Author Response to Reviews of Earth Surface Dynamics Manuscript egusphere-2023-320

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 suggestions. We carefully considered and extensively discussed the possibility of merging the two papers. However, we hold major reservations about merging the two contributions, as we firmly believe that our work can be most effectively conveyed through two separate papers.

As explained more in detail in the following, the main rationale for keeping the two manuscripts separate is content-related, as each paper conveys a distinct message. The overarching contribution of the two companion papers is to test the hypothesis of using random processes to upscale morphodynamic models. However, this cannot be limited to the analysis of erosion events presented in Part 1, because suspended sediment dynamics is not solely influenced by local resuspension but also by advective and mixing processes occurring at the basin scale. Therefore, the characterization of both erosion events and suspended sediment dynamics as Poisson processes is necessary to test the possibility of implementing a synthetic modelling framework accounting for erosion and deposition. This highlights that the two papers are not mere repetitions but rather they address complementary questions on different morphological processes.

To better highlight the complementarity of these works, we have deeply revised the introduction of both papers, as detailed below. Moreover, we have provided a more detailed explanation for the selection of the threshold on suspended sediment concentration, as requested by Reviewer 2.

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 #1

RC1.1: I remain very skeptical about the scientific significance of this work with regards of its companion paper (Part 1). The authors admit that the choice of making two papers is (at least partially) driven by the fact that making only one paper would result in a very long paper with too many figures. But I would argue that it's often the case and that requires synthesizing effort to focus the paper on its essential message.

AR: First of all, it is worth mentioning that the decision to keep the two manuscripts separate was not primarily driven by the issue of avoiding an excessively lengthy paper. Instead, it is a practical consideration among various other factors. However, we gave careful thought to the idea of synthesizing the two manuscripts into one single paper. Upon attempting to do so, we realized that too much fundamental material should have been relocated into the Supplementary Information. This is because there are fundamental differences between the two physical processes at hand, namely bottom shear stress (BSS) and suspended sediment concentration (SSC), that deserve to be highlighted to explain the spatio-temporal dynamics of sediment erosion and suspended sediment concentration, which is the key message of our study. The partial overlap is limited to the introduction and the method section, particularly regarding the peak-over-threshold analysis, which must anyhow be partially retained to explain the differences in the analysis of BSS and SSC. We may also finally note that the request to further differentiate the two manuscripts was explicitly suggested in the first revision round. As a result, the lengths of the manuscripts to some extent reflect these adjustments.

Regardless of the manuscript length, the main rationale for maintaining the two manuscripts separated is content-related, as each paper has its own message. The most significant contribution of our study is to test the hypothesis to use random processes to upscale morphodynamics models. When describing morphodynamic changes, both erosive and depositional processes play a fundamental role. Erosion is generally related to the local BSS and deposition to the available SSC. The peak-over-threshold analysis of BSS presented in Part 1 proves that erosion dynamics can be modelled as a Poisson process. However, this offers only a partial perspective, as it does not address the possibility of modelling depositional dynamics as a stochastic process. Indeed, SSC is not solely influenced by local erosion because of advective and dispersive processes occurring at the basin scale, and, hence, must be analyzed independently. Therefore, the novelty of Part 2 lies in demonstrating that spatio-temporal dynamics of SSC can also be modelled as a random process, which is not proved in Part 1.

The characterization of both BSS and SSC as Poisson processes is necessary to test the possibility of implementing a synthetic modelling framework accounting for erosion and deposition. This highlights the difference and the complementarity of the results and clearly demonstrates that Part 2 is not a mere repetition of Part 1 but rather a fundamental component of our research.

To further substantiate this concept, we modified the introduction of Part 1 as follows:

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> (line 60) *A different perspective would be to directly consider the stochasticity of morphodynamic processes. From this point of view, the first step is to test the possibility of setting up a statistically-based framework in order to generate synthetic, yet reliable, time series to model the morphodynamic evolution on long-term time scales and compare possible 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).

