYBRID DTMS DERIVED BY LIDAR AND COLOUR BATHYMETRY FOR ASSESSING FLUVIAL GEOMORPHIC CHANGES AFTER FLOOD EVENTS IN GRAVEL-BED RIVERS (TAGLIAMENTO, PIAVE AND BRENTA RIVERS, ITALY)

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ABSTRACT

Risk management and flood protection are frequently assessed through geo-morphometric evaluations resulting by floods events. If we aim at elevation models with high resolutions and covering large areas, airborne laser imaging detection and ranging (LiDAR) surveys can represent a good compromise among costs, time and uncertainty. The major limitation of the non-bathymetric LiDAR surveys consists in the detection of wet areas. Indeed, accounting for more than 20 cm of water depth, LiDAR signal increases its error exponentially. In this article we present a comparison of the results concerning the application of a colour bathymetry methodology for the production of hybrid digital terrain models. These elevation models were derived by merging LiDAR data for the dry areas and colour bathymetry for the wet areas. The methodological approach consists in a statistical regression between water depth and RGB band intensity values from contemporary aerial images. This methodology includes the use of filters to reduce possible errors due to the application of the model and to estimate precise 'in-channel' points. The study areas are three different human-impacted gravel-bed rivers of the north-eastern Italy. This methodology has been applied in three sub-reaches of the Brenta River, two of the Piave River and two of the Tagliamento River before and after relevant flood events with return intervals of ≥10 years. Potentials and limitations of the applied bathymetric method, the comparison of its use in different fluvial contexts and its possibility of employment for geo-morphometric evaluations, were then tested. DGPS control points (1841, 2638 and10 473 for the Brenta, Piave and Tagliamento Rivers, respectively) were finally used to evaluate the accuracy of the wet areas. The results showed that, in each model, the wet areas' vertical errors were comparable with those featured by LiDAR data for the dry areas.

Keywords: Colour bathymetry, DGPS survey, floods, geomorphic changes, gravel-bed river, LiDAR data.

1 INTRODUCTION

The study of river morphology and dynamics is essential to understand the factors (natural and anthropic) determining sediment erosion, transport and deposition processes [1]. To better analyse the magnitude of different morphological adjustments occurring in river channels, precise quantitative approaches are now needed. Different methods proved to be able to provide high-resolution digital elevation models (DEMs) of fluvial systems. Recent studies on morphological channel changes have used passive remote sensing techniques, such as digital image processing [2], digital photogrammetry [3], active sensors, including laser imaging detection and ranging (LiDAR) [4], terrestrial laser scanner [5] and acoustic methods [6]. The main problem related to the production of precise fluvial digital terrain models (DTMs) without using bathymetric sensors is due to the absorption of natural (solar) or artificial (LiDAR) electromagnetic radiation in the wetted channels. Surveys of wetted areas can be thus approached using techniques based on the calibration of a depth–reflectance relationship of images, which can be in grey-scale, e.g. [7], coloured [8, 9] or multispectral [10]. All solutions

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need a field survey, contemporary to the flight, to allow the availability of calibration depth points.

This work proposes an analysis of the above-mentioned methodology on the Brenta, Piave and Tagliamento Rivers [9]. This approach consists of a calibration of a dep th-colour model to estimate channel water depths. After a filtering process, the bathymetric points for the wet areas and the LiDAR points for the dry areas will be merged to produce the final hybrid DTMs (HDTMs).

The specific objectives can be summarized as follows: (i) to analyse the results of a bathymetric approach in three different braided river systems, (ii) to evaluate the limits and potentials of this procedure with attention to the factors significantly influencing the quality of final results and (iii) to provide generic rules to minimize possible error sources.

2 STUDY AREA

2.1 Tagliamento River

The Tagliamento River is a gravel-bed river located in the southern Alps in north-eastern Italy (Friuli Venezia Giulia region) and is one of the last European rivers still maintaining a high degree of naturalness. It originates at 1195 m a.s.l. and flows for 178 km to the northern Adriatic Sea, thereby forming a link corridor between the Alps and the Mediterranean zones. Its drainage basin covers 2871 km^2 (Fig. 1).

The hydraulic regime of the Tagliamento River is characterized by an irregular discharge and a high sedimentation load; due to the climatic and geological conditions of the upper part, the annual precipitation can reach 3000 mm.

