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Statistical characterization of erosion and sediment transport mechanics in shallow tidal environments. Part 1: erosion dynamics

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Summary

The authors are grateful to the editorial board and the reviewers for their thoughtful and constructive comments on our paper, which significantly improved the manuscript and how our findings are communicated.

Following the Reviewers' suggestions, we have carefully revised the introduction in order to better highlight how the proposed approach aims to contribute to filling the knowledge gap in long-term morphodynamic modelling and to better frame the potential applicability of this approach.

Moreover, the revised manuscript now includes a more detailed description of the numerical hydrodynamic model used in our analysis and its calibration procedure.

Finally, as suggested by the Reviewers, we provided additional details about some modelling choices that were not properly justified in the previous version of the manuscript. In particular, now we extensively discuss the choice of boundary conditions and the threshold shear stress to apply the peak-over-threshold analysis.

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 addressed them, referencing line numbers in the revised version of the 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 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 is a very interesting paper combining a modeling approach and a statistical analysis of erosion dynamics in the Venice Lagoon. The paper is well written and the findings of potential interest for assessing long-term erosion processes in a computationally-efficient way. I only have minor remarks.

AR: We thank the Reviewer for his/her positive comments on our manuscript and for his/her insightful suggestions that contributed to improving the quality and clarity of our manuscript. Please, find in the following the responses to each detailed comment.

RC2.1: I miss a discussion about the potential applicability of the marked Poisson model for intertidal flats in other environments (e.g., with a different wind regime and/or different tidal regime).

AR: We agree with the Reviewer that a discussion about the applicability of this approach helps the reader to better understand potential and limitations.

First of all, we revised the introduction to better frame the problem and highlight that the proposed approach aims to be used when stochastic processes, such as wind waves and storm surges, play a fundamental role in the morphological evolution of tidal systems. The revised text now reads:

> (line 50) *Several process-based models have been developed to describe erosive processes and investigate the effects of BSS on the morphodynamics of shallow tidal basins. Although these models were originally developed to deal with short-term time scales, various techniques were proposed to accelerate bed evolution and upscale the results at much longer time scales.*
>
> (line 70) *These upscaling techniques are based on the underlying assumption that the actual morphological evolution of a system is equivalent to that resulting from a repetitive pattern representative of the dominant forcing conditions. This hypothesis is reasonable when the main hydrodynamic forcing is represented by tidal oscillation, although attention should also be paid when selecting representative boundary conditions for astronomic tidal patterns (Schrijvershof et al.,2023). Instead, taking into account also merely stochastic processes, such as wind waves and storm surges, is far less straightforward. When wind climate may be reduced to a limited set of representative conditions, multiple simulations can be run and then a weighted average of the different results can be determined to estimate the upscaled morphological evolution (Roelvink, 2006). However, when representative wind and storm climate cannot be reduced to a limited batch of boundary conditions or, more importantly, not only the magnitude but also the temporal succession of these events is likely to strongly affect the morphological evolution of the system, these upscaling techniques cannot be properly applied.*
> *A different perspective would be to directly consider the stochasticity of erosion dynamics. From this point of view, the first step is to test the possibility of effectively describing BSS dynamics within a statistically-based framework. Once verified, this hypothesis will allow one to generate synthetic, yet reliable, BSS time series to model the erosion dynamics on long-term time scales and compare the possible modifications also considering different scenarios in a computationally-effective way through the use of independent Monte Carlo realizations. Although the statistical characterization of the long-term behaviour of several geophysical processes is becoming increasingly popular in hydrology and geomorphology (e.g., Rodriguez-Iturbe et al., 1987; D'Odorico and Fagherazzi, 2003; Botter et al.,*

2007; Park et al., 2014), applications to tidal landscapes are still quite rare (D'Alpaos et al., 2013; Carniello et al., 2016).

