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Statistical characterization of erosion and sediment transport mechanics in shallow tidal environments. Part 2: suspended sediment dynamics

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Summary

The authors wish to thank the Editorial Board and the Reviewers for their overall constructive and insightful comments on our paper, which significantly improved the manuscript and its readability.
We carefully revised the introduction following the Reviewers' suggestions in order to better highlight how the proposed approach contributes to filling the knowledge gap in long-term morphodynamic modelling and to better emphasize its complementarity with the companion paper on erosion dynamics. Moreover, we have significantly expanded the Method section, as suggested by the Reviewers. This expansion includes the description of equations implemented in the numerical sediment transport model, as well as an extended discussion on the choice of the threshold value to apply the peak-over-threshold analysis to suspended sediment concentration time series.
Finally, we provided additional details about some modelling choices that were not properly justified in the previous version of the manuscript, such as the selection of the boundary conditions and the initial bed sediment composition. Reviewers' suggestions on the companion paper that could have been applied also to this manuscript have been implemented, such as details on the study area, wind climate, choice of synthetic descriptors and model performance.
Overall, in the new version of the manuscript, we consistently revised the main text and importantly expanded the Supplementary Information, by adding the detailed model description and figures S2 to S6.
In the following, we discuss in detail all Reviewers' comments and show how we have addressed them in the revised manuscript, referencing line numbers in the revised manuscript with the track changes.
Please note that the Reviewers' comments are in blue, our detailed responses are in black, and the text of the revised manuscript is framed.

Legend

RC: Reviewer Comment

AR: Author Response

☐ :   Modified manuscript text

Note: References to reviewers' comments are indicated as RCx.x and numbered progressively.

Reply to Reviewer #2

RC2.0: This work is part 2 of the study that introduces the idea of using random processes to model the wave-tidal-induced events along the coastal area. The Venice Lagoon, Italy is chosen as the study site due to the availability of multiple bathymetry surveys over the past centuries. The WWTM model coupled with STABEM sediment transport model is used to simulate morphodynamics. Statistics are extracted from simulation results. The author found that over-the-threshold suspended sediment concentration (SSC) events follows can be modeled as marked Poisson process. As Part 1 paper, this work paved a new way to upscale short-term simulations in a wave-tidal environment to long-term, while following the statistical characteristics.

This paper has a very similar structure to the Part 1 paper, as well as employed identical analysis using morphodynamics results. However, different from hydrodynamics simulations, simulating the dynamics of SSC is much more complicated which means more uncertainties. Hence, I recommend the author show more validation of the modeling results. Maybe some changes also need to be adapted in the analysis to address the differences.

Secondly, although I understand the idea behind the "threshold of SSC", in my opinion, the author did not show the physical meaning or mathematical definition of it, which makes it not well-defined, I recommend the author add more work to its definition.

Thirdly, I believe when dealing with a time scale over 4 centuries, the climate can play an important role, and the analysis should take into consideration of it. As the revision in Part 1 paper, I recommend the author add more model details, and the choice of constants.

There are more things that need to be addressed, which are listed below. Overall, I think this work has good potential, but still needs more work.

AR: We thank the Reviewer for the overall positive assessment of our manuscript and for his/her constructive suggestions that contributed to improving the quality and clarity of our manuscript.

The three main points raised here are discussed in detail in the following. Concerning the model and its calibration, we presented the modification to the revised manuscript in our replies to RC2.2, 2.3, 2.4 and 2.8. Our responses to RC2.5 and 2.6 deal with the definition and choice of an SSC threshold. Finally, the Reviewer's concern about the time scale and the effects of climate are discussed in our response to RC2.7.

RC2.1: As the first paper, the knowledge gap in this work is not clear from the literature reviews. The Poisson process is commonly used in describing the occurrence of events. The author needs to show that people have not used this technique in sediment transport events. For example, in Line 201, the author said that there are studies using Poisson processes to describe geophysical processes. Compare to those studies, the author should explicitly point out the new knowledge that the readers can gain from this work.

AR: Following Reviewer's suggestion, we deeply revised the introduction as follows:

> (line 63) *Several numerical models have been developed to describe sediment transport and different techniques have been proposed to upscale the effects on the morphological evolution of tidal systems. For instance, explorative point-based models are extensively used to understand the relative importance of sediment transport processes, because of their simplified parametrization as well as their great conceptual value (Murray, 2007). Furthermore, their reduced computational burden is ideal to investigate trends over long-term time scales. For these reasons, point-based models have been largely adopted, for example, to examine salt-marsh*

fate under different sea level rise scenarios at the century time scale (D'Alpaos et al., 2011; Fagherazzi et al., 2012). However, point-based models potentially miss spatial dynamics associated with sediment transport and, hence, might fail to represent interactions between different morphological units. More detailed, process-based models can fill this gap and account for sediment fluxes between different points up to the whole basin scale (e.g. Lesser et al., 2004; Carniello et al., 2012). But, because of the explicit description of the short-term interaction between hydrodynamics and sediment transport, the application of process-based models to the long-term time scale is often computationally expensive or even prohibitive. A widespread solution to overcome this limitation is to upscale the effects of short-term sediment transport on bed evolution by means of the so-called 'morphological factor', basically a multiplication factor to accelerate the computation of the effects on the morphology (Lesser et al., 2004; Roelvink, 2006). These approaches implicitly assume that the morphological response of a system in the long term can be directly upscaled from the bed-level changes explicitly computed using a representative forcing condition on a much shorter time scale. However, as soon as the morphological evolution of a system is substantially affected by stochastic, episodic events, namely wind waves and storm surges (Tognin et al., 2021), and, therefore, cannot be represented as a continuous process (i.e. purely driven by the tide), this assumption may provide misleading results. Moreover, in tidal systems with fine sediments, because of the effect of consolidation, stratification and armouring of the sediment bed (Mehta et al., 1989), the morphological response is usually critically influenced by the magnitude and the time-history of events (Mathew and Winterwerp, 2022), which obviously cannot be reproduced by considering simplified, repetitive forcing conditions. To explicitly model the effects of stochastic, morphologically-meaningful events as well as their temporal succession, a possible alternative would be to directly consider the physical processes responsible for the morphological evolution (i.e. erosion, transport and deposition of sediment) instead of upscaling the bed level changes. From this perspective, synthetic, statically-based models represent a particularly promising framework to reduce the computation burden associated with the explicit description of these processes through the use of independent Monte Carlo realizations. Notwithstanding the increasing popularity of statistically-based approaches for long-term modelling in hydrological and geomorphological sciences (e.g., Rodriguez-Iturbe et al., 1987; D'Odorico and Fagherazzi, 2003; Botter et al., 2013; Park et al., 2014), applications to tidal systems are still quite unusual (D'Alpaos et al., 2013; Carniello et al., 2016).