Two sub-reaches located near the town of Forgaria nel Friuli were analysed. The upstream sub-reach 'Cornino' shows a predominant braided morphology, with a slope of ~0.35%. Flagogna sub-reach has a predominant wandering morphology with a slope of ~0.30%. For a more detailed description we report to [11].

2.2 Piave River

The Piave River, drainage area of 4500 km^2, lies in the eastern Italian Alps. The main channel flows in south direction for 220 km from its headwaters to the outlet in the Adriatic Sea, near Venice. The climate is temperate-humid with an average annual precipitation of ~1350 mm.

Two study reaches have been selected in the middle portion of the river course (drainage area of 3180 km^2 at the Busche dam) (Fig. 1). The first study reach, Belluno, features a length of ~2.2 km, whereas the second study reach, Praloran, features a length of 3.2 km. The river morphology in the study sub-reaches is dominated by braided and wandering channel patterns; the slope is ~0.45%. For a more detailed description, see [12, 13].

2.3 Brenta River

The Brenta River is located in the south-eastern Alps covering a drainage basin of ~1567 km^2 and a length of 174 km. The study reaches located between Bassano Del Grappa and Carturo (Fig. 1) have a braided and wandering morphology; the active channel width ranges between 300 and 800 m and the average slope is 0.36%.

