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Abstract: Estimating bed surface elevations underwater results in high uncertainty without the use of bathymetric sensors. In our study, a revised approach has been developed in order to create more accurate and detailed Digital Terrain Models (DTMs) by merging LiDAR data for the dry area, with water depth of wet areas derived from a predictive depth-colour relationship. A regression model was implemented that related water depth and intensity of the three colour bands derived from aerial photos. More than 2400 in-channel depth calibration points were taken through a dGPS survey in a wide range of underwater bed forms. LiDAR and depth points were merged and interpolated into a DTM. The resulting DTMs closely matched the field-surveyed ground surface (average error of ± 19 cm with respect to dGPS sections). The method was applied on three sub-reaches of a north-eastern Italian gravel-bed river (Brenta) before and after two consecutive flood events in 2010, with recurrence intervals of 8 and 10 years, respectively. A severe flood event seems to generate riffle-pool migrations in the case with no- nearby natural or -artificial constriction, while a pool enlargement along the channel when they are beside a constriction.

Dear Editor of Catena Jurnal,

Please find attached a manuscript submission entitled **“**Short-term geomorphic analysis in a fluvial disturbed environment by fusion of LiDAR, colour bathymetry and dGPS survey**”.**
The present paper proposes the implementation of a revised methodology for the production of high resolution DTMs of gravel-bed rivers starting from LiDAR surveys which are, generally, associated to aerial images taken during the flight. The work is aimed at evaluating geomorphic changes in the Brenta River as a consequence of flood events occurred in November and December 2010. The specific objectives can be summarized as follows: I) to determine physical and empirical relationships between channel depth and colour intensity and verify which of these variables have more explicative capacity; II) to define factors that increase uncertainty in the final DTMs derived by merging LiDAR data and colour bathymetry data, in order to obtain Hybrid DTMs (HDTMs) at high resolution and low uncertainty; III) to analyze the bed-form changes after severe floods.

The results obtained are a valuable support for planning and management of river morphological recovery.

We hope you could accept our manuscript submission.

Best regards,
Dr Johnny Moretto

Short-term geomorphic analysis in a fluvial disturbed environment by fusion of LiDAR, colour bathymetry and dGPS survey

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Abstract

Estimating bed surface elevations underwater results in high uncertainty without the use of bathymetric sensors. In our study, a revised approach has been developed in order to create more accurate and detailed Digital Terrain Models (DTMs) by merging LiDAR data for the dry area, with water depth of wet areas derived from a predictive depth-colour relationship. A regression model was implemented that related water depth and intensity of the three colour bands derived from aerial photos. More than 2400 in-channel depth calibration points were taken through a dGPS survey in a wide range of underwater bed forms. LiDAR and depth points were merged and interpolated into a DTM. The resulting DTMs closely matched the field-surveyed ground surface (average error of ± 19 cm with respect to dGPS sections). The method was applied on three sub-reaches of a north-eastern Italian gravel-bed river (Brenta) before and after two consecutive flood events in 2010, with recurrence intervals of 8 and 10 years, respectively. A severe flood event seems to generate riffle-pool migrations in the case

with no- nearby natural or -artificial constriction, while a pool enlargement along the channel when they are beside a constriction.

Keywords Fluvial processes; gravel-bed river; colour bathymetry; LiDAR data; floods.

1. INTRODUCTION

The study of river morphology and dynamics is essential for understanding the factors determining sediment erosion, transport and deposition processes. Natural (e.g. climatic and hydrological variations) and anthropic factors (e.g. water captures, grade-control works, gravel mining deforestation) can act at both reach- and basin-scales to change the magnitude or timing of these processes (Buffington, 2012). The geomorphic variations at the reach scale are a direct consequence of sediment erosion and deposition, which are influenced by the size and volume of sediment supply, transport capacity of the flow and local topographic constraints. The quantification of the interaction of these processes is limited by the difficulty of collecting high spatial resolution data in river environments. Traditional approaches based on the application of hydraulic formulas at cross-sections fail when aiming to describe non-uniform natural conditions. Three-dimensional and high-resolution representations of river bed morphology are used in many applications: hydraulic and cellular modelling (e.g. Rumsby *et al.*, 2008); impact evaluation of climate change (e.g. Rumsby and Macklin 1994.); flood hazard management (Macklin and Rumsby, 2007); defining hazardous areas which also involves an assessment of erosion and deposition areas along the river corridor (Stover and Montgomery, 2001; Lane *et al*., 2007). Calculating sediment budgets and estimating sediment transport rates are also fundamental to quantify geomorphological changes due to flood events and changes in flow regime (Ashmore and Church, 1998).

The traditional techniques of terrain survey (e.g. total station devices, dGPS) for evaluating morphological changes in large areas have been demonstrated as being expensive, time-consuming and difficult to apply in areas with limited accessibility. Some innovative methods have shown a good capacity in the production of high-resolution Digital Terrain Models (DTM) of fluvial systems. Recent studies on morphological channel changes have used passive remote sensing techniques such as digital image processing (e.g. Forward Image Model, Legleiter and Roberts, 2009), digital photogrammetry (Dixon *et al*., 1998; Heritage *et al*., 1998; Lane *et al*., 2010), active sensors including Laser Imaging Detection and Ranging (LiDAR) (e.g. Hicks *et al*., 2002; 2006; Kinzel *et al*., 2007; Hicks, 2012) and acoustic methods (e.g. Muste *et al*., 2012; Rennie, 2012).

The main difficult related to the production of precise DTMs with non-bathymetric sensors is due to the absorption of natural (solar) or artificial (LiDAR) electromagnetic radiation in the wet channel. The capacity of the electromagnetic signal to pass through water, reflect from the bed and reach a sensor depends on the water surface texture (pleating, reflexes, etc.), the water column (depth and turbidity) and some bed (substrate type and algae presence) characteristics (Marcus, 2012; Marcus and Fonstad, 2008).

Only a few tools have proved able to provide an accurate and high-resolution measure of the submerged bed surface, and survey precision decreases with the increase in water depth. Bathymetric LiDAR sensors have recently been developed and should enable the survey of underwater bed surfaces. Nevertheless, they feature high costs, relatively low resolutions, and data quality comparable to photogrammetric techniques (Hilldale and Raff, 2008). Progress in the LiDAR acquisition of topographic information from submerged areas has been made with a new technology: Experimental Advanced Airborne Research LiDAR system (EAARL) that records the full waveform of the returning laser pulse. This system is affected by environmental conditions (e.g. turbulence in the pool, bubbles in the water column, turbidity, and low-bottom albedo) and post-processing algorithms even if the accuracy appears comparable to that of airborne terrestrial near-infrared LiDARs (Kinzel *et al*., 2013; McKean *et al*., 2009).

The survey of wet areas can thus be approached using two photogrammetric techniques (manual or automatic) which are able to produce a cloud of elevation points (Rinner, 1969; Fryer, 1983), or with a technique based on the calibration of a depth-reflectance relationship of images, which can be in greyscale (e.g. Winterbottom and Gilvear, 1997), coloured (e.g. Carbonneau *et al*., 2006, Moretto et al, 2013a) or multispectral (Marcus *et al*., 2003; Legleiter, 2011). Both solutions need a field survey, contemporary to the flight, to provide calibration depth points.

The depth-reflectance relationship can be defined using an empirical relationship, using one or more bands (e.g. Legleiter *et al*., 2009), or according to the Beer-Lambert law. In the latter case the amount of light absorbed by a transparent material is proportional to the distance of the light travelling through that material (Carbonneau *et al*., 2006):

$$I_{out} = I_{in}\, e^{-cx} \qquad (1)$$

Where l_{in} is the incoming intensity, l_{out} the outgoing intensity, c is the rate of light absorption, and x the distance.

Once reliable digital elevation models (DEMs) have been obtained, it is possible to detect and interpret, in a quantitative way, geomorphic changes in river systems (e.g. Lane *et al.*, 1994). An important component to be evaluated on DEMs is the uncertainty, which can be influenced by many factors. The most decisive error sources include survey point quality, sampling strategy, surface topographic complexity and interpolation methods (Panissod *et al*., 2009; Milan *et al.*, 2011). Total uncertainty is usually derived from the classical statistical theory of errors (Taylor, 1997) where an estimation of DEM accuracy based on survey data is used as a surrogate for DEM quality (Milan *et al.*, 2007).

This paper proposes the implementation of a revised approach for the production of high resolution DTMs of gravel-bed rivers starting from LiDAR surveys and aerial images acquired during the flight. The aim is to evaluate morphological change patterns in the Brenta River as a consequence of flood events that occurred in November and December 2010. The Brenta river basin, like the majority of Italian rivers (Comiti *et al*., 2011; Surian, 2012), has undergone intense and multiple human impacts starting from phases of deforestation and reforestation, followed by interventions for hydroelectric power generation and irrigation purposes, which have altered both the catchment and the river channel.

The specific objectives can be summarized as follows: I) to determine physical and empirical relationships between channel depth and colour intensity and verify which of these variables have more explicative capacity; II) to define factors that increase uncertainty in the final DTMs derived by merging LiDAR data and colour bathymetry data, in order to obtain Hybrid DTMs (HDTMs) at high resolution and low uncertainty; III) to analyze the bed-form changes after severe floods.