In order to explicitly describe sediment transport and bed evolution in a statistically-based framework, two different complementary processes need to be characterized: bottom shear stress (BSS), which can be considered a proxy for erosion, and suspended sediment concentration (SSC), which represents a measure of the sediment potentially available for deposition. To this goal, the characterization of BSS is provided by D'Alpaos et al. (2023). Here we aim to complete the proposed framework by statistically characterizing SSC and testing the possibility to describe suspended sediment dynamics as a Poisson process in long-term morphodynamic models.

~~Therefore, observation-based approaches have been widely adopted to investigate the suspended sediment concentration (hereafter SSC), using either in situ point measurements (e.g., Wren et al., 2000; Gartner, 2004; Brand et al., 2020) or remote sensing and satellite image analysis (Miller and McKee, 2004; Ruhl et al., 2001; Volpe et al., 2011).~~

SSC dynamics is usually characterized either by in situ point measurements (e.g., Wren et al., 2000; Gartner, 2004; Brand et al., 2020) or by remote sensing and satellite image analysis (Miller and McKee, 2004; Ruhl et al., 2001; Volpe et al., 2011). However, both these techniques have some drawbacks and do not offer the proper spatial and temporal coverage required for the statistical characterization. In situ measurements can provide an accurate description of the temporal dynamics of SSC, but lacks information on its spatial heterogeneity. Moreover, acoustic and optical sensors installed in point turbidity stations require periodic cleaning to prevent failure due to biofouling. Whereas, satellite-based data can supply instantaneous information on SSC spatial variability, but are barely informative on its temporal dynamics. Indeed, SSC events can hardly be fully captured by satellites with fixed and often long revisit periods. Furthermore, intense SSC typically occurs during severe storms, frequently characterized by clouds, which make satellite data useless. As a matter of fact, reliable long-term SSC time series at the basin scale, required for the statistical analysis performed herein, are seldom available. *In order to overcome these shortcomings and to exploit measurements of in situ point observations and satellite images, these data can be combined to calibrate and test numerical models (Ouillon et al., 2004; Carniello et al., 2014; Maciel et al., 2021), thereby, using them as physically-based "interpolators" to compute temporal and spatial SSC dynamics required by this analysis.* ~~However, computing SSC dynamics over time scales of centuries in order to model the morphodynamic evolution of tidal environments through fully-fledged numerical models is rather difficult owing to the computational burden involved. Therefore, modelling the long-term evolution of tidal systems requires comprehending the physics of the processes in order to properly characterize them in the framework of simplified approaches (Murray, 2007). Pointing to the development of a synthetic theoretical framework to represent intense SSC events and to account for their landscape-forming action on tidal basin morphology, we applied a two-dimensional finite element model to simulate the interaction among wind waves, tidal current and sediment transport in several historical configurations of the Venice Lagoon.~~ *Here~~In particular~~, we used a previously-calibrated and widely-tested Wind Wave-Tidal Model (WWTM) (Carniello et al., 2005, 2011) coupled with a sediment transport model (Carniello et al.,2012) to investigate SSC dynamics.*

This study aims to verify if the proposed framework can be properly applied over long-term time scales and, hence, is independent of the specific morphological setting of a tidal basin. Hence, we perform the analysis on the Venice Lagoon, Italy (Figure 1), for which several historical morphological configurations are available in the last four centuries (Carniello et al., 2009; D'Alpaos, 2010; Finotello et al., 2023). In particular, we considered ~~to investigate hydrodynamics and suspended~~sediment ~~dynamics in~~ the following six historical configurations ~~of the Venice Lagoon~~ : 1611, 1810, 1901, 1932, 1970, and 2012. For each of them, we run a one-year-long simulation forced with representative tidal and meteorological boundary conditions. The computed SSC time series have been analyzed on the basis of the peak-over-threshold (POT) theory, following the approach introduced by D'Alpaos et al. (2013) and expanding the analysis performed by Carniello et al. (2016) to study the statistics of SSC in the present configuration of the Venice Lagoon. ~~This study aims to expand this analysis to other historical configurations of the Venice Lagoon (Figure 1) in order to unravel the effects on sediment transport of the morphological and anthropogenic modifications experienced by the lagoon in the last four centuries and to test whether SSC dynamics can be modelled as a marked Poisson process also when accounting for the morphological evolution of~~

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the basin. ~~The latter represents an interesting goal, being the use of stochastic frameworks particularly promising for long-term studies, as pointed out by their increasing popularity in hydrology and geomorphology to describe the long-term behaviour of geophysical processes (e.g., Rodriguez-Iturbe et al., 1987; D'Odorico and Fagherazzi, 2003; Botter et al., 2013; Park et al., 2014; Bertassello et al., 2018) Nonetheless, applications to tidal systems are still quite uncommon (D'Alpaos et al., 2013; Carniello et al., 2016).~~ *Our analysis provides a spatial and temporal characterization of resuspension events for the Venice Lagoon from the beginning of the seventeenth century to the present day, in order to show how morphological modifications affected sediment transport and to set up a stochastic framework to forecast future scenarios.*

To better highlight the overall picture of the stochastic model, the role of the statistical characterization of the SSC dynamics and its complementarity with erosion dynamics, we also modified the abstract as follows:

