Bedforms and morpho-bathymetric evolution of tributary channels in the Po River delta (Italy)

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ABSTRACT: Repeated high-resolution multibeam bathymetry surveys were carried out in 2016 in the Po della Pila (North Adriatic Sea, Italy) delta and tributary channels in order to verify the geomorphological features of the riverbed related to morpho-sedimentary processes. The morpho-bathymetric data allowed to observe and map widespread bedforms fields in the alluvial, non-cohesive deposits of the riverbed consisting of dunes with wavelengths ranging from 8 m to 20 m. Repeated bathymetric surveys, carried out after hours and days along the river thalweg, have shown the migration of the bedforms, enabling the estimation of the average rate. We document the rapid geomorphological changes affecting these ephemeral features and the riverbed, also in relation with changes in the average flow discharge rate occurred during the surveys. This was particularly evident after a major flood, when in a few days the riverbed underwent partial reworking and the bedform migration rate was higher.

1 INTRODUCTION

The Po River is the longest river of Italy (673 km) with a medium flow of 1540 m^3/sec and a watershed of 71.000 km^2. It originates in the western Alps and outflows into the North Adriatic Sea (Fig. 1), where microtidal conditions are present. At its mouth, the river splits into five sub-branches. The Po della Pila is the most active branch of the delta, discharging about 61 % of the total flow of the Po and being responsible for the growth of the recent most delta lobe (Bosman et al. 2020). In historical times, the whole Po delta system has been subjected to extensive anthropogenic impacts, mostly due to land use and freshwater management. Since 1950, in fact, the Po delta has undergone a strong degradation and partial retreat, mainly due to the lack of sediment supply caused by the exploitation of inert material in the riverbed and the hydraulic regulation of watercourses, and subsidence due to the extraction of fluids (Stefani et al. 2005). Climatic change impacts are also affecting the Po River, such as marked drought conditions, enhancing the salt intrusion in the delta and fluvial area. In the framework of the RITMARE Project, funded by the Italian Ministry (MIUR), the Po della Pila delta and tributary channels have been the subject of repeated, high-resolution multibeam bathymetric surveys. The main mouth channel of Po della Pila (Busa Dritta) and two smaller channels (Busa di Tramontana and Busa di Scirocco (see Fig. 1) have been surveyed, showing the occurrence of widespread bedforms fields in the non-cohesive deposits of the riverbed. These features have been mapped and analysed from a morphological point of view. Furthermore, the comparison of time-lapsed, high-resolution bathymetric data acquired along the river thalweg some days after the first survey allowed to observe the short-term