2. STUDY AREA

The Brenta River is located in the South-Eastern Italian Alps, having a drainage basin of approximately 1567 km^2 and a length of 174 km. Average annual precipitation, mainly concentrated in spring and autumn seasons, is about 1100 mm. The geology of the area is rather complex and includes limestone, dolomite, gneiss, phyllite, granite and volcanic rocks.

The study reach is 19.2 km in length and lies between Bassano Del Grappa and Piazzola sul Brenta (Figure 1). The dominant morphologies are wandering and braided, the active channel width varies between 300 m and 800 m, and average slope is about 0.0036 m/m. Within this study reach, three sub-reaches 1.5 km long and 5 km apart were selected as representative of the upper- middle- and down-stream part of the study area and named according to the nearby villages: Nove, Friola and Fontaniva (Figure 1). The upstream sub-reach (Nove) has a single straightened channel morphology with an average width of around 300 m. By contrast, Friola shows a more complex morphological pattern, with the braided channel accounting for high levels of vegetation density and an average width of 500 m. In the downstream sub-reach, Fontaniva, the braided trend is more marked, with the formation of many fluvial islands and the 800 m wide channel divides into several branches.

The Brenta river basin has suffered centuries of disturbances, mostly due to deforestation and reforestation. The water course was regulated for hydroelectric power generation and irrigation purposes and dams were built in many parts of the drainage basin, intercepting sediments from more than 40% of the drainage area. Moreover, between 1953 and 1985, gravel was intensively quarried in the main channel and, starting in the 1930s, effective erosion and torrent control works were executed in the upper basin (Bathurst *et al*., 2003; Lenzi *et al*., 2003; Lenzi, 2006; Rigon *et al*., 2008; Conesa-Garcia and Lenzi, 2010; Surian et al., 2009). Human interventions, especially during the second half of the 20th century, have considerably altered the sediment budget of Alpine rivers (Mao and Lenzi, 2007; Mao *et al*., 2009; Comiti, 2011; Comiti *et al*., 2011; Picco *et al*., 2013). As a result of these impacts, the average riverbed width of the Brenta has narrowed from 442 m at the beginning of the 1800s, to 196 m in 2010, and channel incision has ranged from 2 to 8 m, especially due to the effects of gravel quarrying that only ended during the 1990s (Surian and Cisotto, 2007; Moretto *et al.*, 2012a, 2012b, 2013b; Kaless *et al*., 2013). In recent times, a new adjustment phase seems to be taking place (channel widened to 215 m in 2011) as evidenced by the expanding trend of the active channel with a contemporary increase in vegetated islands over the last twenty years (Moretto *et al.*, 2012a, 2012b, 2013b). Nevertheless, the river presents several localized variations along its course, which are linked to the different erosion-sedimentation processes underway. The recent evolutionary dynamics differ from those in the past and, since the abandonment of gravel mining activities on the river bed (1990s), there has been a partial morphological recovery, especially in the downstream sub-reach, Fontaniva. However, this trend is still unstable and not distributed along the whole study reach. In the upstream area, there are still incision processes and a widening of the active channel as a result of bank erosion (Moretto *et al*., 2012a, 2012b, 2013b).

Two flood events occurred between the LiDAR flights (Figure 2). The November 2010 flood reached a maximum average daily discharge of 720 m^3/s, with a slower drop in the water level compared to the second flood event in December 2010, which had the highest discharge of the last 10 years (maximum average daily discharge of 759 m^3/s). The first flood, caused by prolonged and heavy rainfall between the 31st of October and 2nd of November 2010, which totalled 300 mm with local maximums over 500 mm (Figure 3), with 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 at the basin scale, such as landslides, bank erosion processes and flooding outside the banks. The second flood, originated by intensive precipitations between the 21st and 26th of December that fell mostly in the pre-alpine and piedmont areas, had an RI of about 10 years. Rainfall exceeded 150 mm with local maximums of 300-400 mm and the river registered (at Barzizza station) higher hydrometric levels than the first flood event, probably due to the greater soil saturation at basin scale and, more particularly, the fact that a major reservoir (Corlo) had already been filled by the previous flooding.

The return interval of these floods was estimated from the maximum annual values of the mean daily water discharge over 79 hydrological years. The functions of hydrological probability distribution that were tested are: Log Normal, Log Pearson Type III, Frechet, and Gumbel. The Gumbel distribution (OLS) demonstrated the best performance of the Kolmogoroff test. Taking into account the Gumbel distribution and 90% confidence limits, it was possible to establish the flood values associated with the probability of occurrence (Lenzi *et al*., 2010; Kaless *et al*., 2011; Kaless *et al*., 2013).

3. MATERIAL AND METHODS

To create an accurate digital terrain model, a regression model was calibrated between the water depth and the Red, Green and Blue (RGB) bands values deriving from aerial images acquired during the LiDAR survey. The water depth was estimated indirectly as the difference between the water surface (estimated from interpolation of selected LiDAR points; see details in section 3.2) and bed elevation (measured with dGPS in the field). Hybrid digital terrain models (HDTM) were then created, derived from the interpolation of LiDAR (section 3.4) points for dry areas and colour bathymetry derived points for wet areas. A total of three HDTMs were developed for each considered year referring to the three sub-reaches (Nove, Friola and Fontaniva).

This process (Figure 4) was divided into five principal steps: (A) LiDAR data and field survey, (B) dataset preparation, (C) bathymetric model determination, (D) HDTMs creation and (E) HDTMs validation. At the end, three DEMs of difference (DoDs - one for each sub-reach) were produced for each year, and the volumetric surface change and relative uncertainty calculated. The details of this process are explained in the sub-sections below.

The novel contribution of this approach mainly regards four aspects:

I) The field of application involves complex depth and colour characteristics (due to high periphyton loads on the channel bottom);

II) A revised methodology to estimate the water depths to associate with the colour bands (depths of calibrations), thanks to the difference between the elevation of the water surface (derived from selected LiDAR points) and that of the channel bottom (derived from a dGPS survey performed contemporarily with the LiDAR survey). In this way the application of the approach is also possible without direct water depth measures;

III) The search for the best depth-colour model, testing existing physical models (based on

Beer Lambert law formula) and empirical models through different statistical regression methods;

IV) The application of filters, based on colour variability analysis, to reduce the errors of the bathymetric models (presence of pheriphyton, light reflections, exposed sediment, shadows, suspended load and water turbulence).

3.1. LiDAR data and field survey

Two LiDAR surveys were conducted on the 23rd of August 2010 by Blom GCR Spa with an OPTECH ALTM Gemini sensor and on the 24th of April 2011 by OGS Company with a RIEGL LMS-Q560 sensor (flying height ~ 850 m). For each LiDAR survey a point density able to generate digital terrain models with 0.5 m of resolution (at least 2 ground points per square metre) was commissioned. The average vertical error of LiDAR was evaluated through dGPS points on the final elevation model. LiDAR data were taken along with a series of RGB aerial photos with 0.15 m pixel resolution. The survey were conducted with perfect weather conditions and low hydraulic channel levels. An in-channel dGPS survey was performed, taking different depth levels in a wide range of morphological units. A total of 882 points were surveyed in 2010 and 1526 points in 2011. Finally, two cross-sections for each sub-reach were surveyed through dGPS (dGPS average vertical error ± 0.025 m). It is important to note that the dGPS survey was performed contemporarily with the LiDAR data to avoid the introduction of additional stochastic components.

3.2. Dataset preparation

The raw LiDAR points cloud was analysed and the ground surface was identified through an automatic filtering algorithm (TerraScan, Microstation Application®) and, in critical areas (such as near bridges), using manual checks. 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 resampled from 0.15 m to 0.5 m to minimize the georeferencing error and reduce the possible strong colour variation due to light reflection, exposed sediment, periphyton, shadows and suspended load. This is a crucial point because poor photo georeferencing can significantly increase the error due to a wrong association between water depth and colour intensity. The choice of improving the pixel size to exactly 0.5 is also in relation to the resolution of the final elevation model (value derived from point density analysis).

Wet areas were digitalized through a manual photo-interpretation process. Along the edges of "wet area" shape polygons, LiDAR points able to represent the water surface elevation (*Zwl*) were selected and used to create a water surface elevation raster (Kriging interpolation).

Corresponding colour band intensities and *Zwl* were added to the points acquired in the wet areas (dGPS wet-area survey) obtaining a shape file of points containing five fields (in addition to the spatial coordinates x and y): intensity of the three colour bands, Red (*R*), Green (*G*), Blue (*B*), elevation of the channel bed (*Zwet*) and *Zwl*. Finally, channel depth was calculated as $Dph = Zwl - Zwet$. A similar method was employed by Legleiter (2013) using the difference between the mean water surface elevation and the bed elevation, both derived from GPS survey.

3.3. Determination of the best bathymetric model

Starting from the obtained dataset, the water depth (estimated indirectly) was considered as the dependent variable, with the three intensity colour bands (R, G and B) as independent variables. 80% of the dataset was used for calibrating the depth-colour model and the remaining 20% to verify the efficiency and choose the best model. Physical models based on the Beer Lambert law (Eq. 1) were tested first.

A ratio-based method was employed to detect changes in depth and filter out the effect of changes in bottom albedo (e.g., Dierssen *et al*., 2003). Legleiter *et al*. (2004) and Marcus and Fonstad (2008) demonstrated that the log-transformation of the red-over-green band ratio correlates linearly with water depth across a wide range of substrate types:

$$DPH = \alpha + \beta_0 ln\ (R/G) \qquad (2)$$

where DPH is the water depth, α and β_x are the calibration coefficient, and R and G are the intensities of the red and green bands.