(line 1) A proper understanding of *sediment resuspension and transport processes*~~dynamics, critically including resuspension and deposition processes of suspended sediments,~~ is key to the morphodynamics of shallow tidal environments. *However, a complete spatial and temporal coverage of suspended sediment concentration (SSC) to describe these processes is hardly available, preventing the effective representation of depositional dynamics in long-term modelling approaches.* ~~Aiming to account for deposition mechanics in a synthetic theoretical framework introduced to model erosion dynamics (D'Alpaos et al., 2023), here we investigate suspended sediment dynamics.~~ *Aiming to couple erosion and deposition dynamics in a unique synthetic theoretical framework, here we investigate SSC dynamics following a similar approach to that adopted for erosion (D'Alpaos et al., 2023).* ~~A complete spatial and temporal coverage of suspended sediment concentration (SSC) required to effectively characterize resuspension events is hardly available through observation alone, even combining point measurements and satellite images, but it can be retrieved by properly calibrated and tested numerical models. We analyzed one-year-long time series of SSC computed by a bi-dimensional, finite-element model in six historical configurations of the Venice Lagoon in the last four centuries. Following the peak-over-threshold theory, we statistically characterized suspended sediment dynamics by analyzing interarrival times, intensities and durations of over-threshold SSC events.~~ *The analysis with the peak-over-threshold theory of SSC time series computed using a fully-coupled, bi-dimensional model allows us to identify interarrival times, intensities and durations of over-threshold events and test the hypothesis of modelling SSC dynamics as a Poisson process. The effects of morphological modifications on spatial and temporal SSC patterns are investigated in the Venice Lagoon, for which several historical configurations in the last four centuries are available.* Our results show that, similarly to erosion events, SSC can be modelled as a marked Poisson process in the intertidal flats for all the *analysed morphological lagoon* ~~considered historical~~ configurations ~~the Venice Lagoon~~ because exponentially distributed random variables well describe ~~interarrival times, intensity and duration of~~ over-threshold events. ~~Moreover, interarrival times, intensity and duration describing local erosion and over-threshold SSC events are highly related, although not identical because of the non-local dynamics of suspended sediment transport related to advection and dispersion processes. Owing to this statistical characterization of SSC events, it is possible to generate synthetic, yet realistic, time series of SSC for the long-term~~

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modelling of shallow tidal environments. ~~modelling of shallow tidal environments.~~ *Although erosion and resuspension are intimately intertwined, erosion alone does not suffice to describe also SSC because of the non-local dynamics due to advection and dispersion processes. The statistical characterization of SSC events completes the framework introduced for erosion mechanics and, together, they represent a promising tool to generate synthetic, yet realistic, time series of shear stress and SSC for the long-term modelling of tidal environments.*

RC2.2: Line 137. Please introduce the equations that are used in the sediment transport model, particularly, the choice of entrainment relations for cohesive and non-cohesive materials, as well as the choice of parameters in the equations.

AR: As we noted in our responses to the revision of the companion paper, it is not an easy task to find a good compromise between conciseness and completeness in the description of already-published models.

Thanks to the Reviewers' comments, we realized that the summary we provided in the first version of the manuscript was lacking some necessary details, such as the equations used in the sediment transport model, which are particularly relevant for the subsequent analysis presented, although they cannot be considered the main focus of this paper. For this reason, we included in the Method section the equations implemented in the STABEM model to compute the sediment transport, by modifying the text as follows:

(line 207) *The sediment transport and bed evolution module (STABEM, Carniello et al., 2012) is based on the solution of the advection-diffusion equation and Exner's equation:*

$$\frac{\partial C_i Y}{\partial t} + \nabla \cdot (\boldsymbol{q} C_i) - \nabla \cdot (\boldsymbol{D_h} \nabla C_i) = E_i - D_i \qquad i = s, m \qquad (4)$$

$$(1 - n)\frac{\partial z_b}{\partial t} = \sum_i (D_i - E_i) \qquad (5)$$

where C is the depth-averaged sediment concentration, $\boldsymbol{D_h}(x, y, t)$ represents the space- and time-dependent 2-D diffusion tensor, E and D are the entrainment and deposition rate of bed sediment, z_b is the bed elevation and n is the bed porosity, assumed equal to 0.4. The subscript i refers to the sediment classes, that in shallow tidal environments are typically represented by non-cohesive (sand - s) and cohesive (mud - m) sediment. The relative local content of mud (p_m) can be used to mark off the transition between the cohesive or non-cohesive nature of the mixture and determines the critical value of the bottom shear stress. To discriminate between non-cohesive and cohesive behaviours, the threshold value of mud content p_{mc} is set equal to 10% (van Ledden et al, 2004).
The deposition rate of pure sand, D_s, is given by

$$D_s = w_s r_0 C_s \qquad (6)$$

where w_s is the sand settling velocity and r_0 is the ratio of near-bed to depth-averaged concentration, which is assumed constant and equal to 1.4 (Parker et al., 1987).
The deposition rate of pure cohesive mud, D_m, is computed using Krone's formula:

$$D_m = w_m C_m \max\{0; 1 - \tau_{wc}/\tau_d\} \qquad (7)$$

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where w_m is the mud settling velocity, τ_{wc} is the bottom shear stress, and τ_d is the critical shear stress for deposition. The settling velocities, w_s and w_m, are computed using the formulation proposed by van Rijn (1984) for solitary particles in clear and still water, thus not incorporating flocculation effects that are negligible for particle diameters larger than 20 μm (Mehta et al., 1989). The critical shear stress for deposition, τ_d, largely varies among different tidal systems and, for the Venice Lagoon, we set $\tau_d = 1\ Pa$ on the basis of field measurements (Amos et al, 2004).