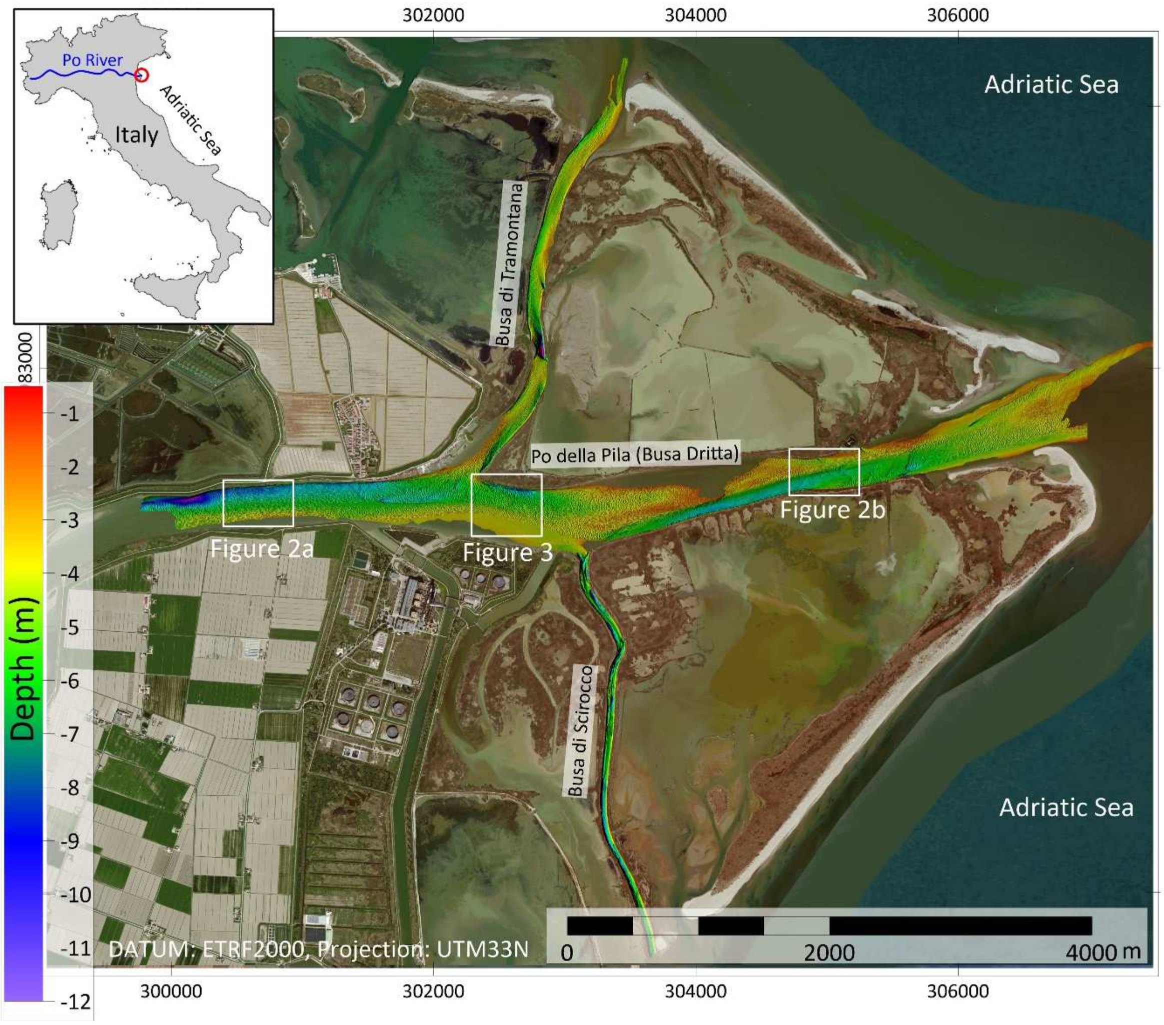

Figure 1. High-resolution Digital Elevation Model of the Po della Pila delta area, investigated by means of multibeam geophysical surveys. The location of the following figures is indicated by boxes. Red circle in the inset indicates the study area.

morphological changes of the bedforms, and to estimate their migration rate at daily scale.

2 DATA AND METHODS

In May 2016, three repeated high-resolution multibeam surveys were carried out along the Po River. High-resolution multibeam data was acquired with a Kongsberg EM2040 single head system, with the frequency that was set to 300 kHz. It was hull-mounted on the vessel 1213 belonging to the Italian Hydrographic Office and allowed a bathymetric coverage between 0.5 m and 7 m water depth. The positioning system was a Kongsberg Seapath 330, corrected with a Fugro HP Differential Global Positioning System (horizontal accuracy: 0.2 m). A Kongsberg Seatex Inertial Motion Reference Unit MRU 5 was used to correct pitch, roll, heave and yaw movements. Sound velocity profiles were collected with a Monitor SVP Valeport sound velocity profiler. For the surveys, a local tidal station belonging to the regional agency of the River Po network was used to measure and correct sea level changes during the surveys (https://www.agenziapo.it/content/monitoraggio-idrografico-0).

All multibeam data were processed using Caris Hips and Sips hydrographic software for bathymetric geophysical correction while QPS-FMGT for backscatter processing and data analysis. During the geophysical survey, a targeted sediment sampling was also carried out by means of a Van Veen grab, and grain-size analyses were obtained with a laser granulometer Malvern Mastersizer 3000.