An empirical linear model evaluating all the colour bands, the possible interactions and the square and cubic terms were then tested:

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

Where α and β_x are the calibration coefficients in the depth colour regression. In this model the significance of each component was tested and deleted when the statistical test adopted (explained below) resulted as negative.

The statistical regressions were performed in R® environment using two methods: the traditional regression method based on statistical significance testing of each variable (p-value < 0.05), and the AICc index (Burnham and Anderson, 2002). The second approach estimates all the significant models, forming a ranking founded on the AICc value (the lower value represents the best model), starting from the most complex plausible model. The AICc method automatically deletes the non-significant variables while the deleting process in the first method is manual. The model featuring the lower error 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 images (raster calculator) to determine the "raw channel depth raster" (RDPH). The RDPH was then transformed into points (2 points/m^2) and filtered in order to delete wrong or suspicious points, mainly due to sunlight reflection, turbulence, and elements (wood or sediment) above the water surface.

The proposed methodology used for filtering possible wrong points is characterized by an analysis of slope changes in neighbouring pixels. When there are very strong slope changes between neighbouring pixels, a potential error of depth estimation exists. We could analyse these variations through a semi-automatic method that forecasts the creation of a "curvature raster" (ESRI® ArcGIS 10), obtaining a value of curvature (slope derivative) for each pixel. The "range" of curvature to consider a difference of depth between two pixels "real" (with our pixel resolution of 0.5 m) was identified as $-600 < x < 700$. The pixel, with curvature values outside this range were removed, as in this case the "gap" between two pixels is greater than 0.6 m. In addition, the upper and lower implausible limits (outliers; < 5% of total points distribution) were deleted.

On the corrected points (*DPH* model), the corresponding *Zwl* was subtracted to obtain, for each point, the estimated river bed elevation (*Zwet = Zwl -DPH;*). Hybrid DTMs (HDTM) were built up with a natural neighbour interpolator, integrating Zdry points (by LiDAR) in the dry areas and Zwet points (by colour bathymetry) in the wet areas.

Finally, the HDTM models were validated by using dGPS cross-section surveys. The error of each "control point" was derived considering the difference between the elevation of the HDTM and corresponding elevation of the dGPS control point.

The accuracy of the HDTMs was estimated separately for wet and dry areas, also taking into account the dGPS error (available from the instrument for each point).

3.5. Analysis of morphological changes

Thanks to the HDTMs obtained with a precise definition in both dry and wet areas, we were able to explore the effects of severe floods. HDTMs comparison, analysing the dynamics of the bed forms (riffle - pool) as a consequence of flood events and natural and artificial "constrictions", was performed in order to integrate the erosion-deposition patterns analysis described in Moretto *et al*. 2012a for the same study area.

Canopy surface models (CSM), derived from the difference between digital surface models (DSM) and DTMs, were produced to identify the natural (fluvial islands) and artificial (embankments and bridges) vertical construction in the analysed sub-reaches. In addition to the bathymetric rasters, three water depth classes (0 – 0.5m; 0.5 – 1m and > 1 m) were applied to identify the different bed forms.

4. RESULTS

4.1. Colour bathymetry models

To understand the variability and average depth of the channel, before calibrating the model regression, the average, standard deviation and maximum depth of 2010 and 2011 wet channels were estimated. 2010 was characterized by an average depth of 0.53 m, a standard deviation of 0.34 m and maximum known depth of 1.62 m. 2011 had a greater average depth than 2010 and equal to 0.63 m, a standard deviation of 0.28 m and maximum known depth of 1.63 m.

The search for the best depth-colour model started by testing a physical model, based on the Beer Lambert law (Eq. 2) for each year (2010 and 2011) and with the two statistical regression methods (traditional regression and AICc index; Section 3.3).

The application of the traditional regression method and the AICc index produced the same depth colour model for 2010:

$$DPH = -0.119 + 2.725 \ln (R/G) \quad (5)$$

Where *DPH* is the water depth and *ln(R/G)* are the colour bands arranged according to the Beer Lambert law.

This model has a statistically significant p-value << 0.05, r^2 of 0.34 and an average error derived from the test points of ± 0.27 m.

A similar result was obtained with the 2011 model; also in this case the two statistical regression methods have produced the same result:

$$DPH = -0.73 + 2.043 \ln (R/G) \quad (6)$$

This model has a statistically significant p-value << 0.05, r^2 of 0.25 and an average error derived from the test points of ± 0.20 m.

The *depth-colour (RGB)* statistical regressions performed in the empirical model with the two different approaches allowed two bathymetric models to be obtained for each year (2010 and 2011). The average errors, detected in the two models by comparing the test points of 2010, are equal to ± 0.26 m and highlighted negligible differences accounting for the same magnitude of the estimation errors (0.003 m of difference of average error). Therefore, the model resulting from the traditional method (reported below; with verified p-value) was preferred because of its simpler structure with fewer factors if compared to the AICc model:

$$DPH = 5.31 + 0.07513\,R - 0.1869\,G - 0.01475\,B - 0.0004582\,RB + 0.001056\,G^2 + 0.0003352\,B^2 - 0.000002142\,G^3 \quad (7)$$

Where *DPH* is the estimated water depth and R, G and B are the red, green and blue bands, respectively. The model presents an r^2 of 0.46, 12 percentage points more than the 2010 physical model.

In 2011, on the other hand, the two different methodologies (traditional and AICc index) of statistical regression generated the same model:

$$DPH = -0.607 + 0.03508\,R - 0.06376\,G - 0.1377\,B + 0.002257\,RG - 0.001096\,RB + 0.002303\,GB - 0.0007273\,R^2 - 0.002956\,G^2 + 0.0009993\,B^2 + 0.000002837\,G^3 - 0.00000685\,B^3 \quad (8)$$

In this case, r^2 is equal to 38%, whereas the estimated depth average error, resulting from the test points, accounts for ± 0.19 m. Both physical and empirical models proved to be statistically significant (p-value << 0.05), but the empirical models seem to have more predictive capacity than the physical model. In addition, all three colour bands significantly contribute to depth estimation, so the presence of interactions between the colour bands (as reported in Figure 5) should be taken into consideration.

We therefore decided to use the empirical models because, despite the similar average errors on the test points, they feature a more predictive capacity than the physical one and also take into consideration the interactions (correlations) between the colour bands.

Figure 6 shows one of the outputs deriving from the model application (Eq. 8) on the Friola sub-reach. It appears that depth variations are generally respected, and variations in the colour tone, due for example to the presence of periphyton in these areas joined to slower water flow, 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.

It is important to note that the model error reported above was evaluated comparing the test points, on the 20% of the dataset not used for the statistical regressions. This is therefore not the final error; indeed the next section discusses the effects of the filters (as described in section 3.4) to delete the majority of these errors.

4.2. HDTM production and validation

After filtering raw depth points deemed wrong due to the model application on the altered pixel colour value (caused by river bed colour, water turbulence, light reflections, shadows, suspended load, exposed sediment), dry areas were integrated using the LiDAR flight. The LiDAR points cloud (excluding wet areas) featured an average density of 2.07 points/m^2 for 2010 and 2.64 points/m^2 for 2011; the final HDTMs were generated using a 0.5 x 0.5 m cell size. The final HDTMs, three for 2010 and three for 2011 (Nove, Friola and Fontaniva sub-reaches) are reported in Figure 7. It is worth noting the accuracy in the bed-forms definition (riffles and pools) within the wet channels estimated through the bathymetric process.

The data validation (Table 1) was performed separately for both wet and dry areas, obtaining average uncertainty values (by field survey comparison) for each HDTM that include dGPS, LiDAR and DPH estimated errors. The average uncertainty associated to wet areas accounts for from a minimum of ± 0.19 m (Friola 2011) to a maximum of ± 0.26 m (Nove - Fontaniva 2010 and 2011), whereas in the dry areas the average uncertainty ranges from a minimum of ± 0.14 m (Nove 2010) to a maximum of ± 0.26 m (Fontaniva 2010). The chosen colour bathymetric models (empirical depth-RGB) generated similar error levels for both 2010 and 2011. Moreover, the average weighted uncertainty was calculated in the final HDTMs, and ranges from ± 0.16 m (Nove 2010 – 2011 and Friola 2011) to ± 0.26 m (Fontaniva 2010).

The last phase of the HDTM production process consists of model validation with dGPS cross-sections. Figure 8 shows an example of comparison of three cross-sections for 2011, obtained with three different types of data (dGPS survey, LiDAR, and HDTM). The section reference is the dGPS, in which the measured points have an average error of about 0.025 m. The main topographical variations result as being faithfully reproduced, except for the thalweg, which was difficult to detect with a dGPS survey. Comparing the dGPS and LiDAR profiles, the inability of the LiDAR signal to penetrate wet areas more than 20 cm was confirmed (with consequent underestimation of the calculated volumes). Instead, comparing dGPS and HDTM profiles, it appears that, overall, the ground points are fairly well replicated**.**

4.3. Morphological change detection

From Figure 7 reporting the HDTMs comparison, an interesting change after the floods can be noted: where the main channel had less lateral constriction, it seems to have an increased sinuosity. Indeed, Nove sub-reach is the most constrained laterally due to artificial left enbarkments and also presents the highest incision degree. It therefore has less increase of sinuosity than Friola and Fontaniva sub-reaches. Comparing these two reaches, Friola presents less change in sinuosity than Fontaniva, probably due to the position next to the artificial banks (on the left side) of the main 2010 channel.