Both sand and mud erosion rates strongly depend on the cohesive nature of the mixture. The erosion rate for pure sand, E_s, is described by the van Rijn (1984) formulation when the mixture is non-cohesive ($p_m \leq p_{mc}$) and by the Partheniades' formula for cohesive mixtures ($p_m > p_{mc}$):

$$E_s = \begin{cases} (1-p_m)w_s \cdot 1.5\left(\frac{D_{50}/Y}{D_*^{0.3}}\right)T^{1.5} & \text{for } p_m \leq p_{mc} \\ (1-p_m)\cdot M_c T & \text{for } p_m > p_{mc} \end{cases} \tag{8}$$

The erosion rate for pure mud, E_s, is described by the formulation proposed by van Ledden et al. (2004) for non-cohesive mixtures ($p_m \leq p_{mc}$) and by the Partheniades' formula for cohesive mixtures ($p_m > p_{mc}$):

$$E_m = \begin{cases} \frac{p_m}{1-p_m}\cdot M_{nc}T & \text{for } p_m \leq p_{mc} \\ p_m \cdot M_c T & \text{for } p_m > p_{mc} \end{cases} \tag{9}$$

In Eqs. 8 and 9, D_* denotes the dimensionless grain size and it is computed as $D_* = D_{50}[(s-1)g/v^2]^{1/3}$, where s is the sediment-specific density and v is the water kinematic viscosity; T is the transport parameter; M_{nc} and M_c are the specific entrainments for non-cohesive and cohesive mixtures, respectively, which can be computed as (van Rijn, 1984; van Ledden et al, 2004):

$$M_{nc} = \alpha \frac{\sqrt{(s-1)gD_{50}}}{D_*^{0.9}}$$

$$M_c = \left(\frac{M_{nc}}{M_m}\cdot \frac{1}{1-p_{mc}}\right)^{\frac{1-p_m}{1-p_{mc}}}\cdot M_m \tag{10}$$

where M_m is the specific entrainment for pure mud and it is set equal to $5 \cdot 10^{-2}$ g m s^{-1} and the parameter α is equal to $1 \cdot 10^{-5}$ (Carniello et al., 2012).

(line 271) Finally, erosion and deposition rates of sand and mud result in a variation of bed level and composition through time, which is computed using Eq. 5 and updating the local mud content.

The description of the transport parameter T (line 257) is reported in our response to RC2.4.

RC2.3: Line 144, the initial bed composition is very important in the simulation of suspended sediment concentration. More details are needed to show how the local bed composition is determined. Furthermore, it will be helpful to show data such as grain size distributions, and show how the sediment properties in this 2-sediment-class model are determined.

AR: To meet the Reviewer's suggestion, we added more details on the initial bed composition in the Method section as follows:

(line 297) *To correctly model SSC as well as bed evolution, the knowledge of the bed sediment composition is crucial. Sufficiently detailed, spatially-distributed grain-size data are available for the present-day configuration of the Venice Lagoon (Amos et al., 2004; Umgiesser et al., 2006). Using this dataset, Carniello et al. (2012) empirically related the median grain size D_{50} to the local bottom elevation and the distance from the inlets:*

$$D_f = \begin{cases} \max\{\,300;\ 50(-h_f - 0.8)^{0.75}\} & \text{if } h_f \leq 1 \text{ m a.m.s.l.} \\ 15 & \text{if } h_f > 1 \text{ m a.m.s.l.} \end{cases} \qquad (12)$$

$$D_{50} = D_{hf} + 100e^{-0.0097L^3} \qquad (13)$$

where h_f is the bottom elevation in m a.m.s.l.; L is the linear distance from the closer inlet in km; D_{50} and D_{hf} are the grain diameter μm. This relationship describes a coarsening of the sediment grain size distribution at deeper locations (i.e. channels) and at shorter distances from the sea (Figure S2). Because bottom elevation and the distance from the inlet are the two main parameters describing the spatial variation in sediment grain size, we assume that this relationship holds independently on the specific morphological configuration of the Venice Lagoon and we used Eqs 12 and 13 to compute the distribution of median grain size D_{50} in all the six selected historical configurations.
The spatial distribution of mud content, p_m, is then computed as a combination of the local D_{50} and the typical grain size of mud and sand fractions (Umgiesser et al., 2006)

$$p_m = 1 - \frac{\ln(D_{50}/D_m)}{\ln(D_s/D_m)} \qquad (14)$$

where D_m and D_s are the typical grain size of mud and sand, respectively. Analysing the grain size distribution measured in the Venice Lagoon (Amos et al., 2004; Umgiesser et al., 2006), we set $D_m = 20\mu m$ and $D_s = 200\mu m$.

RC2.4: Line 151. The author mentioned that bottom shear stress and critical shear stress are determined using a stochastic approach from Grass (1970). Please give more details on how it is implemented. Is the implementation validated using benchmark tests? How do the results look like compared to the classic deterministic approach?

AR: Following Reviewer's suggestion, we added more details on the stochastic approach for the computation of the transport parameter as follows:

(line 257) *The transport parameter, T, is usually defined as $T = \max\{\,0;\ \tau_{wc}/\tau_c - 1\}$ where τ_c is the critical shear stress for erosion and can be assumed to vary monotonically between the critical value for pure sand, τ_{cs}, and the critical value for pure mud, τ_{cm}, depending on the mud content (van Ledden et al, 2004):*

$$\tau_c = \begin{cases} (1 + p_m)\tau_{cs} & \text{for } p_m \leq p_{mc} \\ \frac{\tau_{cs}(1+p_{mc}) - \tau_{cm}}{1 - p_{mc}}(1 - p_m) + \tau_{cm} & \text{for } p_m > p_{mc} \end{cases} \qquad (11)$$

However, this classic definition of the transport parameter describes a sharp transition between T = 0 and $T = \tau_{wc}/\tau_c - 1$ that does not take into account the

spatial and temporal variability of both τ_{wc} and τ_c. Indeed, in real tidal systems, the bottom shear stress slightly varies owing to the non-uniform flow velocity, wave characteristics and small-scale bottom heterogeneity, while the critical shear stress is also affected by the random grain exposure and bed composition in time and space. Hence, following the stochastic approach suggested by Grass (1970), both the total bottom shear stress, τ_{wc}, and the critical shear stress for erosion, τ_c, are treated as random variables (τ_{wc}', and τ_c', respectively) with lognormal distributions, and their expected values are those calculated by WWTM and STABEM. Consequently, the erosion rate depends on the probability that τ_{wc}' exceeds τ_c' (Carniello et al., 2012). The result of this stochastic approach is a smooth transition between $T = 0$ and $T = \tau_{wc}/\tau_c - 1$. The comparison with SSC field measurements shows a much better agreement of the stochastic approach compared to that of the classic formulation (Supplementary information and Figure S3).