3 MORPHOMETRY AND BACKSCATTER DATA ANALYSIS

The Po della Pila riverbed is characterized by a shallow depth (mostly within a few metres) and a mainly sub-flat morphology, with local depressions where the depth is locally > 10 m (Fig. 1).

transversal with respect to the flow direction. They rarely have three-dimensional shape (Lefebvre, 2019) and locally show a crescentic shape in correspondence with hydraulic narrowing and deepening of the channel (Fig. 2b). Considering their size, these bedforms can be classified as river dunes (Bosman & Orlando 2017).

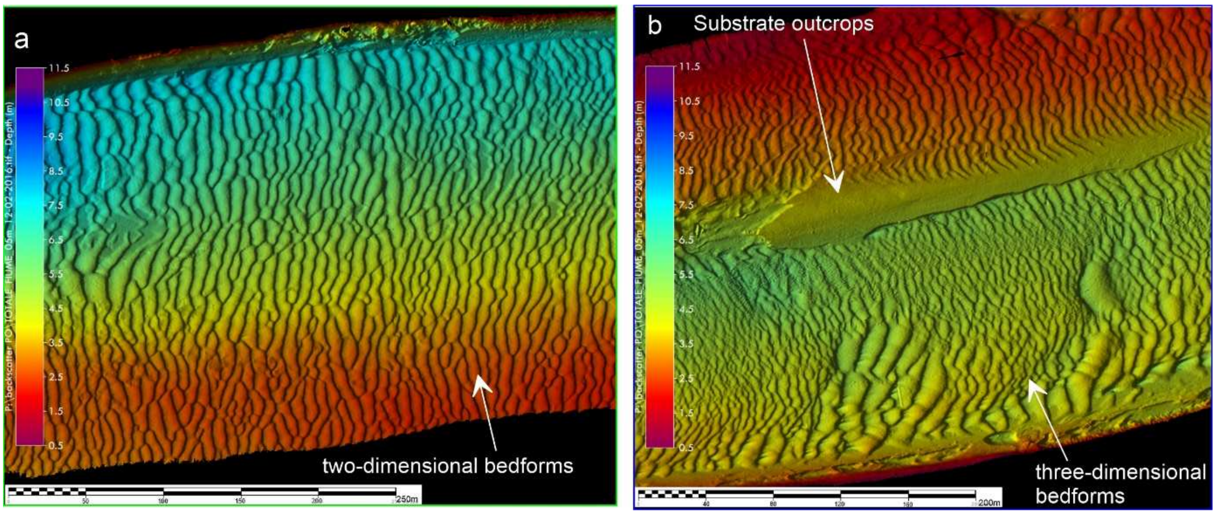

Figure 2. High-resolution Digital Elevation Model of the Busa Dritta tributary channel, showing a uniform distribution of bedforms along the thalweg (a). The bedforms are generally two-dimensional with elongated crests and rarely have three-dimensional shape (b) in correspondence with hydraulic narrowing and deepening of the channel. See Figure 1 for location.

In the studied area, the Busa Dritta channel has a width between 240 and 450 m and a depth between about 1 and 10 m, gradually increasing towards the northern side, on the hydrographical left (Fig. 2a) or towards the southern side on the hydrographical right (Fig. 2b) closer to the river mouth. The thalweg is entirely characterized by bedforms (Fig. 2), apart from locally depressed areas where the substrate crops out (Fig. 2b). The bedforms have different wavelengths, ranging from a minimum of 8 m to a maximum of 20 m, with an average value of about 10 m. They are asymmetrical in cross-section, with a slope of about 3°-5° upstream (stoss side) and of 15°-20° downstream (lee side). The height of the bedforms is approximately constant and ranges from 0.2 m to 0.5 m. The bedform shape is usually two-dimensional (Fig. 2a) with mostly linear or slightly sinuous crests, aligned perpendicular to the slight slope gradient of the river bed (Fig. 1), and

Backscatter data, recorded through the multibeam survey (Fig. 3a), show that the bedforms crests are overall characterized by medium-low intensity values, while the deepest part of the troughs show higher values. These differences might be explained in terms of sediment texture.