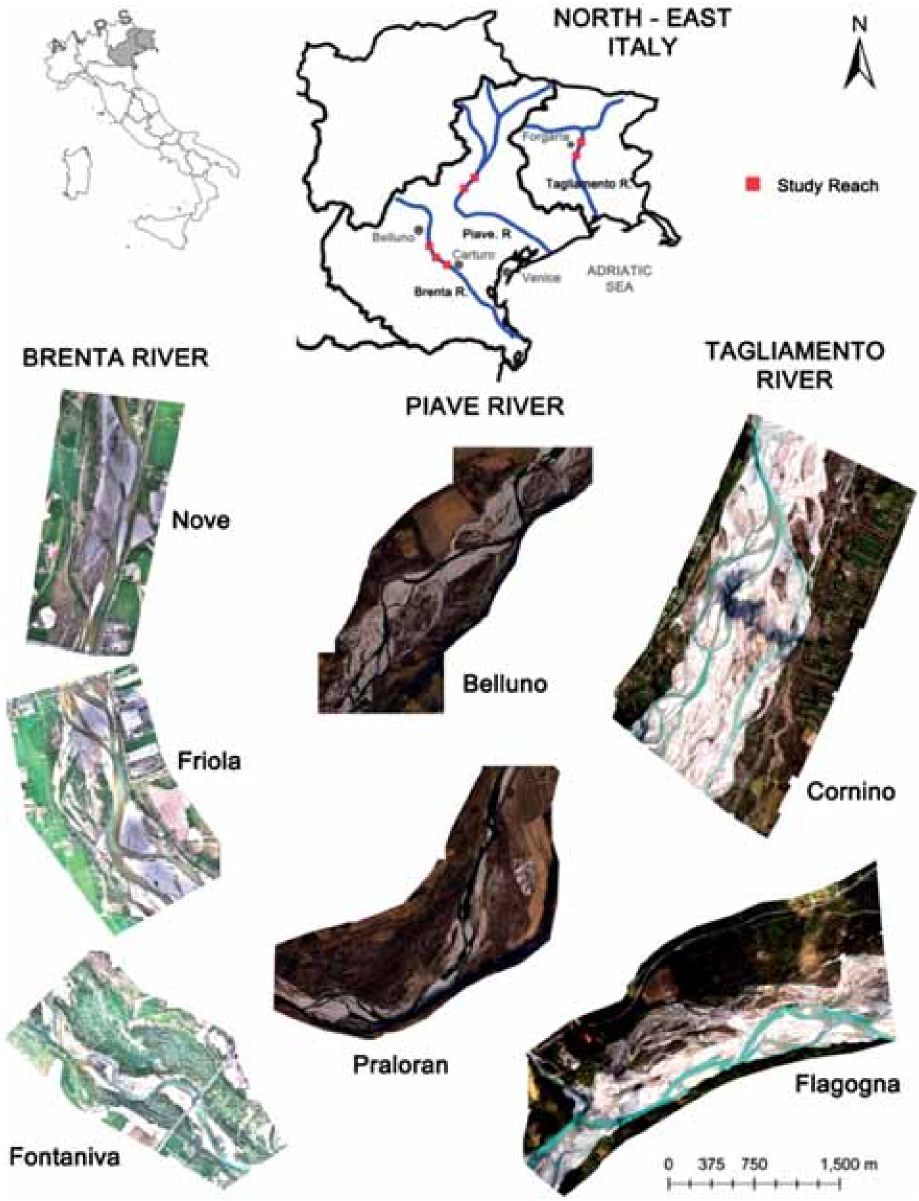

Figure 1: Study areas of the Brenta, Piave and Tagliamento Rivers.

Human impacts on this river were very intense; dams, gravel mining and torrent control works have caused severe effects. The average annual precipitation, mainly concentrated in spring and autumn seasons, is ~1100 mm.

Three sub-reaches 1.5 km long and 5 km apart from each other were selected and named according to the nomenclature of the nearby villages: Nove, Friola and Fontaniva (Fig. 1). For more details, see [1, 14].

3 MATERIALS AND METHODS

This article analyses the methodology applied in [9] for producing DTMs derived from LiDAR data, acquired contemporary to aerial photos and a DGPS survey, accounting for the highest possible accuracy in the wet areas. The principal steps are summarized below.

3.1 Data acquisition

Two LiDAR surveys were commissioned: the first in 2010 and the second in 2011 after the significant floods registered in November and December 2010 (Fig. 2). For each LiDAR survey, a point density sufficient to generate digital terrain models with 0.5 m of pixel resolution (at least 2 ground points per square meter) was required. LiDAR data were taken together with a series of RGB aerial photos with 0.15 m of pixel resolution. In-channel DGPS points acquisition was performed taking different depth levels in a wide range of morphological units. Totally, 399 (2010) and 1421 (2011) points for the Brenta River, 337 (2010) and 2301 (2011) points for the Piave River, 1107 (2010) and 9366 (2011) points for the Tagliamento River were acquired.

3.2 Indirect estimates of water level and dataset preparing

The edges of the 'wet areas were identified' through shape polygons and reliable LiDAR points able to represent water surface elevation (*Zwl*) in our inference zone were selected. The corresponding intensity of the colour bands 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 spatial coordinates X and Y): the intensity of the three colour bands, red (*R*), green (*G*), blue (*B*), the elevation of the channel bed (*Zwet*) and *Zwl*. Finally, channel depth was calculated as $Dph = Zwl - Zwet$.

3.3 Bathymetric model determination

An empirical depth linear model testing all the colour bands, the possible interaction of variables and the square and cubic terms was tested as follows:

$$Dph = \alpha + \beta_0 R + \beta_1 G + \beta_2 B + \beta_3 RB + \beta_4 RG + \beta_5 GB + \beta_6 RGB + \beta_7 R^2 + \beta_8 G^2 + \beta_9 B^2 + \beta_{10} R^3 + \beta_{11} G^3 + \beta_{12} B^3 \quad (1)$$

Figure 2: Floods of November 2011, Brenta River: Friola reach.

where α and β_x are the calibration coefficients in the depth-colour regression. In this model, the significance of each component was tested, deleting statistically negative values.

The statistical regressions have been performed in R® environment using the 80% of the calibration points and two methods: the traditional regression method based on the statistical significance, tested on each variable (p-value<0.05), and the AICc index [15]. The model featuring the lowest error (tested with the 20% of the DGPS points not used to calibrate the model) was used to build the 'Raw channel Depth raster (RDph)'.

3.4 Hybrid DTM creation and validation

The best bathymetric model was applied to the georeferenced photos (raster calculator, ArcGIS®10) to determine the RDph. The RDph was then filtered in order to delete incorrect points, mainly due to sunlight reflections, turbulence and elements (wood or sediment) above the water surface [9]. The corresponding *Zwl* was added to the corrected points (Dph model) to obtain, for each point, the estimated elevation of the river bed (*Zwet= Dph + Zwl).* Hybrid DTMs were built up with the natural neighbour interpolator, integrating Zdry points (by LiDAR) in the dry areas and Zwet points (by colour bathymetry) in the wet areas.