A detailed description of the implementation and validation of this approach was already provided by Carniello et al. (2012). We deem that repeating this information would be redundant and unnecessarily lengthens the manuscript compared to the little benefit for the reader. Therefore, we believe that these details would better fit the supplementary material. We report here for the Reviewer's convenience the text and the figure we added as Supplementary Information:

Supplementary Information

The stochastic approach for the computation of the transport parameter

The transport parameter, T, is usually defined as

$$T = \max\left\{0; \frac{\tau_{wc}}{\tau_c} - 1\right\} \qquad (1)$$

where τ_{wc} is the total bottom shear stress and τ_c is the critical shear stress for erosion.

This definition describes a sharp transition between $T = 0$ and $T = \tau_{wc}/\tau_c - 1$ that cannot take into account the spatial and temporal variability of both τ_{wc} and τ_c in real tidal systems. Indeed, the bottom shear stress is very unsteady because of the non-uniform flow velocity, wave characteristics and small-scale bottom heterogeneity within a computational element, while the critical shear stress is also affected by the random grain exposure and bed composition in time and space.

Similarly to the stochastic approach proposed by Grass (1970), we assume that both bed shear stress, τ_{wc}, and critical shear stress, τ_c, are random and distributed according to a log-normal probability density function Grass, 1970; Bridge and Bennett, 1992). Therefore, we can write

$$T = \frac{1}{\tau_c} \int_0^\infty \left[\int_{\widetilde{\tau_c}}^\infty (\widetilde{\tau_{wc}} - \widetilde{\tau_c}) \cdot p_{wc}(\widetilde{\tau_{wc}}) d\widetilde{\tau_{wc}} \right] \cdot p_c(\widetilde{\tau_c}) d\widetilde{\tau_c} \qquad (2)$$

where $p_{wc}(\cdot)$ and $p_c(\cdot)$ are the probability density function of τ_{wc} and τ_c respectively, and $\widetilde{\tau_{wc}}$, τ_{wc} are the correspondent dummy variables of integration.
The result of this stochastic approach is a smooth transition between $T = 0$ and $T = \tau_{wc}/\tau_c - 1$.
*An adequate interpolation of Eq. 2, which is implemented in the numerical model, is given by*

$$T = -1 + \left(1 + \left(\frac{\tau_b}{\tau_c}\right)^\varepsilon\right)^{1/\varepsilon} \qquad (3)$$

where ε is a non-dimensional calibration parameter, that accounts for the shape of the log-normal distribution.

We report here as an example a comparison of the measured and computed SSC at the LT7 station (see Figure S2) for an intense north-easterly Bora wind event in April 2003 (Figure S3). Numerical simulations were performed either by using the classic formulation (Eq. 1) (black thin line) or computing T considering Eq. 3.

Using the classic formulation, the model is not able to correctly compute the time evolution of the local turbidity at near-threshold conditions, especially at the beginning of the event (first peak on the 2nd April 2003). On the contrary, the agreement between measured and computed data is quite good when using the stochastic approach.

For the Reviewer's convenience, we report here Figure S3 added to the Supplementary information
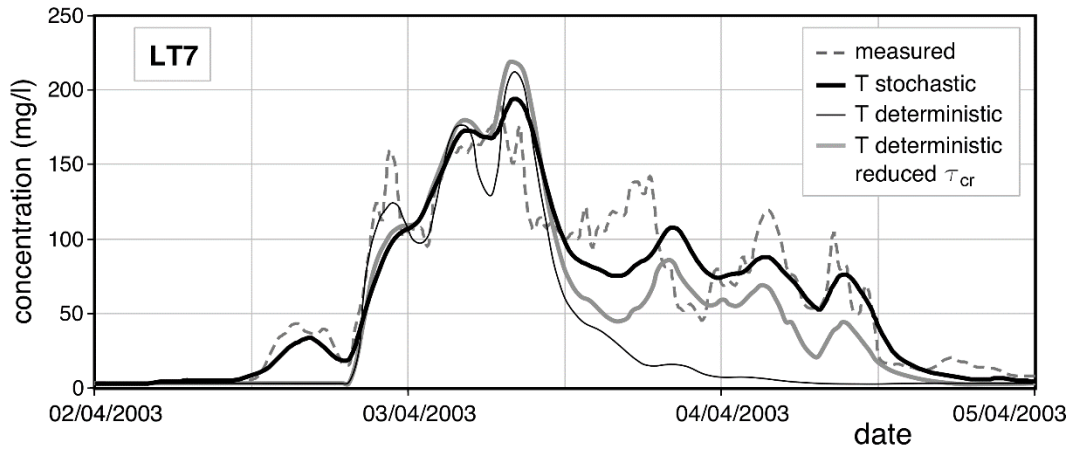
Figure S3. Stochastic approach for the computation of suspended sediment transport. Comparison of measured (dashed line) and computed (solid lines) suspended sediment concentration at the station LT7 (see Figure S2 for the location). The computed suspended sediment concentration was computed by estimating the transport parameter, T , (i) following the probabilistic approach (black bold line, Eq. 3; (ii) using the classic formulation (Eq. 1) without modifying the critical shear stress value (black thin line); (iii) using the classic formulation and reducing the critical shear stress value ($\tau_{cr,S} = 0.3$ Pa; $\tau_{cr,M} = 0.6$ Pa; grey line)

AR: These two observations are closely related, so we decided to merge our responses to RC2.5 and 2.6.