Figure 9 shows the CSMs with pool locations (e.g. P1, P2) on the wet areas of Nove, Friola and Fontaniva sub-reaches in 2010 and 2011. Pools are identified as dark areas, i.e. the zones with the higher water depth with respect to the riffles. It is noteworthy that after the floods, the old pools are longer on average. This phenomenon is particularly evident in Friola sub-reach (pool P3 and P4 2011) and Fontaniva (pool P4 2011). Observing the models, the new pools and the old one still presents do not seem to have formed and evolved in casual positions. The embankments and fluvial islands appear to have played an important role in the bed-form dynamics during the floods. Indeed, the pools in each 2011 sub-reach are located mainly at the side of the wet area with a more compact lateral surface with embankments and/or vegetated bars. On the other hand, riffles are mainly located where no significant "constrictions" were present on either side of the wet areas. The dislocation of the 2010 bed forms does not seem to follow the same principles.

DISCUSSION

5.1. Analysis of the proposed method for geomorphic change detection

The proposed method is a revised procedure for the production of high resolution DTMs on gravel-bed rivers, integrating LiDAR points with filtered bathymetric points estimated through a regression model implemented on wet areas with high heterogeneity.

The bathymetric points can be derived from a physical and empirical relationship between water depth and RGB bands of aerial images taken concurrently with LiDAR data.

The model calibration requires a dGPS survey of the water level, without needing direct water depth measurements. It is crucial to acquire dGPS points nearly contemporary to LiDAR and aerial images, as already pointed out by Legleiter (2011). In fact, the calibration of the model does not need direct field surveys of water depth because this is indirectly estimated. Depth estimation entailed the subtraction of the water level raster (water surface) from the corresponding dGPS elevation points (bottom surface) of the channel bed (Zwet). This method is an effective approach for the indirect estimation of water depth and a similar technique was used by Carbonneau *et al.,* (2006). Checking the results obtained from direct measurements of water depth, using gauge rods in correspondence to dGPS points, we noticed that the values obtained from the same points by indirect estimation account for an average error of 0.15 m. This error may also be due to the speed of the water flux during the direct sampling, that created some turbulence around the graduated bar.

Indirectly estimated depths (see section 3.2), together with the corresponding RGB values, made up the dataset for the statistical calibration of the regression models. The statistical analysis showed that all three bands (R, G, B) and also some of the other constituent factors (interactions among bands and square and cubic terms) are significant (p-value < 0.05) to predict the water depth. This statistical significance was also confirmed by two different statistical regression methods (verification of p-value and AICc index). The “ad hoc” calibration for each study year was necessary because of the different water stage during the LiDAR survey.

This study has demonstrated that in a very heterogeneous wet area, with different depths and different colours on the channel bottom (due to the presence of periphyton), the tested physical models have a lower degree of significance than the empirical models. The empirical models use all the colour bands, and also take into consideration their interactions (non-independence from the explicative variables), the presence of which is demonstrated in Figure 5. All the estimated models (physical and empirical) have an r^2 lower than other similar studies (e.g. Carbonneau *et al.*, 2006; Legleiter *et al.*, 2011), but this is due to the very strong colour and depth variability. Despite a lower r^2, the final validations of the elevation models (shown in Figure 8 and Table 1) have demonstrated a bathymetric uncertainty comparable with the LiDAR data.

Table 2 shows that in our case the optimal application range of the estimated bathymetric models is between 0.2 m and 1.0 m for 2010 and 2011, respectivelly. The error of estimated water depth increases, in the first 20 cm from the water surface, due to strong colour variations at the bottom (periphyton, exposed pebbles, woody debris, etc.). This error was eliminated by substituting those areas with LiDAR points, capable of penetrating this first water layer. The capacity of the LiDAR signal to produce a reliable estimate in the first 20 cm of the water column was confirmed by dGPS and LiDAR cross-section comparison (Figure 8).

Nevertheless, the possible sources of error in the proposed colour bathymetry can generate elevation models of wet areas with an error on our data of less than ± 0.22 m for 95% of the 2010 wet area and less than ± 0.26 m for 99%. For 2011 we obtained an error of less than ± 0.24 m for 80% of the wet area and less than ± 0.32 m for 89%. Hydraulic conditions differed between 2010 and 2011 (see section 4.1), and the number of calibration points can play a significant role especially in a very variable fluvial environment.

To confirm the importance of using a bathymetric method if the aim is to evaluate erosion – deposition patterns by applying numerical models or developing sediment budgets, table 1 reports the loss of volume without applying colour bathymetry. These volumes were derived by subtraction between HDTMs and DTMs (derived entirely from LiDAR). The minimum loss (possible erosion and/or deposition) of 529,813 m^3 is registered at Nove and the maximum of 4,743,783 m^3 in Fontaniva. Therefore the loss of potential erosion and deposition without applying a bathymetric method cannot be excluded to avoid obtaining results far from the reality.

A comparison of the 2011 raw HDTM and the HDTM derived from the profiles of Friola wet areas is shown in Figure 10. Four types of errors were identified on raw HDTM: light reflection, water turbulence, periphyton and exposed sediment (sources of errors highlighted also by Legleiter *et al.*, 2009). The light reflections and water turbulence (white pixels) produce strongly negative depth estimates and substantially different (about 1 - 2 m) from adjacent pixels not affected by these problems. The 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 with respect to the adjacent pixels). The correction method, which involves the use of a filter based on the curvature and removal of outliers (points with errors exceeding 95% confidence interval), has provided excellent results as evidenced by Figure 10. The proposed filtering approach of erroneous points due to the causes listed above is the new element of the proposed colour bathymetric methodology.

Shadows represent a disturbance factor difficult to correct and remove because they tend to cause an overestimation of the channel depth. However, their presence was minimal in the study sites, thanks to the image acquisition being done at midday. A further limitation is a water depth greater than 1.0 - 1.10 m, where the model tends to produce underestimations. This is partially due to the low availability of calibration points (for safety reasons) in the deepest areas of the water channel. Legleiter (2013) explained that depth estimates through aerial images become less reliable in deeper water due to the increase in saturation of the radiance signal.

In the HDTM profile there are some small areas lower than the dGPS profiles (Figure 8). This may be due, in part, to the presence of large boulders in the water channel that have altered the comparison between precise dGPS measurements and those derived from a mediated profile by HDTM cells of 0.5 x 0.5 m. These deviations are localized and on average included in the total average error detected in this reach (± 0.16 m). Consequently, the HDTMs produced can be considered a satisfactory topographical representation (considering the resolution of the final elevation models) for a homogeneous study of morphological variations.

5.2. Geomorphic changes after November and December 2010 floods

The morphological evolution of the Brenta River over the last 30 years has been strongly influenced by human impacts and flood events (Moretto *et al*., 2013b). Lateral annual adjustment is directly correlated with the mean annual peak discharge (Moretto *et al*., 2012a, 2013b), thus a higher magnitude of flooding corresponds to greater active channel widening. Substantial increases in channel width and reductions of riparian vegetation occur with flood events with an RI of more than 5 years, as already highlighted by other works concerning similar fluvial environments (e.g. Bertoldi *et al*., 2009; Comiti *et al*., 2011; Picco *et al*., 2012a, 2012b; Kaless *et al*., 2013). The flood events of November-December 2010 (RI = 8-10 years) have caused an expansion of the active channel average width by about 10% (from 196 m to 215 m) with the consequent removal of 10 ha of riparian vegetation (11% less) in the study reach (for more detailed information see Moretto *et al*., 2012a, 2012b). The sediment processes can be analysed in detail at sub-reach level thanks to the HDTMs developed with the proposed methodology.

A severe flood event seems to generate riffle-pool migrations in the case with no nearby -natural or -artificial constrictions (e.g. P1 of Friola and Fontaniva 2010), while a pool enlargement along the channel when they are beside a constriction (e.g. P4 of Nove and P3 – P4 of Friola 2011). The location and geometry of the new bed forms seem to be related to the natural (vegetated bar) and anthropic (embankments and bridges) constrictions. Comparing the 2010 and 2011 pools it can also be noted that after a severe flood event, they are generally longer and the migrations are more concentrated beside the more compact lateral sides (Figure 9). The embankments and fluvial islands seem to have played an important role in the bed-form dynamics during the floods. Indeed, the pools of each 2011 sub-reach are located mainly next to more compact lateral surface with embankments and/or vegetated bars. On the other hand, riffles are mainly located over old pools and where no significant "constrictions" were present on either side of the wet areas.

The different behaviour of the three sub-reaches seems to be attributable to their diverse morphological characteristics (natural and imposed) and the availability of sediment from the upstream reach (Moretto *et al*., 2012a, 2012b, 2013b). The first sub-reach is the most studied and the most affected by erosion processes (Moretto *et al*., 2012a). The conditions of Nove sub-reach can be summarized as follows: i) past and present heavy incision of the active channel with modifications in section shape and from the river basin; ii) very little sediment supply from upstream reaches; iii) almost total absence of vegetation on the floodplain; iv) increase of local slope.