Moreover, we clearly specified the applicability range of this approach in the revised text, both in the "Result and Discussion" and "Conclusion" sections, as follows:

(line 354) The KS test is verified over subtidal platforms and tidal flats, where current-induced BSSs are typically below the critical value, but wave-induced BSSs mainly contribute to the total BSS. Locations where interarrival time, duration and intensity follow an exponential distribution (see red areas in Figure 3), remain the vast majority of the tidal basin in all the configurations. As a result, a synthetic framework that models erosion as a Poisson process is deemed to be suitable for wide tidal-flat areas. *More generally, the chance to model erosion as a Poisson process lies in the intrinsic nature of BSS drivers. Wherever the stochastic action of wind waves and storm surges plays a prominent role in generating BSS compared to the deterministic tidal component, erosion is likely to be properly described by a Poisson process. This is the case of shallow tidal environments where the open water surface allows for the generation of wind waves, such as in back-barrier lagoons. On the contrary, the chance to use the Poisson-process-based approach diminishes where tidal currents substantially modulate BSS dynamics and mask the signature of stochastic processes, such as in tidal inlets and narrow meso- or macrotidal estuaries.*

(line 466) Our results provide a statistical characterization of sediment erosion dynamics, aimed at testing the possibility to describe erosion events as a Poisson process in a synthetic modelling framework able to reproduce the long-term evolution of shallow tidal systems. *The proposed approach aims to better describe erosion events in shallow tidal environments, where BSS dynamics are strongly affected by wind conditions.*

RC2.2: I also miss a discussion on the sensibility of the study results and conclusions to some key parameters (e.g., critical bottom shear for erosion, here fixed at 0.4 Pa, but greatly varying in the literature).

AR: We understand the Reviewer's point of view and we recognize that, in the first version of the manuscript, the choice of the critical shear stress and its implications were too condensed and, therefore, would benefit from a more detailed comment.
We added a more detailed explanation in the Method section as follows:

(line 232) In this work, at any location within each considered configuration of the Venice Lagoon, we used the peak-over-threshold (POT) theory (Balkema and de Haan, 1974) to analyze the temporal and spatial evolution of the total BSS, τ_{wc}. ~~The threshold value of the BSS, τ_{ϵ}, was set equal to 0.4 Pa (Amos et al., 2004)~~.
In general, the selection of the threshold for the POT method must satisfy two contrasting requirements. On the one hand, the threshold must be large enough to discern stochastic events from the deterministic background. On the other hand, the threshold should not be too high to avoid the loss of important information and the need for a much longer time series to compute meaningful statistics, because of the lower number of threshold exceedances. Moreover, the extreme value theory postulates the general emergence of Poisson processes whenever the censoring threshold is high enough (Cramér and Leadbetter, 1967). To comply with these requirements, in the present analysis, the threshold is maintained well below the

maximum observed values, in order to remove only the background modulation induced by tidal currents without losing significant information on the stochastic wave-driven erosion process.
In applying the POT method to BSS time series, setting the threshold equal to a critical BSS for erosion, τ_c, presents the non-trivial advantage of preserving also the physical meaning of the erosion mechanism. Values of critical BSS for erosion for fine, cohesive mixtures typical of shallow tidal settings largely vary in the literature and are affected by multiple physical and biotic factors (Mehta et al., 1989). Erosion shear stress from in-situ measurements on the tidal flats of the Venice Lagoon ranges between 0.2 and 2.3 Pa (0.7 ± 0.5 Pa - median ± standard deviation), with values higher than 0.9 Pa usually recorded within densely vegetated patches (Amos et al., 2004). In the present analysis, we cannot take into account the role of the biotic component, because of the impossibility to reconstruct the spatial distribution of vegetated tidal flats in the ancient configurations of the Venice Lagoon. For all the above reasons and following the approach suggested by D'Alpaos et al. (2013), we set the critical shear stress, τ_c, equal to 0.4 Pa for all the selected historical configurations of the Venice Lagoon.
Before performing the POT analysis, the time series of BSSs were processed by applying a moving average filter, in order to remove spurious upcrossings and downcrossings of the prescribed threshold. This low-pass filter with a time window of 6 hours removes short-term fluctuations, preserving the modulation given by the semidiurnal tidal oscillation. Thanks to this preprocessing procedure, over-threshold events satisfy the independence assumption required by the statistical analysis applied.