We agree with the Reviewer's observations that the choice of the threshold value C_0 needs to be explained more in detail. To this aim, following also the suggestions of Reviewer 1, we have completely rewritten the subsection where we introduce the Peak-Over-Threshold analysis as follows:

(line 324) ~~Sediment transport dynamics in tidal environments are the results of the complex interplay among hydrodynamic, biologic, and geomorphologic processes. This interplay between different factors can be fully framed only by taking into account both its deterministic and stochastic components. As an example, Carniello et al. (2011) argued that morphological dynamics in the Venice Lagoon are mostly linked to a few severe resuspension events induced by wind waves, whose dynamics are markedly stochastic in the present configuration (D'Alpaos et al., 2013; Carniello et al., 2016). Measurements confirm that high SSC events are also important sediment suppliers for salt marshes (Tognin et al., 2021).~~
~~In the present work, we used the peak-over-threshold theory (POT) (Balkema and de Haan, 1974) to analyze temporal and spatial dynamics of the total SSC at any location within each selected configuration of the Venice lagoon.~~
~~First, a minimum-intensity threshold, C_0, was chosen to identify the set of over-threshold events from the modelled SSC record, and then a statistical analysis of interarrival times, durations and intensities of the exceedances of the threshold was carried out.~~

The interplay among the different drivers that control suspended sediment dynamics in shallow tidal environments can be fully framed only by taking into account also its stochastic components, associated with wind waves and storm surges, which are largely responsible for the morphodynamic evolution of these systems (Carniello et al., 2011; Tognin et al., 2021).

To this aim, in the present work, we statistically characterize the spatial and temporal dynamics of resuspension events by applying the peak-over-threshold theory (POT) (Balkema and de Haan, 1974) to the one-year-long time series of SSC computed with the numerical model described above for the different configurations of the Venice Lagoon.

Before applying the POT analysis, the SSC time series provided by the numerical simulations were low-pass filtered by applying a moving average procedure with a time window of 6 hours, in order to preserve the tide-induced modulation of the signal but, at the same time, to remove artificial upcrossing and downcrossing of the threshold, generated by short-term fluctuations. This pre-processing procedure prevents the identification of a false dependence of subsequent over-threshold events due to spurious fluctuations.

Once a proper threshold, C_0, is chosen, the POT identifies three different random variables: interarrival times, durations and intensities of the exceedances of the threshold. The interarrival time is defined as the time interval between two consecutive upcrossings of the threshold, the duration of the events is the time elapsed between any upcrossing and the subsequent downcrossing of the threshold, and, finally, the intensity is calculated as the largest exceedance of the threshold in the time-lapse between an upcrossing and the subsequent downcrossing. These

random variables are characterized by their probability density functions and the corresponding moments for any location in all the considered configurations of the Venice Lagoon, in order to provide a complete description of the SSC pattern. *Besides synthetically characterising over-threshold events, these three variables can be combined to compute more complex metrics to describe SSC dynamics (e.g. the volume of sediment reworked in a selected time frame).*

The nature of the stochastic processes can be determined by the analysis of the interarrival times distribution. Indeed, resuspension events can be mathematically modelled as a Poisson process if the interarrival times between subsequent exceedances of the threshold, C_0, are independent and exponentially distributed random variables *(Cramér and Leadbetter, 1967; Gallager, 2013).*

Moreover, the memorylessness of the Poisson process guarantees that the number of events observed in disjoint subperiods is an independent, Poisson-distributed random variable (Gallager, 2013). When the sequence of random events that define a 1-D Poisson process along the time axis can be associated with a vector of random marks that defines the duration and intensity of each over-threshold event, the process can be defined as a marked Poisson process. The distribution of these marks does not affect the chance to model the process as Poissonian, which, indeed, relies only on the exponentiality of interarrival times. However, when also duration and intensity are exponentially distributed, the set-up of a stochastic framework can be further simplified. In order to assess that over-threshold SSC events can be modelled as a marked Poisson process, we performed the Kolmogorov-Smirnov (KS) goodness of fit test on the distribution of the interarrival times, intensity and duration of over-threshold events.

In the POT analysis, the threshold value plays a critical role and its choice deserves careful attention. In the case of erosion dynamics (D'Alpaos et al., 2023), the identification of the threshold with the critical shear stress for erosion seems to be quite straightforward and has the advantage of preserving also the physical meaning of the process. Instead, when dealing with SSC, the absence of a clear physical threshold mechanism may make the identification of the threshold value less direct. The present analysis aims to characterize the bulk effect of morphologically meaningful SSC events, rather than to describe only the extreme events, and, simultaneously, to remove the weak resuspension events induced by periodic tidal currents that can be described as a recurrent, deterministic process. From this point of view, the choice of a threshold value, C_0, that identifies morphologically significant over-threshold SSC events, has to consider two opposite requirements. On the one hand, stochastic sediment concentration generated by storm-induced wind waves can be distinguished from tide-modulated daily concentration only if C_0 is large enough. On the other hand, too high values of C_0 either require a long, computationally prohibitive simulated time series or can lead to a non-informative analysis because of the large number of events unaccounted for. These observations narrow the range in which the threshold can be selected. The lower boundary is set by the SSC observed in the absence of wind and, therefore, associated exclusively with the tide. While the upper boundary has to be maintained well below the maximum observed values to consider all the morphologically meaningful events. In the specific case of the Venice Lagoon, to satisfy these requirements, the C_0 value has to fall between 30 and 60 mg l^{-1}, as suggested by in-situ SSC measurements (Carniello et al., 2012, 2014).

The sensitivity analysis performed on the present-day configuration of the Venice Lagoon (Carniello et al., 2016) suggests that the chance to model SSC events as a Poisson process is weakly affected by the specific threshold value in the above

range. Indeed, using threshold values equal to 30, 40, 50 or 60 mg l⁻¹ hardly changes the areas where interarrival times are not exponentially distributed and, therefore, wind-induced SSC cannot be described as a Poisson process (Figure S6). On the basis of these observations and to allow the comparison among the different configurations, in the present analysis, we used a constant threshold, C_0, equal to 40 mg l⁻¹.