In the second sub-reach, Friola, the Brenta River has a lower slope and is less constrained laterally than in the upstream area, as confirmed by the presence of a large island and a secondary channel to the right. During severe floods, therefore, the main channel can migrate forming new deposition bars. On the other hand the dynamics of Fontaniva are related to: i) greater availability of eroded sediments coming from the upper sub-reaches; ii) more balanced erosion deposition pattern (Moretto *et al*., 2012a, 2012b, 2013b); iii) increase in the average elevation of the active channel in the last 30 years; iv) presence of extended and stable vegetation in the floodplain area which is increasingly affected by flood events; v) reduction of local slope; vi) presence of infrastructures (2 bridges). The slope reduction, together with the increase in average elevation of the active channel in the last 30 years (Moretto *et al*., 2012a, 2012b, 2013b), determine a greater spatial mobility of the flood flow than in the past (with RI > 5 years), above all in external areas where dense and stable riparian vegetation is present (Figure 1). This means increased roughness and a river slowdown with the reduction of transport capacity.

The morphological changes that occurred in the Brenta River as a consequence of the flood events in 2010 (RI of about 8 and 10 years) are of great importance to evaluate the fluvial hydro-morphological quality, because they highlight the processes that are taking place, and provide insights into their future evolution as required by the EU Water Framework Directive. Nevertheless, for implementing evolutionary models and estimating sediment transport, a better assessment of the quantity of incoming and outbound sediment in the study reach and a detailed analysis of the transport rate in relation to the event magnitude are needed. Several works apply the morphological approach for estimating the sediment budget starting from transversal sections (i.e. Lane, 1998; Surian and Cisotto, 2007, Bertoldi *et al*., 2010), nonetheless a much more accurate spatial definition can be obtained from remote sensing data (i.e. Hicks *et al*., 2006; Hicks, 2012; Rennie, 2012; Milan and Heritage, 2012). The traditional methodologies of terrain change detection (e.g. with dGPS cross-sections) report a high precision punctual definition, however the determination of volume changes at reach scale may be improved with the assessment of DEMs differences (Lane *et al*., 2003). The implementation of LiDAR data and colour bathymetry with the proposed methodology allowed us to obtain a terrain digital model with sufficient accuracy to derive patterns of sediment transfer, in particular within the water channels. The information obtained from such an analysis should be integrated with direct field measurements.

6. FINAL REMARKS

The proposed methodology allows high-resolution DTMs of wet areas to be produced with an associated uncertainty that has proved to be comparable to the LiDAR data. The bathymetric model calibration requires only a dGPS survey in the wet areas contemporary to aerial image acquisition. Statistical analyses have demonstrated both that all three colour bands (R, G, B) significantly correlate with water depth and a good performance of the empirical models. In addition the presence of an interaction between the colour bands cannot be neglected.

Error sources (reflections, turbulences, strong colour variations at the bottom, shadows, suspended load, exposed sediment, etc.) were mostly intercepted through the two proposed filters for the curvature assessment and eliminating the implausible upper and lower limits in the bathymetric raster. The validation of the Hybrid Digital Terrain Models (HDTM) resulted as being satisfactory for distributed evaluations of morphological variations.

If the aim is to quantify erosion-deposition patterns, apply numerical models or develop sediment budgets, as demonstrated in table 1, the bathymetric methods are fundamental to obtain realistic evaluations.

The flood events of November-December 2010 (RI= 8 and 10 years) have caused significant geomorphic changes in the three sub-reaches. The different behaviour of the sub-reaches seems to be attributable to their diverse morphological characteristics (natural and imposed) and the availability of sediment from the upstream reach.

The riffle-pool dynamics seems not be casual, but influenced by the natural (vegetated bar) and anthropic (embankments and bridges) constrictions. After a severe flood event, the pools seem be located mainly on the side of the wet area with a more compact lateral surface with embankments and/or vegetated bars. On the other hand, riffles seem be located mainly where no significant “constrictions” were present on either side of the wet areas.

The results of this study can be a valuable support to generate precise elevation models also for wet areas, useful for evaluating erosion-deposition patterns, improving sediment budget calculations and the implementation of 2D and 3D numerical hydrodynamic models.

Notation

dGPS	Differential Global Positioning System
DEM	Digital Elevation Model
DPH	Channel Depth
DTM	Digital Terrain Model
HDTM	Hybrid Digital Terrain Model
LiDAR	Light Detection And Ranging
RDPH	Raw channel depth model (raster and/or points)
RGB	Red Green Blue
RI	Recurrence Interval
Zdry	Z coordinate of dry area
Zwet	Z coordinate of wet area
Zwl	Z coordinate of water level

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Table 1 Estimated uncertainty for HDTM and 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
N° 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
N° 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
Volume loss without colour bathymetry	(m^3)	917559	529812	1206848	397470	4386814	4743783

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.

Table 2 Error analysis of depth-colour models at different water stages for 2010 and 2011. The average error and standard deviation have been weighted with the corrispondence inference area.

2010)

Depth	**Surface covered**		**DPH (R, G, B)**		**Calibration**
(m)	(ha)	%	error (m)	St. dev. (m)	**points**
0.00 - 0.19	20.07	34.0	0.26	0.22	107
0.20 - 0.39	14.38	24.3	0.26	0.24	87
0.40 - 0.59	13.12	22.2	0.21	0.20	75
0.60 - 0.79	8.82	14.9	0.22	0.18	59
0.80 - 0.99	2.11	3.6	0.26	0.15	32
1.00 - 1.19	0.54	0.9	0.51	0.21	20
> 1.20	0.06	0.1	0.69	0.14	13
TOTAL	**59.09**	**100**	**0.25**	**0.21**	**393**

2011)

Depth	**Surface covered**		**DPH (R, G, B)**		**Calibration**
(m)	(ha)	%	error (m)	St. dev. (m)	**points**
0.00 - 0.19	0.37	0.5	0.27	0.11	61
0.20 - 0.39	5.16	7.1	0.18	0.11	248
0.40 - 0.59	18.17	25.0	0.13	0.11	427
0.60 - 0.79	19.79	27.3	0.14	0.13	343
0.80 - 0.99	14.35	19.8	0.24	0.19	187
1.00 - 1.19	6.85	9.4	0.32	0.19	100
1.20 - 1.39	4.13	5.7	0.40	0.13	35
> 1.40	3.73	5.1	0.56	0.10	20
TOTAL	**72.53**	**100**	**0.21**	**0.14**	**1421**

FIGURE CAPTIONS

Figure 1. General view of the Brenta river and the study reaches: Nove, Friola and Fontaniva.

Figure 2. Hydrographs of the study period (average daily discharges as measured at the Barzizza gauging station).

Figure 3. The Brenta river at the Friola reach during the November 2010 flood event.

Figure 4. HDTM creation process: (A) LiDAR data and field survey, (B) data preparation for process application, (C) bathymetric model determination, (D) hybrid DTM creation, (E) DTM validation.

Figure 5. Correlation between Red, Green and Blue colour bands.

Figure 6. Model application (2) at Friola sub-reach (2011). The brown zones on the left side are due to the presence of periphyton on the channel bottom.

Figure 7. Hybrid Digital Terrain Models (HDTM) of Nove, Friola and Fontaniva sub-reaches, 2010 and 2011, cell size 0.5 x 0.5 m.

Figure 8. Cross-section comparison between dGPS, HDTM and LiDAR survey of Nove (a), Friola (b) and Fontaniva (c) 2011.

Figure 9. Canopy surface models (CSM) with pools locations (P1, P2, etc.) through bathymetric raster on wet area of Nove, Friola and Fontaniva sub-reaches 2010 and 2011.

Figure 10. Example of filtering process in a cross-section of Friola 2011 sub-reach.

Short-term geomorphic analysis in a fluvial disturbed environment by fusion of LiDAR, colour bathymetry and dGPS survey

Highlights

i) Physical and Empirical relationship between channel depth and colour intensity;

ii) Factors that increase uncertainty of the final DTM;

iii) Hybrid DTMs (HDTMs) at high resolution and low uncertainty;

iv) Morphological processes in a regulated gravel-bed river after two several floods.