The final step was the validation of the HDTM models, which was carried out by comparison with DGPS surveys (1841 points for the Brenta River, 2638 points for the Piave River and 10 473 points for the Tagliamento River). The accuracy of the HDTMs was estimated for wet areas considering colour bathymetry errors at different water-stage levels grouped in classes incremented by 20 cm (see Table 1).

4 RESULTS

4.1 Tagliamento River depth-colour model

The 2010 statistical regression has demonstrated that, as in the Brenta and Piave Rivers, all the colour bands are significantly correlated with water depth and are expresses as follows:

$$\begin{aligned} Dph = {} & -0.207 + 0.09R + 0.1151G + 0.007827B + 0.001573G^2 + \\ & 0.0006577B^2 - 0.000005273G^3 - 0.000002425B^3 - 0.0006273RG - \\ & 0.0008327RB - 0.0004865GB + 0.00000649RGB \end{aligned} \tag{2}$$

This model is able to reach, such as for the Brenta River, 0.80 m of water depth with an error of < ± 0.20 m (Table 1). Similar results were featured for 2011:

$$\begin{aligned} Dph = {} & -0.69 + 0.0235R - 0.02822G + 0.008599B + 0.000061G^2 + 0.00009621B^2 - \\ & 0.00000006799R^3 - 0.0000004239B^3 - 0.00009157RG - 0.00004429RB - \\ & 0.00004228GB + 0.0000005079RGB \end{aligned} \tag{3}$$

An example regarding the result of the model application is reported in Fig. 3. From a general point of view, the model seems to be able to produce a good water depth estimation comparing the aerial photos.

This model, compared with the control points, estimates wet areas with an average error of < ± 0.20 m up to 1.40 m (Table 1) of water depth.

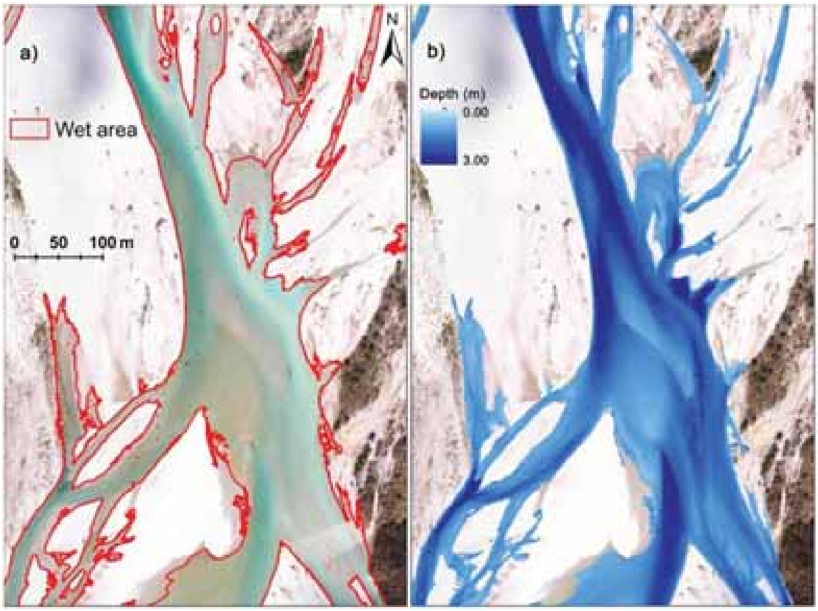

Figure 3: Wet areas and colour bathymetry application on Cornino sub-reach in 2011 (Tagliamento River).

4.2 Piave River depth-colour model

From the statistical regressions performed in 2010, as in the Brenta River all the three colour bands have proved to be significantly correlated with water depth:

$$Dph = 6.96 + 0.06222\,R - 0.01419\,G - 0.2581\,B - 0.0001518\,R^2 + 0.002002\,B^2 - 0.000005091\,B^3 \quad (4)$$

This model reaches 1.40 m of water depth, with an error of < ± 0.20 m. Similarly, a regression model for 2011 was performed:

$$Dph = 0.83 - 0.004607\,R + 0.009665\,G - 0.04102\,B - 0.000205\,R^2 - 0.0006412\,G^2 + 0.0002062\,B^2 + 0.000002987\,G^3 + 0.0005447\,RG + 0.0005339\,RB - 0.000004473\,RGB \quad (5)$$

In this case, the maximum reached depth with an error of < ± 0.20 m is equal to 0.60 m (Table 1).