~~According to the extreme value theory, a Poisson process emerges from a stochastic signal whenever enough high censoring threshold is chosen (Cramér and Leadbetter, 1967). However, as this present analysis is designed to remove only the weak resuspension events induced by periodic tidal currents, the critical threshold is well below the maximum observed values. As a consequence, the aim of the proposed analysis is to characterize the bulk effect of morphologically meaningful SSC events, rather than to describe the extreme events. Notwithstanding the increasing popularity of Poisson processes for the analytical modelling of the long-term evolution of geophysical processes controlled by stochastic drivers in hydrological and geomorphological sciences (e.g., Rodriguez-Iturbe et al., 1987; D'Odorico and Fagherazzi, 2003; Botter et al., 2013; Park et al., 2014; Bertassello et al., 2018), only in the last few years this approach has been adopted for tidal systems (D'Alpaos et al., 2013; Carniello et al., 2016) and the applications portray an encouraging framework.~~

For the Reviewer's convenience, we report here Figure S6 added to the Supplementary information showing the results of the KS test using different C_0 thresholds.
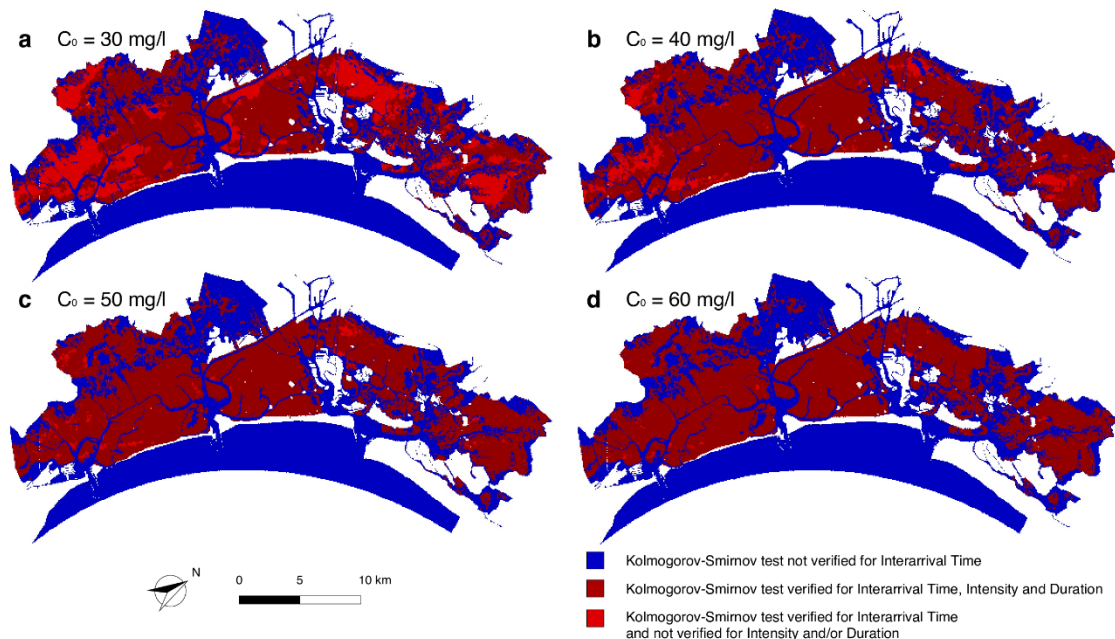
Figure S6. Sensitivity analysis of the threshold C_0. Spatial distribution of Kolmogorov-Smirnov (KS) test at significance level ($\alpha = 0.05$) for different values of the threshold, C_0: (a) 30 mg/l; (b) 40 mg/l; (c) 50 mg/l; (d) 60 mg/l. In the maps we can distinguish areas where the KS test is: not verified (dark blue); verified for all the considered stochastic variables (interarrival time, intensity over the threshold and duration) (dark red); verified for the interarrival time and not for intensity and/or duration (light red). Maps show little to no influence of the threshold value within the selected range on the possibility to model over-threshold SSC events as a Poisson process.

When talking about the comparison in the past centuries, it might be important to consider the impact of climate change.

AR: We thank the Reviewer for the comment, which helped us to clarify some of our modelling choices.

As we have already explained in the revision of the companion paper, relative sea level changes surely play a fundamental role in shaping the lagoon morphology and, therefore, we cannot neglect this process. Indeed, we accounted for sea level changes, because each bathymetrical survey and, hence, the correspondent elevation of the computational grid was referred to the coeval mean sea level. Thanks to the Reviewer's comment we realized that this important concept was not properly described in the original version of the manuscript and, therefore, we better highlighted it in the revised version, as follows:

> (line 170) *Each bathymetry and, hence, the elevation of grid elements refers to the local mean sea level at the time when each survey was performed.*
>
> (line 295) *Because bed elevation in each computational grid refers to the mean sea level at the time of each survey, we implicitly take into account the effects of historical relative sea level variations.*

Moreover, we must repeat that, although climate changed in the last four centuries, human interventions undeniably played a primary role in affecting the morphological changes in the same period (Carniello et al., 2009; D'Alpaos, 2010a, 2010b; Finotello et al., 2023; Silvestri et al., 2018). Therefore, we can conclude that the effects of changes in climate on the morphology of the Venice Lagoon are small compared to those resulting from human interventions. In the revised version of the manuscript, we highlighted this concept by modifying the text as follows:

> (line 144) *The Venice Lagoon (Figure 1) underwent different morphological changes over the last four centuries, mainly associated with anthropogenic modifications (Carniello et al., 2009; D'Alpaos, 2010; Finotello et al., 2023).*
>
> (line 162) *As a result, the morphological evolution of the lagoon in the last four centuries has been strongly affected by anthropogenic interventions, along with sea level rise.*

As already noted for the bottom shear stress analysis in the companion paper, we must also stress that, rather than trying to reconstruct the exact climate forcing that gave rise to the present-day morphology, this study aims to understand how morphological changes affect the parameters driving sediment reworking. From this point of view, setting the same boundary conditions is necessary to highlight the specific role of the morphology in affecting the hydrodynamic and wave fields and, therefore, the sediment transport process. By using different boundary conditions for the different historical configurations (although clearly impossible due to data unavailability), it would have been impossible to distinguish the effect on SSC related to the morphology and those due to the different boundary conditions. Indeed, one of the main advantages of numerical modelling is the possibility to isolate the effects of one single parameter, that, in this case, is the morphology, to unravel mechanisms that are otherwise intermingled within a variety of processes.