Figure 1
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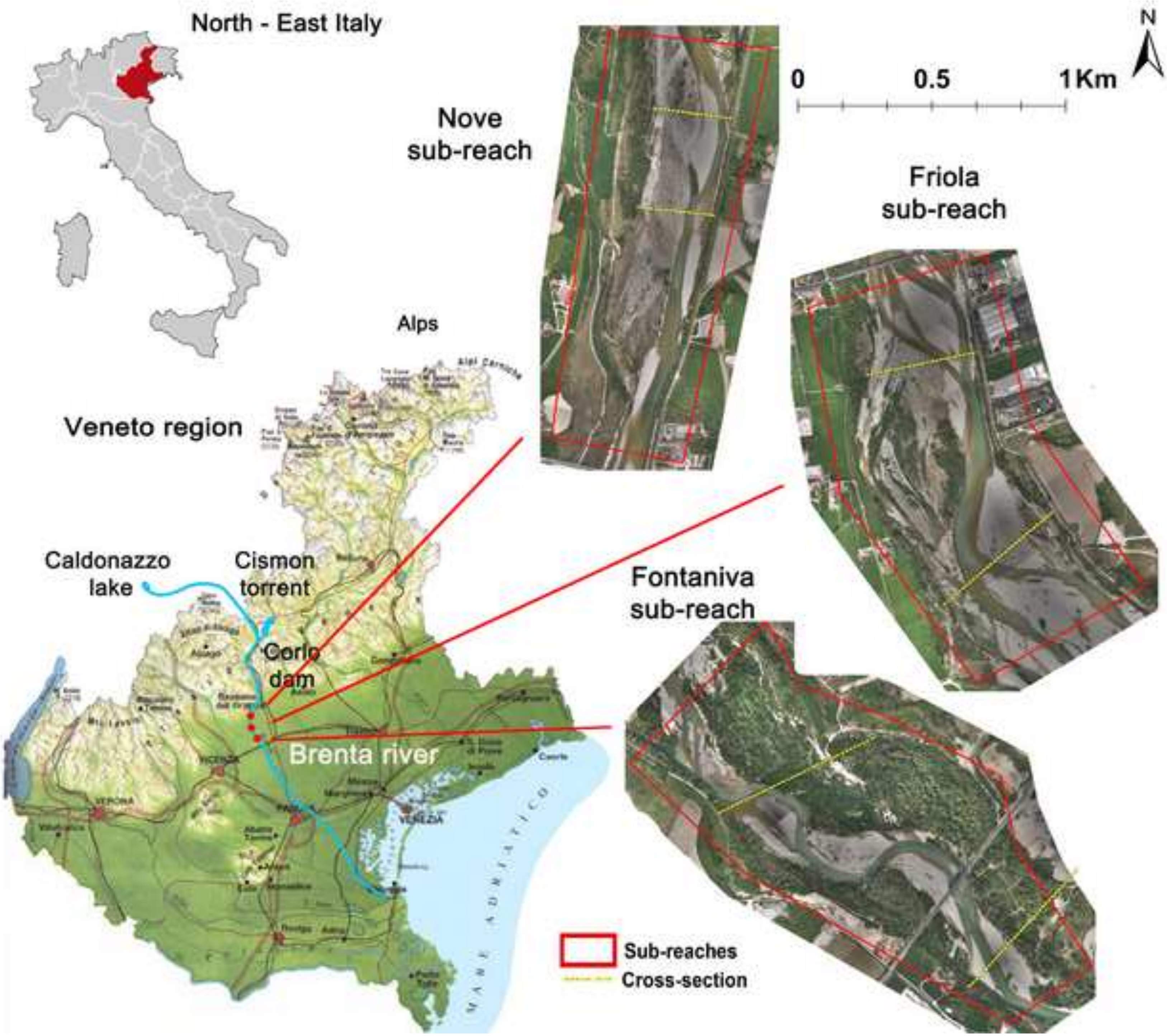

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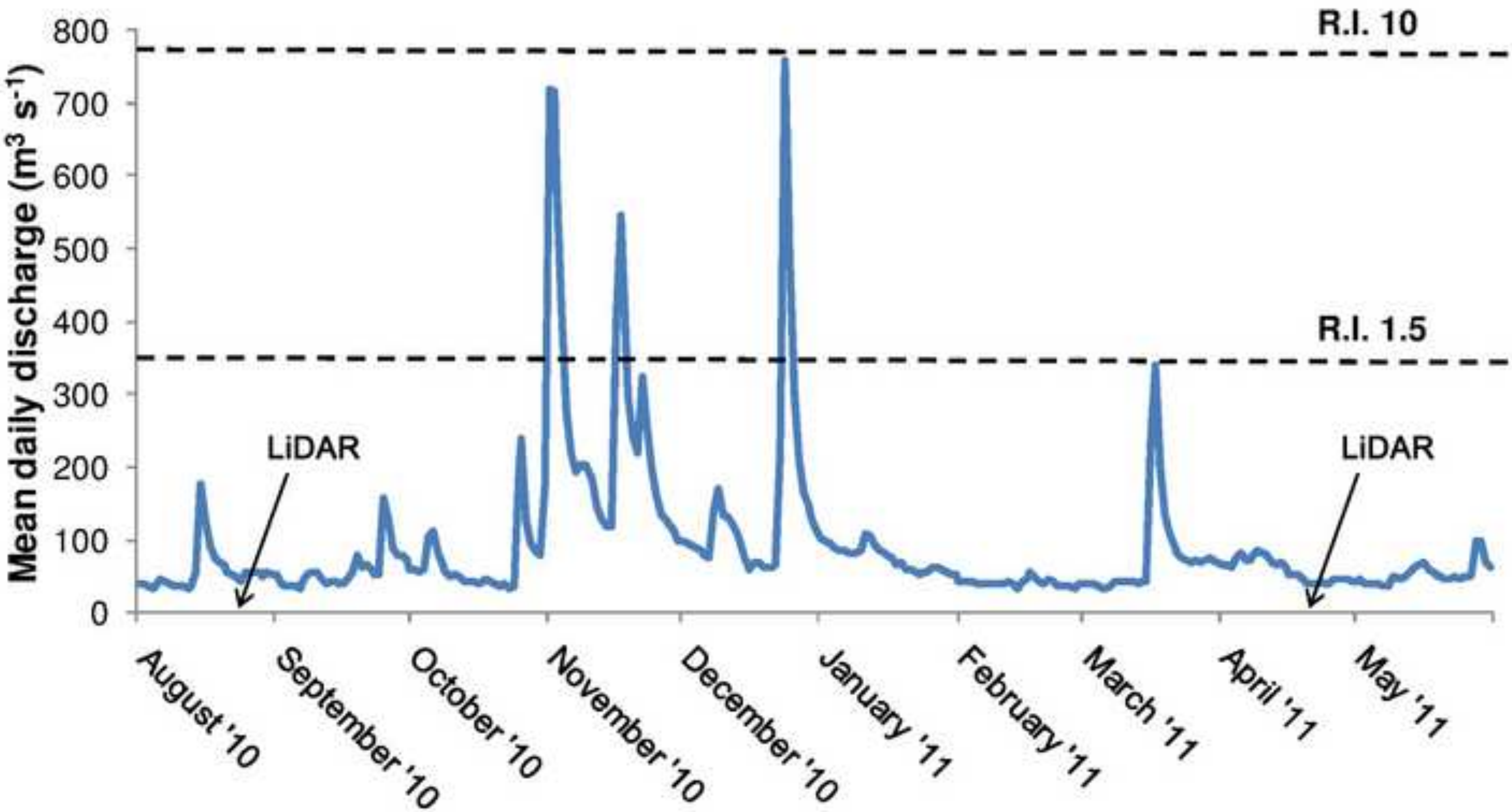

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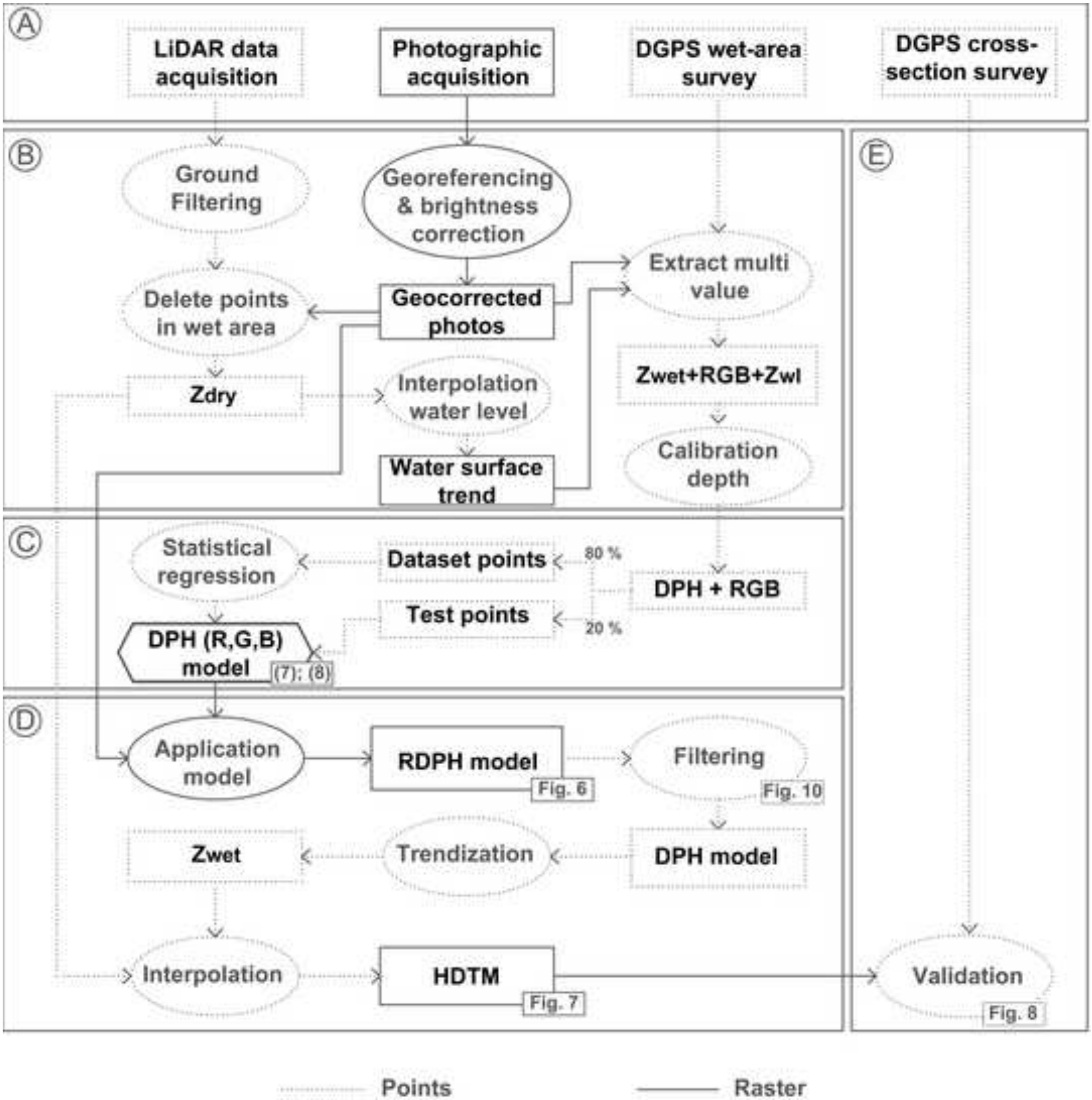