4.3 Brenta River depth-colour model

The performed statistical regressions have produced the best bathymetric models for each inter-flood period. The maximum water depth estimated with an error of < ± 0.20 m has reached 0.80 m (Table 1) for this colour model:

$$Dph = 5.31 + 0.07513\,R - 0.1869\,G - 0.01475\,B - 0.0004582\,RB + 0.001056\,G^2 + 0.0003352\,B^2 - 0.000002142\,G^3 \quad (6)$$

Table 1: The error analysis of depth-colour models applied at different water stages for 2010 and 2011 on Brenta, Piave and Tagliamento Rivers.

REACH	Brenta 2010			Piave 2010			Tagliamento 2010		
Depth	Dph (R, G, B)			Dph (R, G, B)			Dph (R, G, B)		
(m)	error (m)	dev. St. (m)	Calib. points	error (m)	dev. St. (m)	Calib. points	error (m)	dev. St. (m)	Calib. points
0.00–0.19	0.26	0.22	107	0.43	0.28	7	0.15	0.11	232
0.20–0.39	0.26	0.24	87	0.21	0.16	42	0.10	0.09	327
0.40–0.59	0.21	0.20	75	0.08	0.15	81	0.10	0.09	275
0.60–0.79	0.22	0.18	59	0.00	0.17	70	0.18	0.13	184
0.80–0.99	0.26	0.15	32	0.08	0.18	50	0.32	0.19	64
1.00–1.19	0.51	0.21	20	0.20	0.23	38	0.54	0.22	15
1.20–1.39	0.69	0.14	13	0.11	0.22	27	0.46	0.21	9
1.40–1.59				0.29	0.23	11	-	-	1
1.60–1.79				0.13	0.13	8			
1.80–1.99				0.25	0.33	3			
> 2.00									
TOTAL			393			337			1107

REACH	Brenta 2011			Piave 2011			Tagliamento 2011		
Depth	Dph (R, G, B)			Dph (R, G, B)			Dph (R, G, B)		
(m)	error (m)	dev. St. (m)	Calib. points	error (m)	dev. St. (m)	Calib. points	error (m)	dev. St. (m)	Calib. points
0.00–0.19	0.27	0.11	61	0.05	0.09	221	0.37	0.11	127
0.20–0.39	0.18	0.11	248	0.04	0.11	967	0.21	0.11	599
0.40–0.59	0.13	0.11	427	0.19	0.11	628	0.14	0.11	1631
0.60–0.79	0.14	0.13	343	0.31	0.13	301	0.12	0.10	2233
0.80–0.99	0.24	0.19	187	0.45	0.18	123	0.13	0.10	2089
1.00–1.19	0.32	0.19	100	0.51	0.29	36	0.15	0.13	1419
1.20–1.39	0.40	0.13	35	0.62	0.30	8	0.18	0.16	755
1.40–1.59	0.56	0.10	20	0.69	0.56	4	0.26	0.18	341
1.60–1.79				0.59	0.70	7	0.38	0.21	123
1.80–1.99				1.08	0.54	6	0.49	0.19	39
> 2.00							0.61	0.12	10
TOTAL			1421			2301			9366

where *Dph* is the estimated water depth, and R, G and B are the red, green and blue bands, respectively. A similar model structure was found on the 2011:

$$Dph = -0.607 + 0.03508\,R - 0.06376\,G - 0.1377\,B + 0.002257\,RG - 0.001096\,RB + 0.002303\,GB - 0.0007273\,R^2 - 0.002956\,G^2 + 0.0009993\,B^2 + 0.000002837\,G^3 - 0.00000685\,B^3 \quad (7)$$

In this case, the water depth estimated with an error of < ± 0.20 m has reached the same results of 0.80 m obtained for 2010 (Table 1).

Figure 4 shows one of the output deriving from the model application (eqn 7) at Friola sub-reach. It appears that depth variations are generally respected, and variations in the colour tone, e.g. due to the presence of periphyton in these areas joined to the lower flow velocity, do not seem to strongly influence the estimation of water depth. In this sub-reach, the maximum estimated depth from the models is up to 2 m.