Concerning the sensitivity analysis, we added a paragraph as follows:

(line 281) *The result of modelling erosion events as a Poisson process stands regardless of the specific value of the censoring threshold selected for the POT analysis, provided that it is high enough to exclude deterministic exceedances, and this is confirmed also by the sensitivity analysis performed by D'Alpaos et al. (2013) on the present-day configuration of the Venice Lagoon. Indeed, when considering too low values of the threshold (e.g., τ_c = 0.2 Pa), deterministic exceedances driven by tidal currents occur and make the interarrival time not exponentially distributed. On the contrary, as the threshold value increases (e.g., $\tau_c \geq$ 0.6 Pa), the KS test is still verified, thus confirming that the process remains Poisson for increasing censoring thresholds (see Figure 6 in D'Alpaos et al. (2013) for further details).*

For the Reviewer's convenience, we report here Figure 6 from D'Alpaos et al. (2013) showing the results of the KS test using different BSS thresholds.

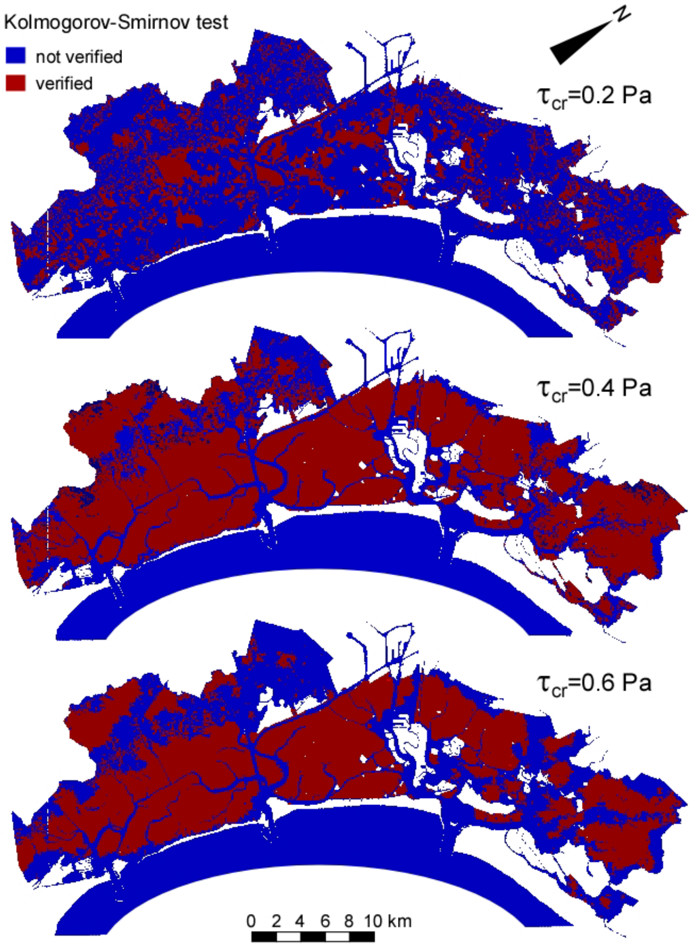

Figure 1. Spatial distribution of Kolmogorov-Smirnov (KS) test at a significance level (α = 0.05) on interarrival times assuming a threshold value for the shear stress equal to: $\tau_c = 0.2$ Pa (upper panel), $\tau_c = 0.4$ Pa (central panel) and $\tau_c = 0.6$ Pa (lower panel) (from D'Alpaos et al., 2013).

RC2.3: Line 67: Not clear if this tidal range or amplitude.

AR: We thank the Reviewer for noting it. We amended the text as follows:

> (line 118) In the present-day morphology, the lagoon is connected to the sea with three inlets, namely Lido, Malamocco, and Chioggia (Figure 1), through which *the tide propagates within the back-barrier system. The tidal regime is semidiurnal with a maximum tidal amplitude of about 0.75 m, typical of the northern Adriatic Sea* ~~the semidiurnal tide with a maximum tidal oscillation of about 0.75 m typical of the northern Adriatic Sea propagates within the lagoon.~~ (D'Alpaos et al., 2013, Valle-Levinson et al., 2021).