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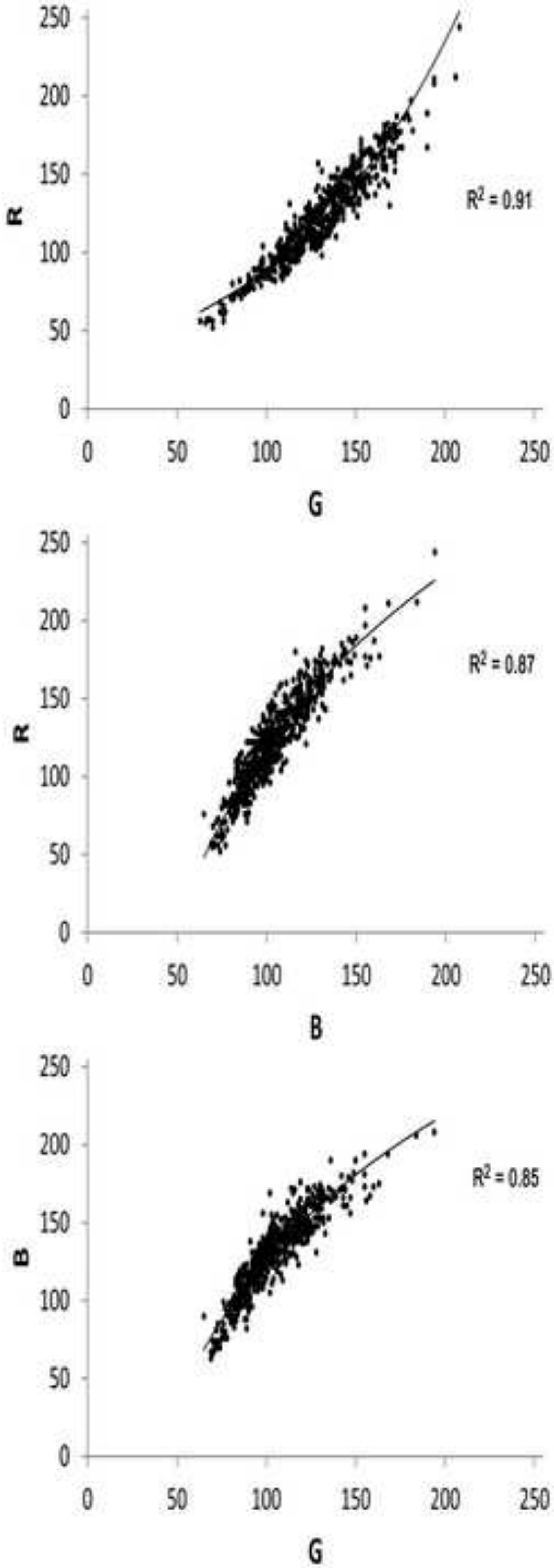

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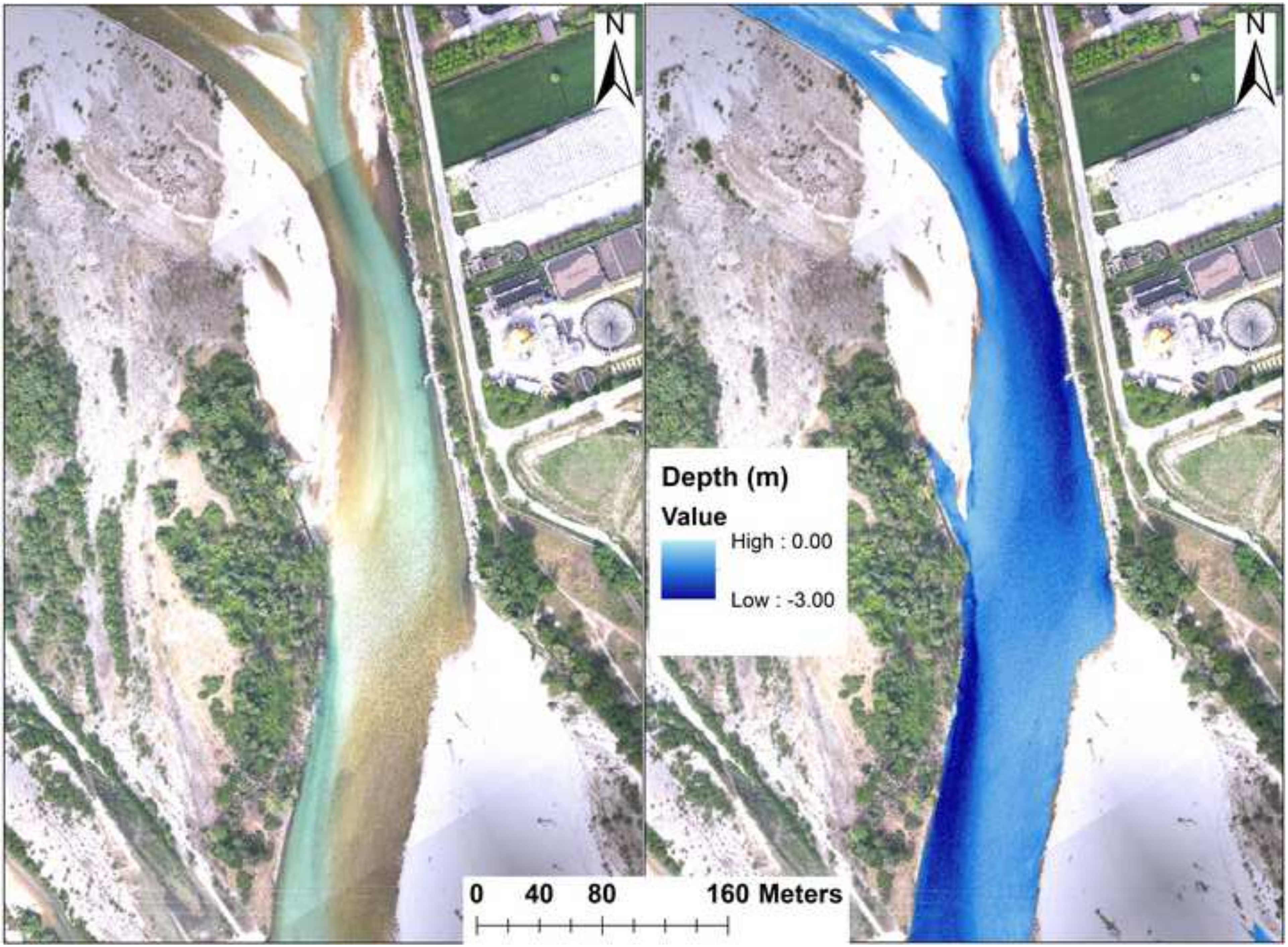

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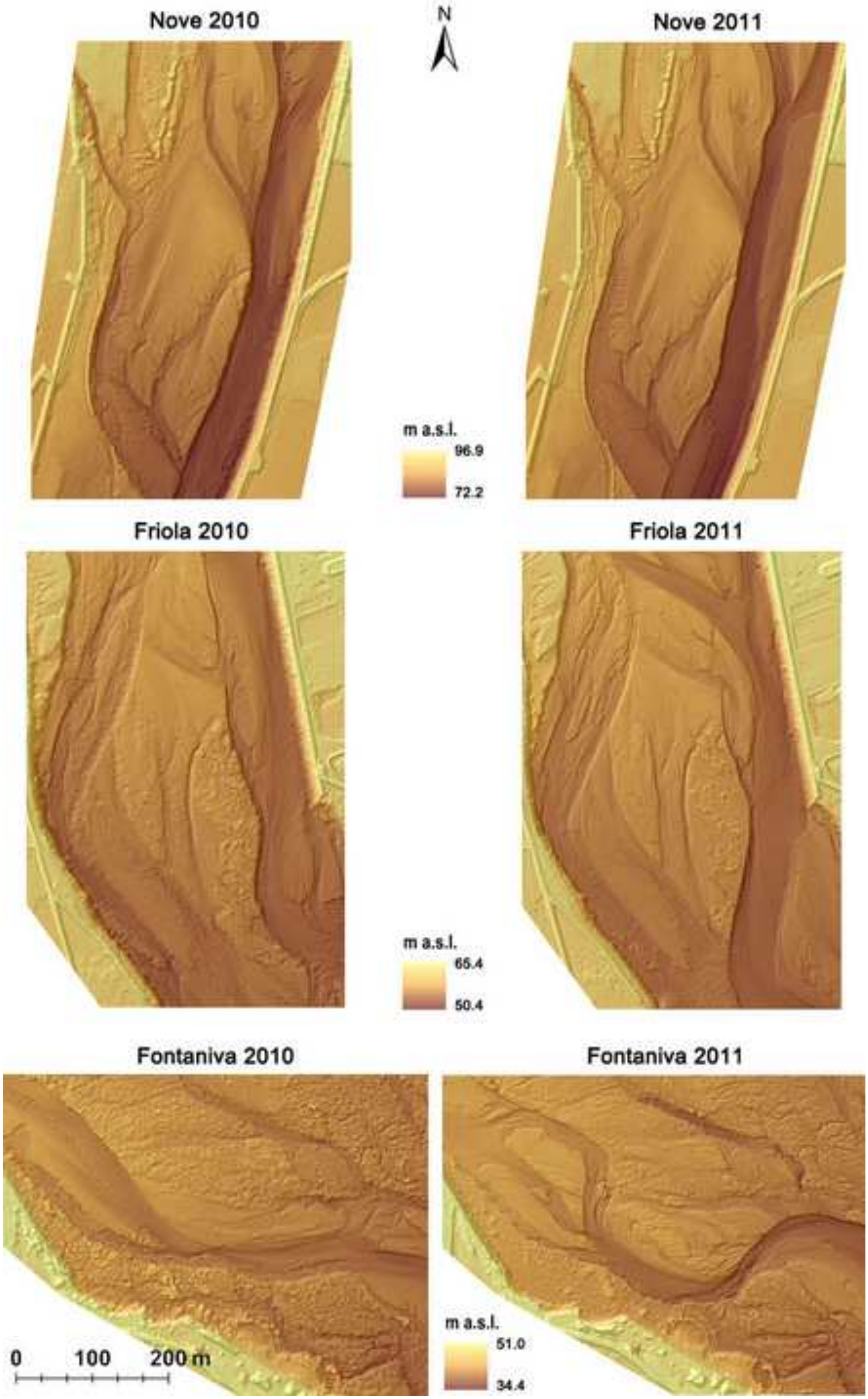