4.4 Filtering and HDTM interpolation

A comparison of 2011 raw HDTM and the HDTM derived by the profiles of Friola wetted areas is shown in Fig. 5. Concerning raw HDTM four types of errors were identified: light reflection, water turbulence, periphyton and exposed sediment (sources of errors also confirmed by Moretto *et al*. [9]. The light reflections and water turbulence (white pixels) produce depth estimates strongly negative and substantially different (about 1–2 m) from the adjacent pixels not affected by these problems. The exposed or nearly exposed periphyton (green and

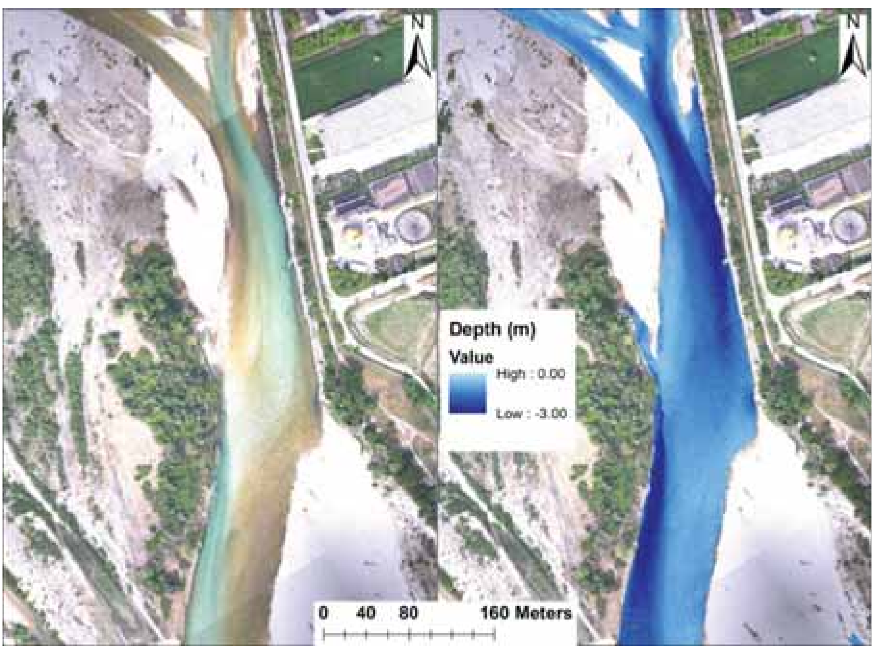

Figure 4: The wet area and colour bathymetry application on a sub-reach of Friola 2011 (Brenta River). The dark zones in the wet areas on the left-hand side are due to the presence of periphyton at the channel bottom.

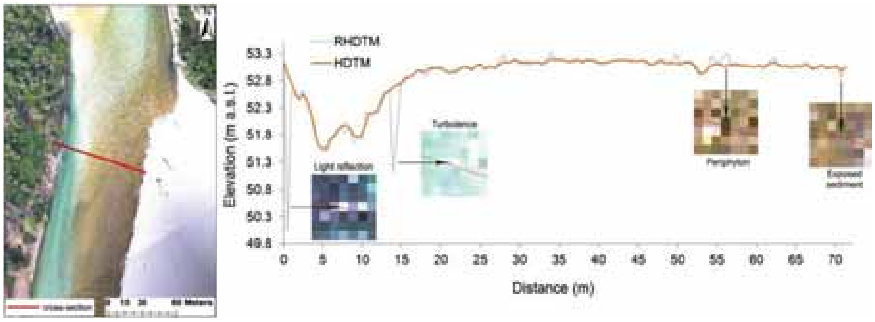

Figure 5: An example of a filtering process in a cross-section of the Friola 2011 sub-reach (Brenta River).

brown pixels) and the exposed sediment (grey pixels) produce an underestimation or overestimation of water depth (about ± 0.40–0.60 cm of difference with respect to the adjacent pixels). The correction method, which involves the use of a filter based on the curvature and the removal of outliers (points with errors exceeding 95% confidence interval), has provided excellent results as evidenced by Fig. 5.

After filtering raw depth points deemed wrong due to the model application on the altered pixel colour value (caused by river bed colour, turbulence, light reflections, shadows, suspended load and exposed sediment), dry areas were integrated using LiDAR flights. LiDAR point clouds (filtered from vegetation and excluding wet areas) featured an average density in each sub-reach greater than 2.00 points/m^2; therefore, final HDTMs were generated using a 0.5×0.5 m cell size.