4 SAMPLES

Grain size analyses of samples collected in 2016 on lower- and higher- backscatter areas, supported the interpretation of backscatter intensity as mostly related to the grain size of the sediment lying on the seabed. In particular, sample BF1 (location in Fig. 3a) collected at 3.8 m water depth in a sector with well-developed bedforms, in correspondence of

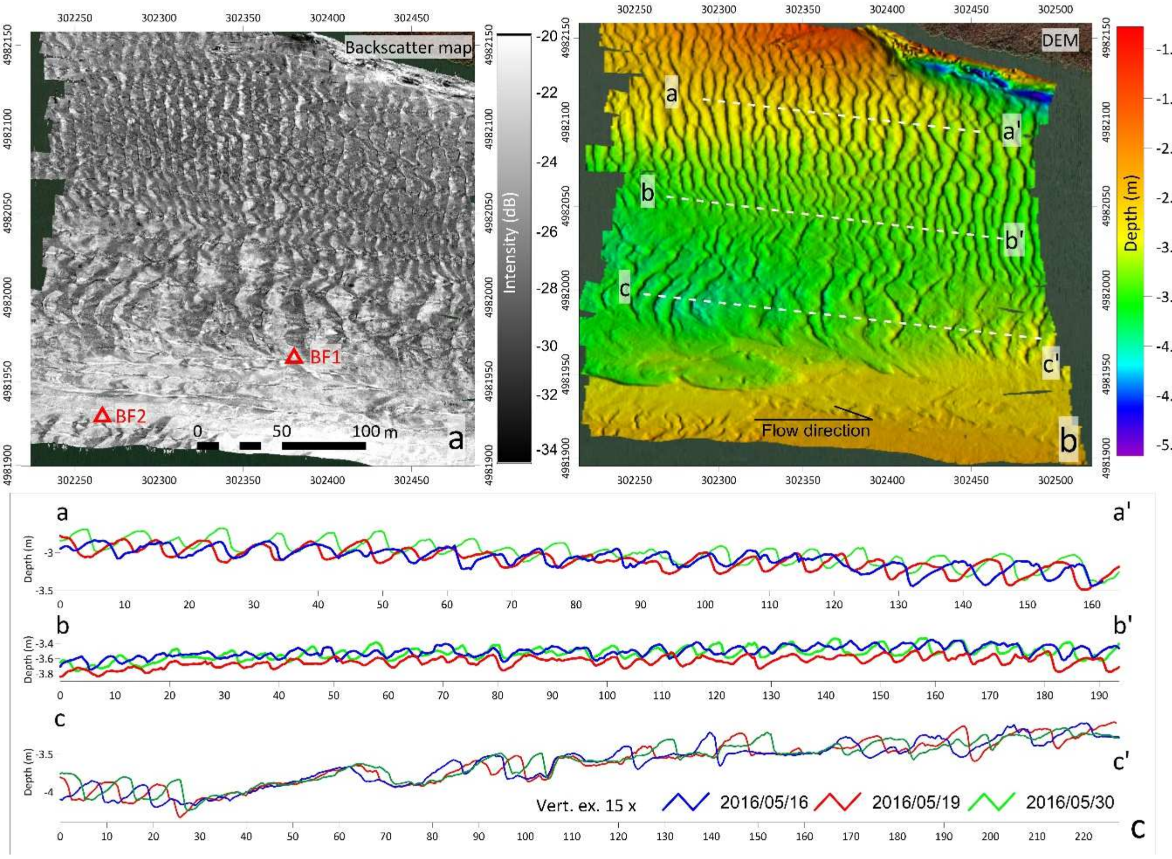

Figure 3. Comparison between bathymetry (b) and backscatter intensity data (a) in the monitored area. See Figure 1 for location. a) The backscatter intensity shows a clear zonation, in relation with the sediment texture: medium-low backscatter areas correspond to the dunes' crest, while higher backscatter indicates coarse sediments located in the trough. Red triangles indicate the location of the sampling sites c) Bathymetric sections (see location in a) show the migration of the dunes, 3 and 14 days (red and green profiles, respectively) after the first survey of May 16 (blue profile).

