SUPPLEMENTARY MATERIAL

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Tidal modulation of river-flood deposits: How low can you go?

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Location of E16-I and E16-II

Box-cores E16-I and E16-II are located in the Adriatic Sea (water depth of ~16 m), 2 km east of the Pila mouth of the Po River, Italy (Lat: 44.974° N; Long: 12.575° E). This site has been selected following the results of Palinkas et al. (2005) and Wheatcroft et al. (2006). By using x-radiography and ⁷Be penetration, the studies quantified the thickness distribution of a flood deposit (fall 2000 flood) in the Po River prodelta region and highlighted that the maximum sediment accumulation is recorded just offshore of Pila mouth, where station E16 is located (Fig. S1).

Figure S1. Left: Contour map of ^7Be penetration depth from sediment samples (Palinkas et al., 2005). Right: Isopach map of the fall 2000 Po River flood deposit based on sampling (modified from Wheatcroft et al., 2006).

Data acquisition and processing

Continuous profiles of salinity and transmittance were obtained in the prodelta region using a Sea-Bird CTD profiler (Tesi et al., 2011). Water samples at 1 m below the sea surface and 2 m above seabed were collected for suspended sediment concentrations (SSC) using a CTD Rosette system equipped with Niskin bottles (Mod. SBE 911 plus). Water samples were filtered on pre-combusted and pre-weighed GF/F filters, that were rinsed with MilliQ water and oven-dried (50 °C) on the ship for SSC. In the laboratory, pre-weighed GF/F filters were oven-dried at 50 °C for 24 hours to ensure complete removal of moisture. Two filters for each sample were then weighed to calculate the total suspended matter (SSC, mg/l).

Sediment samples were collected using a box-corer (box size I.D. 32.4 cm cross-section, 52 cm height). Box-core E16-I was collected at 14:30, April 30, while E16-II at 12:02, May 5. Slabs of sediment were extracted orthogonal to the layering on deck, and then x-radiographed 10 days after the cruise and sampled at 1 cm intervals for grain size analyses. Samples were dispersed in sodium metaphosphate and then sieved with a 125 μm prior to analysis on Micromeritics SediGraph 5120.

X-ray intensity is related to sediment bulk density that, in turn, is influenced by sediment texture and porosity (Wheatcroft et al., 2006), so that light layers (high intensity) are coarser grained, whereas dark layers (low intensity) have higher mud content (see Fig. 2 in the main manuscript).

The discharge values reported in the manuscript refer to the Cavanella gauging station (Fig. 1A in the manuscript), selected as a reference because of the small tidal influence and the proximity to the Pila mouth (33 km). Assuming a mean current speed of 2.5 ms⁻¹ during floods (Burnelli et al., 2006), the time elapsed for the water to reach the sea is ~3.5 hours, so, for the aim of this study, it is possible to assume that the flood arrived at the same time at Cavanella and at Pila mouth.

Interpretation of the flood deposit in core E16-II

Figure S3 shows the interpretation of the flood deposit proposed by Tesi et al. (2011), in which the basal sand layer and the mud atop of it represent a single event, compared to the interpretation proposed in this study, where the upper 17 cm of core E16-II represent two events: a sandy deposit formed during the storm of 27-28 April 2009, and the flood deposit accumulated between April 30 and May 5. ^7Be profiles (Fig. S2) indicate the recent deposition of both event layers but do not allow to differentiate their timing, as ^7Be penetration gives an estimate of sediment younger than ~200 days (see

Palinkas et al., 2005) while the two events are only a few days apart. However, the integration of the sedimentological and oceanographic datasets acquired at specific times with the information deriving from the hydrographic stations allow differentiating the two events. In detail, 15 hours before the sampling of box-core E16-I, CTD data do not show evidence of a sediment plume flowing across the prodelta region as the peak of the flood had not yet been reached. Yet, the X-radiograph of E16-I shows a 2-cm-thick and sandy deposit at the core top, that we interpreted as formed by wave-enhanced gravity flows generated by the April 27-28 storm.

Figure S2. ^7Be profiles, grain sizes, and comparison between the interpretation of core E16-II proposed by Tesi et al. (2011) and this study (reported in green).

Numerical model: set-up and calibration

To simulate the evolution of the water profile and the bed morphology during the flooding event, a simplified 1D numerical model was developed, by means of the well-known code Hec-Ras version 5.0.7 (Brunner, 2016). As geometrical input data, the river cross-sections measured in 2005 during a LiDAR campaign were used (cross-sections available at geoportale.agenziapo.it/cms/index.php?option=com_aipografd3), in combination with cross-sections of the delta front and prodelta (bathymetric data from Trincardi et al., 2014). For this latter part, the cross-