5 DISCUSSION

The different water depth errors estimated from LiDAR and from the proposed colour bathymetric approach have been compared with 2010 and 2011 Brenta, Piave and Tagliamento DGPS surveys and reported in Table 1.

The results confirm that the more depth increases, the greater light is adsorbed, as described by Legleiter [16], raising the variability of R, G and B colour bands. This greater variability decreases the quality of results of the colour models. Despite this decrease in quality, an adequate number of calibration points allows to reach an acceptable error in function of the final goal.

To provide some guidelines to perform a ‘colour bathymetry survey’, the expected error associated depth and calibration points is implemented in Fig. 6. Four ‘error models’ are reported, one for each river (interpolating 2010 and 2011 error data reported in Table 1) and a last one representing the average ‘error trend’ obtained by interpolating all ‘error data’ from each river. To provide more solid general rules, suspicious points were deleted. Therefore, for 2010 Piave, points above 0.8 m (Table 1) of water depth were not considered.

The lower resulting error seems to be erroneous if compared with the other survey. The reason is based on the worse luminosity conditions of the aerial photos. The different calibration point number among the different years and surveys at different water levels seems to suggest some general rules: (i) a minimum number of 250 calibration points for each water range level (with a step of 0.2 m) seems to guarantee an average error of < ± 0.2 m, from 0 to 1.5 m of water depth; (ii) between 1.5 and 2 m of depth (the deepest range surveyed), the

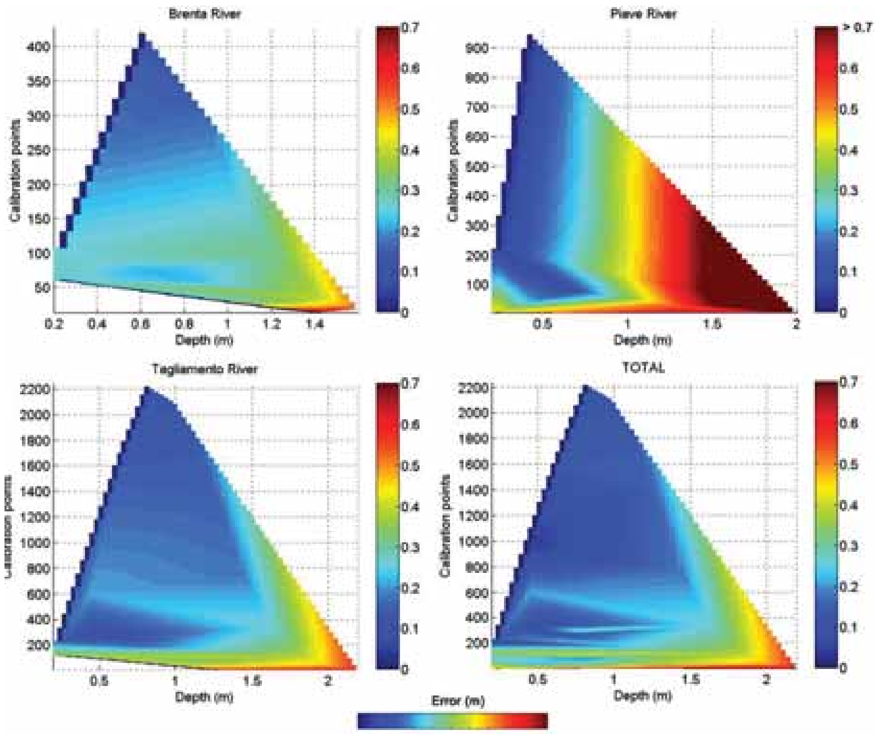

Figure 6: The errors expected (based on our surveys) at different water depths and the number of calibration points.

error is generally > ± 0.2 m and also between 0.3–0.4 with at least 250 calibration points; (iii) the different 'error' trends among the analysed rivers suggest that the error is not only in function of different depth and calibration points but also in function of 'photo conditions' such as luminosity, flight time, etc. Indeed, the high presence of shadows and the low luminosity due to survey time featuring sunrise conditions founded in 2011 in Piave reaches has caused a greater error than in the other reaches. Therefore, a preliminary analysis to know both range of depths and possible 'surfaces of noise' (sources of shadows, artificial structures next to the wet area, etc.) in the study reach is required.