higher backscatter intensity (values from -23 dB and -26 dB; light grey on the map), resulted to be a muddy sand, mostly composed of fine sand (59.3%) with a muddy fraction of 40.7%). Conversely, sample BF2 (location in Fig. 2a) collected at 3.4 m depth from a smoother area of the channel seabed, slightly raised with respect to the channel thalweg and characterized by slightly lower backscatter intensity (values from -27 dB to -30 dB; dark grey tones on time lapse analysis the map) resulted composed by finer-grained sediment, i.e. sandy mud. In detail, mostly muddy sediment (mud 71%) with lower percentage of sand (29%) was sampled at the river bed lying above a sandier substrate (sand 45.3%, mud 54.7%).

5 TIME-LAPSE ANALYSIS

The possibility of collecting repeated high-resolution bathymetric data in the same river bed area of about 260 x 300 m, allowed to characterize the bedforms dynamic. The multibeam data were collected with the same operating procedures on three different days, on the 16th, 19th and 30th of the May 2016. The data recorded 3 and 14 days after the first survey show a significant mobility of bedforms, likely in response to different conditions of hydraulic regime. Bathymetric sections illustrated in figure 3 C show, in fact, how the dunes have a strong mobility along the entire investigated area, both in the central part of the riverbed (section b-b') and near the

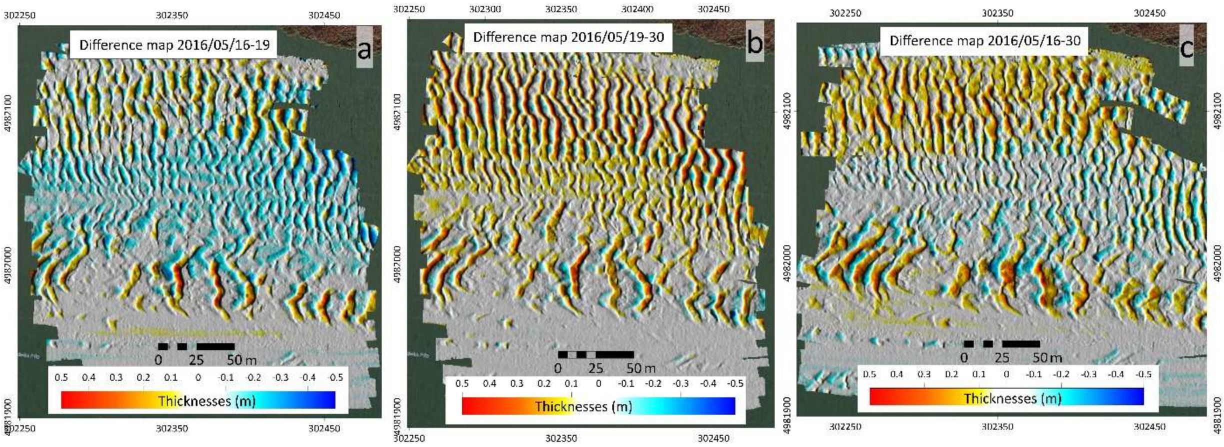

Figure 4. Difference maps between the bathymetric surveys conducted 3, 11 and 14 days after the first survey (a, b and c, respectively). The maps show differences in the seabed up to tens of centimetres, mostly due to the dune migration. A generalized lowering of the riverbed in the central part (section b-b’ in Figure 3c) is visible between the first and second survey (map a), while an overall accumulation occurs between the second and the third (map b).

natural banks (sections a-a’ and c-c’). The dunes migrate differently along bathymetric sections (Fig. 3c).

Bathymetric residues (difference maps in Fig. 4) obtained as the difference among the Digital Elevation Models (DEMs) collected during three days of the survey, show a meter-scale migration of the dunes throughout the investigated section.