We have better highlighted this aspect in several points of the revised manuscript:

> (line 13) *The analysis with the peak-over-threshold theory of SSC time series computed using a fully-coupled, bi-dimensional model allow us to identify interarrival times, intensities and durations of over-threshold events and test the*

hypothesis of modelling SSC dynamics as a Poisson process. The effects of morphological modifications on spatial and temporal SSC patterns are investigated in the Venice Lagoon, for which several historical configurations in the last four centuries are available. Our results show that, similarly to erosion events, SSC can be modelled as a marked Poisson process in the intertidal flats for all the *different morphological*~~considered historical~~ configurations *considered*~~of the Venice Lagoon~~ because exponentially distributed random variables well describe ~~interarrival times, intensity and duration of~~ over-threshold events. ~~Moreover, interarrival times, intensity and duration describing local erosion and over-threshold SSC events are highly related, although not identical because of the non-local dynamics of suspended sediment transport related to advection and dispersion processes. Owing to this statistical characterization of SSC events, it is possible to generate synthetic, yet realistic, time series of SSC for the long-term modelling of shallow tidal environments.~~ *Although erosion and resuspension are intimately intertwined, erosion alone does not suffice to describe also SSC because of the non-local dynamics due to advection and dispersion processes. The statistical characterization of SSC events completes the framework introduced for erosion mechanics and together they represent a promising tool to generate synthetic, yet realistic, time series of shear stress and SSC for the long-term modelling of tidal environments.*

(line 293) Forcing all the historical configurations of the Venice Lagoon with the same wind and tidal conditions enables us to isolate the effects of the morphological modifications on the wind-wave field, hydrodynamics and sediment dynamics.

RC2.8: In the introduction, the author stated that there exists field-measured data and remote sensing data for SSC. I think it is necessary to show the comparison between the simulated results and those datasets as model validation.

AR: We believe that reporting in the main text a detailed description of the model performance against measured data would importantly lengthen the manuscript without a real benefit for the reader because the validation has already been published in more than one paper.
However, we understand the Reviewer's concern and we deem that the best solution is adding a paragraph on the model performance in the Method section, to provide the reader with more information on the capability of the model to describe the sediment transport dynamics, leaving additional Figures showing a detailed comparison between numerical modelling and measured data in the Supplementary Information. The revised version of the main text now reads:

(line 273) The model has been widely calibrated and tested in the most recent configuration of the Venice Lagoon, i.e., when field data are available. Since the hydrodynamic model performance has been reported when considering the erosion dynamics (D'Alpaos et al., 2023), here we summarize the ability of the sediment transport model to reproduce SSC by reporting the standard Nash-Sutcliffe Model Efficiency (NSE) parameter computed when field data are available and refer the interested reader to the Supplementary Information (Figures S4 and S5) and the literature (Carniello et al., 2012; Tognin et al., 2022) for a more detailed comparison. Adopting the classification proposed by Allen et al. (2007), the model performance can be rated from excellent to poor (i.e., $NSE > 0.65$ excellent; $0.5 < NSE < 0.65$ very good; $0.2 < NSE < 0.5$ good; $NSE < 0.2$ poor). The STABEM model is very good to excellent in reproducing SSC ($NSE_{mean} = 0.65$, $NSE_{median} =$

0.62, NSE$_{std}$= 0.17, statistics are derived from calibration reported in Carniello et al., 2012, their Tables 2 and 3, and Tognin et al. (2022), their Table S2). Importantly, the sediment transport model not only correctly reproduces the magnitude of the SSC but also captures its modulation induced by tidal currents and wind-wave variations (Figures S4 and S5).

A more detailed explanation, along with figures, is reported in the Supplementary Information as follows:

Supplementary Information

Model calibration

The calibration of the model was performed for different periods when SSC field measurements are available (Figure S2), but, for the sake of brevity, we report in the following some examples related to intense and weak resuspension events, referring the reader to Carniello et al. (2012) for a more detailed analysis. Model capability to capture the process is evaluated by means of the Nash-Sutcliffe Model Efficiency (NSE) (Allen et al., 2007).
Focusing on intense resuspension events, we report in the following the results of three periods characterized by intense wind speed, namely: i) 2–5 April 2003 characterized by Bora wind with speeds up to 16 m/s; ii) 9–13 December 2005 characterized by Bora wind with speeds up to 20 m/s; iii) 29 July–2 August 2007 characterized by Bora wind with speeds up to 20 m/s. The comparison with measured data for simulations with an intense wind event in different stations located within the lagoon shows that the model performance to reproduce SSC is from very good to excellent (NSE$_{mean}$ = 0.70, NSE$_{median}$ = 0.67, NSE$_{std}$= 0.13). In these inner stations, the main contribution to SSC is provided by the mud fraction being negligible the sand content far from the inlets. Interestingly, the model not only correctly predicts the magnitude of the SSC but also captures its modulation induced by tidal level and wind-wave variations (Figure S4).
Additional tests were also carried out considering events characterized by very low wind speed. In particular, we report the results for the period 12-18 April 2006 when turbidity data at six stations close to three inlets are available. At these locations, the sand contribution to the computed SSC is relatively large and of the same order of magnitude as mud contribution (i.e. mud concentration ~10 mg/l and sand concentration ~2–3 mg/l) because close to the inlets the bed composition is richer in sand content than in the inner lagoon. Also in this case the model performance is rated from very good to excellent (NSE$_{mean}$ = 0.62, NSE$_{median}$ = 0.59, NSE$_{std}$= 0.13). The numerical model correctly reproduces SSC also in the case of very low wind velocity, when the measured SSC can be one order of magnitude lower than that measured with high wind speed (Figure S5).

For the sake of brevity, we do not report here the Figures we added in the Supplementary Information (see Figure S2 to S5).

RC2.9: In the captions in Figure 2, 3, 4, 5, 7, 8, 9 The description of subfigures is confusing. Recommend switching the order of the year and sub-figure numbering. For example, use "(a) 1611; (b) 1810; ..." instead.

AR: We thank the Reviewer for this suggestion. Done.