On raw HDTMs (before the filtering process; see Section 3.4), four types of errors were identified: light reflection, water turbulence, periphyton and exposed sediment (sources of errors also confirmed by [17]). Light reflections and water turbulence (white pixels) produce depth estimates strongly negative and substantially different (~1–2 m) from the adjacent pixels not affected by these problems. Exposed or nearly exposed periphyton (green and brown pixels) and exposed sediment (grey pixels) produce an underestimation or overestimation of water depth (about ± 0.40–0.60 cm of difference in respect to the adjacent pixels; Fig. 4). The correction method, which involves the use of a filter based on curvature and removal of outliers [9], has provided excellent results as evidenced by Fig. 5.

Other important rules to produce reliable colour bathymetry are (i) commissioning LiDAR and aerial photos surveys with the lowest water depth and suspended sediment load (ii) flight

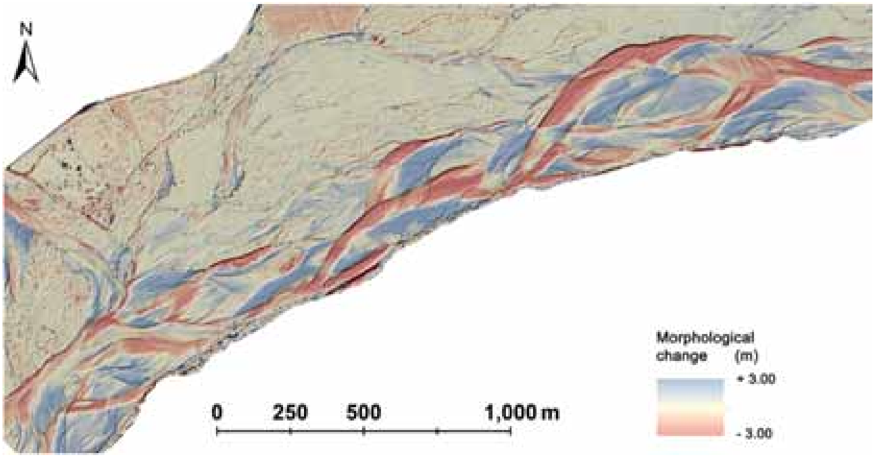

Figure 7: Difference of DEMs (DoD) of Flagogna reach (Tagliamento River).

time around midday to avoid shadows that can introduce more errors in the colour models, (iii) perfect photo-georeferenziation and (iv) good water level estimation.

The difference of DEMs (DoD) derived from 2011 and 2010 HDTMs difference for Flagogna sub-reach is reported in Fig. 7 These changes are due to the flood events of November–December 2010 (RI > 10 years). The most part of the variations has occurred in the wet areas, as highlighted in [9, 11, 13]. The results confirm that if we aim at geomorphic changes evaluation in environments with a significant presence of wet areas, bathymetric techniques are required to provide close-to-real results.

6 CONCLUSIONS

The proposed methodology allows the production of high-resolution DTMs of wetted areas with an associated uncertainty comparable to LiDAR data [9]. The statistical analyses have demonstrated that all the three colour bands (R, G and B) in the three rivers are significantly related to water depth.

The different number of calibration points acquired (Brenta: 399 in 2010 and 1421 in 2011; Piave: 337 in 2010 and 2301 in 2011; Tagliamento: 1107 in 2010 and 9366 in 2011) at different water levels has underlined that the error of colour bathymetry is significantly related to water depth and water stage. A minimum number of 250 calibration points for each water range level (with a step of 0.2 m) seems to be the threshold to guarantee an average error of $< \pm 0.2$ m from 0 to 1.5 m of water depth.

The raster of difference (DoD) highlights the consequences of the flood events of November–December 2010 (RI>10 years), indicating that deposition and erosion areas are more concentrated in the wet areas. In the analysis of braided morphologies, the calculation uncorrected estimations of change in those areas can lead to volumetric results far from real values. The results of this study can be a valuable support to generate precise elevation models, also in wet areas, that can be useful to evaluate erosion–deposition patterns, to improve sediment budget calculation and numerical modeling and to develop more effective river management strategies.

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