RC2.4: Line 105: Provide the Strickler equation.

AR: We thank the Reviewer for the suggestion. This piece of information is indeed crucial in this work and was actually missing in the original version of the manuscript. We provided the formulation adopted in the model of the Strickler equation by modifying the text as follows:

> (line 165) The bottom shear stress induced by currents, τ_{tc}, is evaluated using the Strickler equation considering the case of a turbulent flow over a rough wall, *which can be written as (Defina, 2000)*

$\tau_{tc} = \rho\, g\, Y \left(\frac{|\boldsymbol{q}|}{K_S^2 H^{10/3}}\right) \boldsymbol{q}$

where ρ is water density, g is the gravity acceleration, Y is the effective water depth, defined as the volume of water per unit area actually ponding the bottom, $\boldsymbol{q}$ is the flow rate per unit width, K_s is the Strickler roughness coefficient, and H is an equivalent water depth that accounts for the typical height of ground irregularities.

RC2.5: Line 112: Provide the BSS induced by wind waves.

AR: To complete the description of the formulation of BSS adopted in the model, we modified the text as follows:

(line 176) The wind-wave module computes the bottom shear stress induced by wind waves as (*Carniello, 2005)*

$\tau_{ww} = \frac{1}{2} \rho\, f_w\, u_m^2$

where u_m is the maximum horizontal orbital velocity associated with wave propagation and f_w is the wave friction factor. According to the linear theory, the bottom velocity u_m can be evaluated as

$u_m = \frac{\pi H_w}{T\ \sinh(kh)}$

where H_w is the wave height, T denotes the wave period, k is the wave number, and h is the water depth. The wave friction factor can be approximated as (Soulsby, 1997)

$\mathrm{f_w} = 1.39 \left[\frac{u_m T}{2\,\pi (D_{50}/12)}\right]^{-0.52}$

where D_{50} is the median grain size.

RC2.6: Lines 144-145: I am wondering if the largest exceedance of the threshold is really the most appropriate here. I feel that the integral of the exceedance makes more sense, as it will determine the total amount of sediments that will be eroded during that event. Can you comment on that?

AR: We totally agree with the Reviewer that the integral of the exceedance is the best metric to describe the total amount of eroded sediment during an event. Indeed, we computed the erosion work, which exactly matches this definition and fits this purpose (see Eq. 2 and 3 in the first version of the manuscript). However, the description of the process solely through the integral does not allow to understand whether the variation in erosion depends on an intensity or on a duration variation. Instead, describing the processes using these two variables (together with the interarrival time to provide the frequency), besides being simple and intuitive, does not prevent the computation of more specific metrics, such as the over-threshold integral (i.e., erosion work) which can be approximated by their combination (see Table 1 and Supplementary Figure S16).
To better justify this choice, we added a comment in the revised manuscript as follows:

(line 256) The POT method allowed us to identify:

- the interarrival time of over-threshold events, defined as the time between two consecutive upcrossings of the threshold;
- the duration of over-threshold events, that is the time elapsed between any upcrossing and the subsequent downcrossing of the threshold;
- its intensity, calculated as the largest exceedance of the threshold in the time elapsed between an upcrossing and the following downcrossing.

These three random variables synthetically characterize the over-threshold erosion events and can be combined to obtain further metrics to describe the erosion process (e.g., see the erosion work defined later on).

RC2.7: Lines 150-162: This paragraph seems central to the entire paper. However, it is very short and does not cite any reference where the supporting theory is fully developed. I expect more details to support the theory, either as supplementary material or as cited literature.

AR: We probably took for granted that reader is familiar with stochastic processes, but we agree with the Reviewer that it is better to provide some additional information for the interested reader. We added the reference to these two classic textbooks which provide both a general overview of stochastic processes and detailed explanations of the properties of the Poisson process:

- Cramér, H. and Leadbetter, M. R.: Stationary and related stochastic processes, John Wiley & Sons, Ltd, New York, 1967.
- Gallager, R. G.: Stochastic Processes: Theory for Applications, Cambridge University Press, https://doi.org/10.1017/CBO9781139626514, 2013

RC2.8: Lines 167-171: This should be in the methods section.