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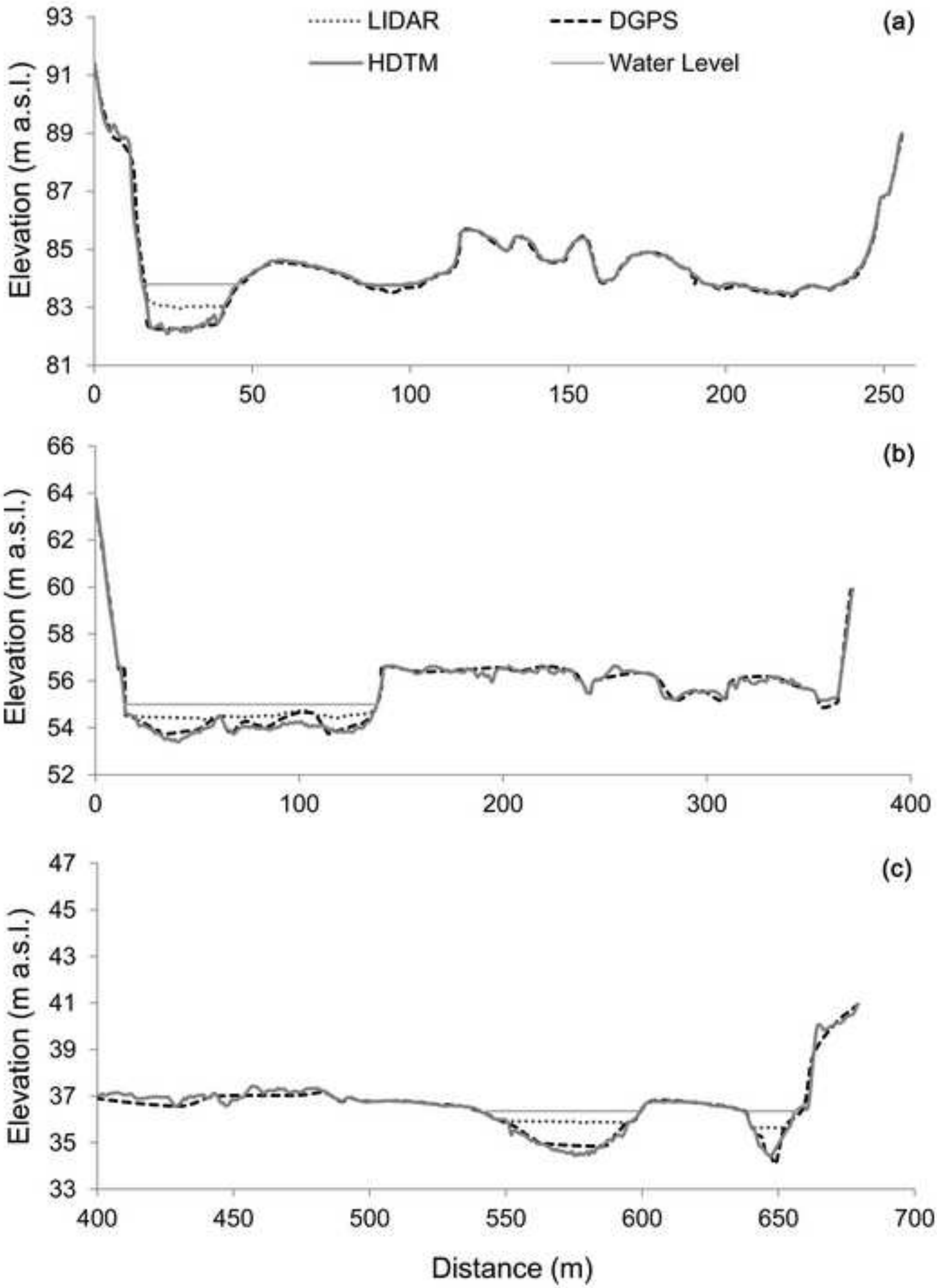

Figure 9

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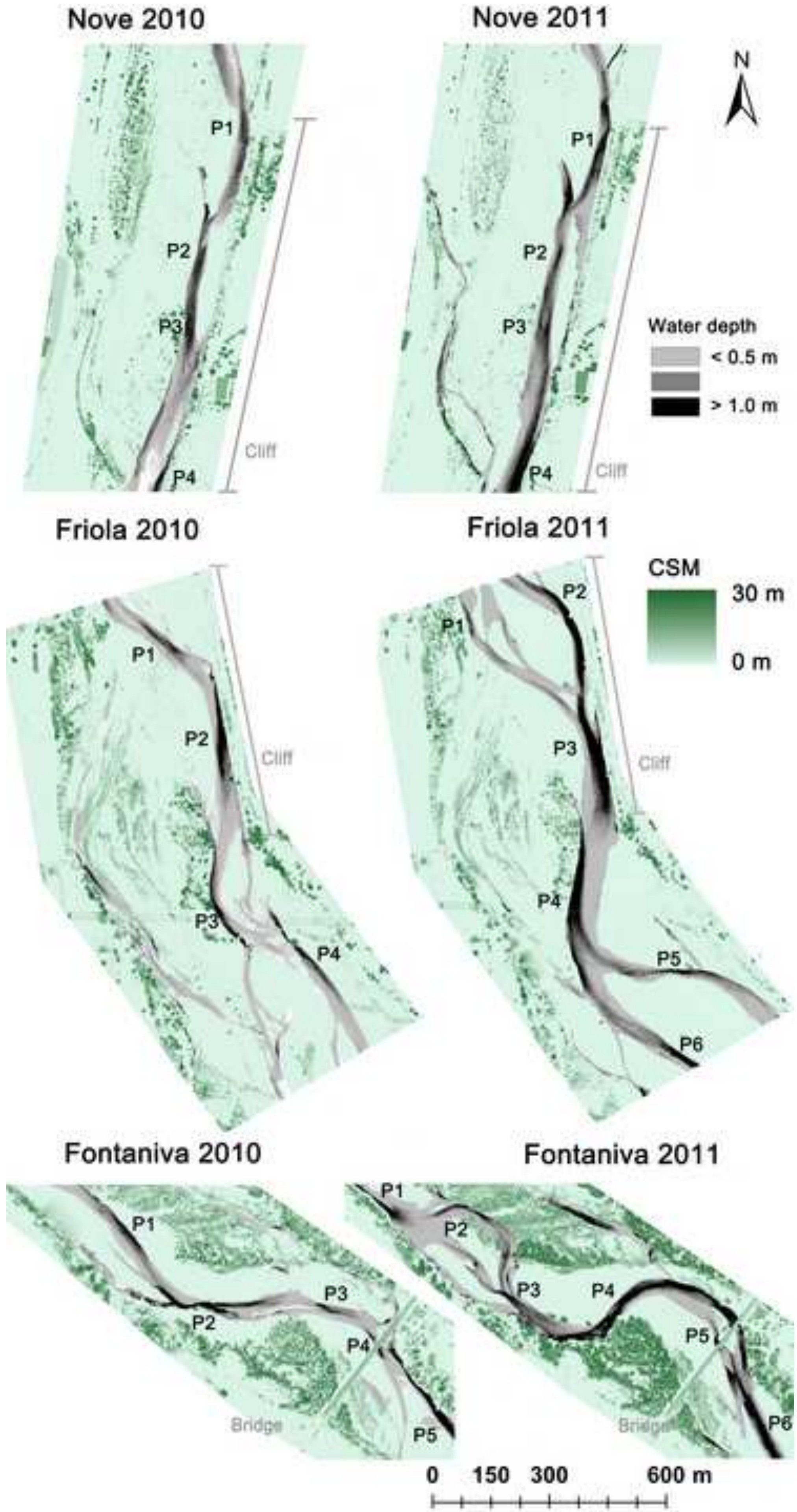

Figure 10
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