The difference between the DEMs relating to the days of May, 16 and 19 (3 days of difference) show a variable migration of the dune crests between 2 m and 4 m, which corresponds to an estimated average velocity of 4 cm per hour. The difference between the DEMs of May 19 and May 30 (11 days of difference) shows, instead, a variable migration from 4 m to 5.5 m which corresponds to about 2 cm per hour. These values, although averaged on different time spans, suggest a slower rate in the dune migration after May 19, as river discharge reach value < 2000 m^3/sec. Finally, using the difference between DEMs collected in the first (May 16) and the last day of the survey (May 30), an average velocity of about 1.5 cm per hour can be obtained. These differences are attributable to the different hydraulic regime occurring during the bathymetric surveys.

By considering the average flow discharge and the hydrometric level recorded on the Po River at the Pontelagoscuro station (blue line and red line, respectively in Fig. 5) a river flood event is recognizable on 2016/05/16. The flow discharge amount changed, in fact, from about 2792 m3/sec on May 16 to 1793 m^3/sec on May 19, while after this date a markedly lower flow discharge (gradually decreasing to about 1200 m^3/sec) was measured. Similarly, the hydrometric level shows a difference of about 3 m between May 16 and May 19 (Fig. 5). The effects of this major flood event are also recognizable on morphologies: between the first and second surveys (May, 16-19) the central part of the riverbed underwent a marked reworking and lowering of some tens of cm (Figs. 4a, 3c section b-b’).

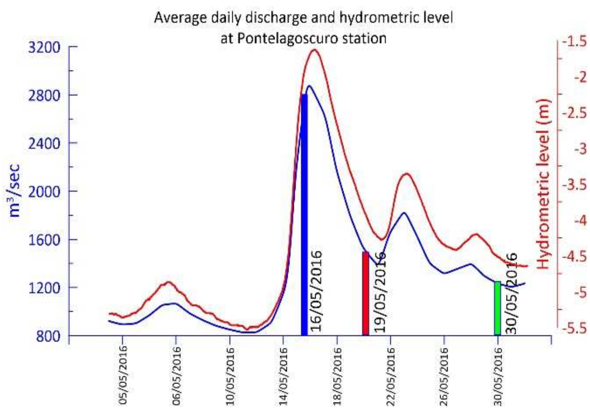

Figure 5. Average discharge and hydrometric level at Pontelagoscuro station located on the final tract of the Po River (from Arpae Emilia Romagna https://simc.arpae.it/dext3r/). Colored bars correspond to the dates of the high-resolution multibeam bathymetry surveys.

6 DISCUSSION & CONCLUSIONS

Bedforms in fluvial and marine environments are commonly considered as cyclic depositional and erosional features formed during bedload transport processes, being controlled by flow velocity, grain size and water depth (Yang et al. 2022 and references therein). Widespread bedform fields have been observed in the riverbed of the Po della Pila, the most active branch of the Po delta. Their shape is similar to that of typical bedforms of river environments (Nittrouer et al. 2008; Bosman et al. 2017) with wavelengths ranging from 8 m to 20 m and heights of a few decimetres. The different intensity of backscattering also appeared to be related to the sediment texture, as also confirmed by the results of grain size analyses. High-resolution multibeam bathymetric monitoring allowed to understand bedforms dynamic at time span of a few days, that strongly derive from the hydrological conditions of the river. Therefore, they are not relict bedforms, but active dunes with variable migration rate, according to the discharge of the river with mobility of a few centimeters (2-4 cm) per hour. Nevertheless, their morphological variations and mobility support the occurrence of a solid transport (bed load) towards the river mouth, capable of feeding the submerged lobe of Po della Pila (Bosman et al. 2020; Trincardi et al., 2020). Despite the Po delta is presently affected by a marked degradation, mostly due to the reduction in sediment transport for anthropogenic and natural (climatic) factors (Stefani et al. 2005), local progradation in response to main flooding events has been recently claimed for the northern portion of the Po della Pila on the base of satellite images (Ninfo et al. 2018) and marine surveys (Bosman et al. 2020). More frequent bedload measurements are requested to better quantify the solid transport in the Po River bed. It is undoubtedly necessary to repeat bathymetric surveys at least annually, to verify the evolutionary state of the submerged sectors (erosion/deposition) of the river and of the delta area, since monitoring only based on remote sensing techniques is insufficient to understand the complex physical processes acting on a fragile and vulnerable of the Po della Pila system.

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