section shape was derived from the bathymetry, assuming a spatial resolution of 100-500 m, resulting in a rather regular cross-section shape. Aiming to allow for a better spatial resolution, the measured sections were automatically interpolated imposing a maximum separation of 50 m. The hydrological boundary conditions were defined through the 30-minute averaged discharge at the upstream end (Pontelagoscuro), as derived from the discharge-stage relationship. Following Syvitski et al. (2005), such discharges were reduced to 60% to account for the distributary channel. The downstream boundary conditions were set using the water level measured at the river mouth. All the water levels were derived from the AIPO - Po Water Authority website (www.agenziapo.it/content/monitoraggio-idrografico-0). As for the sediment transport, the bed grain size composition was derived from field bed sample made by AIPO in the early 2000s along the Po River and the box-core samples in the prodelta presented in this study. Equilibrium conditions between sediments and water flow at the upstream end, and the Meyer Peter Muller for computing the sediment transport were imposed. The reliability of the proposed approach was already verified in Maselli et al. (2018) and Nones et al. (2018), even if on different reaches of the same river.

A series of unsteady simulations were performed imposing an integration time-step of 30'' for reducing the numerical instability. The model was calibrated and validated, in terms of bed roughness, in the period April 10-May 10, using the first two weeks as calibration period and the rest for the validation. A comparison between the measured and computed water levels in the intermediate section of Polesella suggested that a Manning coefficient of $0.020 \text{ s/m}^{1/3}$ in the main channel provides reliable values for all the water levels observed in the period. In the last part, being offshore, a Manning value of $0.10 \text{ s/m}^{1/3}$ was imposed.

Numerical model – results

The effects of the tidal oscillations are visible in the river discharge computed at the cross-section E16 (Fig. S3a): the lower the discharge, the higher the influence of the tide on the prodelta, even if during flooding conditions. However, given that the water surface is mostly controlled by the tidal variations, oscillations of the river discharge have a lower impact on it. The proposed 1D model computes the velocity averaging the values over the width and the depth (Fig. S3b), therefore it is not possible to derive a velocity field from this simple model. Nonetheless, one can recognize the tidal oscillations also from the computed velocities, even if with a lower resolution.

As the sediment transport is correlated with the velocity (in particular the suspended load), it is possible to conclude that the tidal oscillations have a major influence on the sediment transport during low flow conditions, while, in the case of high flow conditions, it is the river discharge that drives the overall process. Indeed, lower discharges have less power and a lower capacity for moving sediments, resulting in a lower bed shear stress (Fig. S3c). Furthermore, the shear stress, and consequently the sediment transport and the erosion/deposition process, is clearly controlled by the tidal oscillations, even during high flow conditions. For high discharges (flooding conditions), the influence of the downstream boundary conditions (tide) is lower, with respect to low discharges, therefore these oscillations are smoothed. The modelling results indicate that the critical bed shear stress for a grain size of $60 \mu\text{m}$, calculated as $1.7 \cdot 10^{-2} \text{ Pa}$ following Wilkerson & Parker (2011), is never reached at the location of the core on the prodelta.

The low shear stress results in low transport capacity, and only finer sediments can be moved offshore (Fig. S3d). In particular, the flooding event contributed to transport sediments having a median diameter $>30 \mu\text{m}$, while during low flow conditions only very fine material can be moved. This results in a stratification, as pointed out by the box-core E16-II.

Figure S3. Modelling parameters computed in the prodelta at the location of sampling station E-16: a) water discharge, b) section averaged flow velocity, c) bed shear stress, d) median diameter.

The model shows that a drawdown M2 profile characterizes the water surface for all discharges during the flood and that water profiles with gentler slopes occur during high tides (Fig. S4). Regardless of the tide, the drawdown profile starts from the Pila mouth and last around 15-20 km in the case of high discharges, while during low flow the influence is reduced to only 8-10 km, and the tide is not changing the water surface in a significant manner.

Figure S4. Modelled water surface profiles in three conditions: maximum discharge ($Q=8,000 \text{ m}^3/\text{s}$) and high tide in blue, maximum discharge and low tide in red, minimum discharge ($Q=1,000 \text{ m}^3/\text{s}$) in green. The thalweg is represented with a black line.

Leonardi et al. (2015) monitored flow velocity and water level of a distributary channel of the Apalachicola Delta (Florida, USA) by using an Acoustic Doppler Current Profiler (ADCP). The Apalachicola bay is a micro-tidal system: M2 and S2 tidal components with amplitudes of 0.38 and 0.12 m respectively, and K1 and O1 components with amplitudes of 0.43 and 0.37 m, respectively. ADCP data during a flood event with river discharge up to $3,100 \text{ m}^3/\text{s}$ show that peak flow velocities are in phase with tidal minima (Fig. S5). This result indicates that the drop in sea level during low tides forces the drawdown of the backwater profile of the river, thus increasing river flow velocity. The model applied in our study shows a similar result, with steeper backwater profiles during low tides (Fig. S4, red line) corresponding to a peak in the flow velocity.

Figure S5. ADCP measurements of water surface elevation and flow velocity at the mouth of the Apalachicola River, Florida (modified from Leonardi et al., 2015).

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