AR: We agree with the Reviewer. As reported in our response to RC2.2, we moved this paragraph to the method section (line 137 of the first version of the manuscript).

RC2.9: Lines 184-186: Results in Figures 4-6 correspond to areas in red or yellow in Figure 3. Why not to areas in red only? Can you elaborate on that choice? Is it not relevant whether intensity and/or duration are exponentially distributed random variables?

AR: We agree that the choice of showing mean values of intensity and durations also where they are not exponentially distributed needs an additional comment to be better understood.
Whether intensity and duration can be described by exponential distributions does not affect the chance to model erosion as a Poisson process, which indeed relies only on the exponential distribution of interarrival times, but it can simplify the setup of the final stochastic framework. However, even if these marks of the Poisson process cannot be described by an exponential distribution, mean values of peak excess and duration can still be considered informative of the trend of these random variables and, thus, it is still worth showing them in the figures.
We reported this justification in the revised text, which now reads:

(line 301) *We analyzed the time series of computed total BSSs, τ_{wc}, at any element of the computational grids reproducing the six selected configurations of the Venice Lagoon on the basis of the POT method, in order to characterize the over-threshold erosion events in terms of interarrival times, peak excess and duration. The KS test is then performed in each element of the six domains in order to test where interarrival times can be described by an exponential distribution and thus, the over-threshold erosion events can be modelled as a Poisson process. We performed the KS test also on peak excess and duration to test if these marks of the process can also be described by exponential distributions. Whether peak excess and duration can be described by exponential distributions does not affect the chance to model erosion as a Poisson process, which indeed relies only on the exponentiality of interarrival times, but it can simplify the setup of the final stochastic framework.*
Therefore, in the spatial distribution of KS test results (Figure 3), ~~In particular,~~ we distinguished:

- the dark blue area, where the KS test is not verified for the interarrival time, i.e. wave-induced erosion events can not be described as a Poisson process;
- the red area, where the KS test is verified for all the three considered stochastic variables, namely interarrival times, intensity, and duration, i.e. wave-induced erosion events are indeed a marked Poisson process where its marks, intensity and duration, are *also* exponentially distributed random variables;
- the yellow area, where the KS test is verified for the interarrival time but it is not verified for the intensity and/or duration, i.e. wave-induced erosion events are a marked Poisson process but at least one between intensity and duration is not an exponentially distributed random variable.

The mean interarrival times (Figure 4), mean peak excesses (Figure 5) and mean durations of over-threshold erosion events (Figure 6) in the six selected configurations of the Venice Lagoon are shown in every location where the KS test is satisfied for interarrival times (Figure 3), and, thus, erosion events, can be described as a Poisson process. *Mean peak excess and mean duration are shown also where at least interarrival times are exponentially distributed (i.e., yellow areas in Figure 3) because mean values are anyway considered to be informative and erosion events can still be modelled as a Poisson process, although the marks are described by a distribution different from the exponential one.*

RC2.10: Lines 233-236: Please elaborate on the morphological features that remain the same through the last four centuries.

AR: To complete the description of the lagoon morphology, we added a comment in the geomorphological setting section, that now reads:

(line 140) *Only in the northern lagoon, the morphological degradation was less pronounced because of the sheltering effect provided by the mainland against the north-easterly Bora wind and the less intense human pressure. Therefore, the northern basin displays also in the present-day configuration relatively shallow intertidal flats and larger salt-marsh areas, compared to the central and southern lagoon (Figure 2f)*

Moreover, we added a comment to highlight the effects on interarrival times of preserved morphological features:

(line 374) *On a tidal flat in the northern lagoon named ``Palude Maggiore" (see station S1 in Figure 1a), as in most areas of the lagoon, the mean interarrival time* $\overline{\lambda}_t$ *between two subsequent over-threshold events increases through time (Figure 8a). This is because this area preserved the same morphological features, i.e. relatively shallow tidal flats protected by the mainland and salt marshes, over the last four centuries.*

Additional references

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