The morphological evolution of tidal systems can be described by Exner's equation:

$$(1-n)\frac{\partial z_b}{\partial t}+\nabla \boldsymbol{q_b}=D-E \qquad (1)$$

where n *is the bed porosity,* z_b *is the bed elevation,* $\boldsymbol{q_b}$ *is the bedload, D and E are the deposition and entrainment rates of sediment, respectively. In mud-dominated tidal systems, sediment is primarily transported in suspension and the bedload is negligible, hence, the bed level changes can be determined by accurately describing erosion and deposition. Erosion, E, is directly influenced by the local bottom shear stress (BSS), which results from the interaction between tidal currents and wind waves in shallow tidal systems (Green and Coco, 2014). Instead, deposition, D, is linked to the suspended sediment concentration (SSC). However, SSC is largely affected by advection and dispersion processes at a larger scale and, therefore cannot be solely determined by local resuspension. Consequently, to effectively model bed-level variations, it is essential to accurately describe both BSS and SSC. This contribution focuses on characterizing BSS, while the analysis of SSC is presented in the companion paper (Tognin et al., 2023).*

In the introduction of Part 2, we added a very brief recall to Exner's equation presented in Part 1 and discussed the differences in the analysis of SSC as follows:

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(line 51) *A comprehensive understanding of morphological processes is key to addressing management and restoration strategies for shallow tidal landscapes. The morphodynamic evolution of these systems can be described by Exner's equation:*

$$(1-n)\frac{\partial z_b}{\partial t}+\nabla \boldsymbol{q_b}=D-E \qquad (1)$$

where n *is the bed porosity,* z_b *is the bed elevation,* $\boldsymbol{q_b}$ *is the bedload, D and E are the deposition and entrainment rates of sediment, respectively. Bedload is usually negligible in mud-dominated tidal systems, because sediment transport mainly occurs in suspension, and, thus, the bed level changes are essentially a function of erosion and deposition processes. In order to complete the stochastic framework introduced by D'Alpaos et al. (2023) for the description of erosion events, this study deals with the statistical characterization of suspended sediment concentration (SSC), considered a proxy for depositional processes.*

Suspended sediment dynamics in shallow tidal systems are influenced by different hydrodynamic and sedimentological factors that vary over a wide range of spatial and temporal scales (Woodroffe, 2002; Masselink et al., 2014). Both tide and waves represent key drivers controlling sediment entrainment and transport in shallow tidal environments (Wang, 2012), with stochastic wave-forced resuspension occasionally increasing by far cyclic tide-driven sediment reworking, especially under storm conditions. Wave resuspension together with tide- and wave-driven sediment transport give rise to advection and dispersion mechanisms leading to basin-wide sediment movement, which largely affect local suspended sediment dynamics (e.g., Nichols and Boon, 1994; Carniello et al., 2011; Green and Coco, 2014). Owing to the complexity of the underlying processes, suspended sediment dynamics in shallow tidal systems is rather entangled and it is not only linked to the local bottom resuspension. Therefore, to effectively describe suspended sediment transport in shallow tidal systems, a dedicated analysis is required.

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 for investigating 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.

Reply to Reviewer #2

RC2.1: The paper has been improved after the reviewing process. However, I think more work will be needed in order to publish this paper as a separate paper that uses identical structure and analysis as its companion paper. In my opinion, the most significant contribution of this paper is to introduce the methodology of using random process to upscale the morphodynamics models. This knowledge gap has been filled by its companion paper. Hence it is not necessary to publish a second paper to repeat it.

AR: We appreciate the Reviewer's recognition of our efforts in revising the initial manuscript. After careful consideration of the comment, we realized that, despite our best efforts in the revision, we could not adequately substantiate the need to keep the two contributions separate.

The main reason for keeping the two manuscripts separate is that each paper has a distinct message. As the Reviewer aptly pointed out, the most significant contribution of our study is to test the hypothesis to use random processes to upscale morphodynamics models. When describing morphodynamic changes, both erosive and depositional processes play a fundamental role. Erosion is generally related to the local bottom shear stress (BSS) and deposition to the available suspended sediment concentration (SSC). The peak-over-threshold analysis of BSS presented in Part 1 proves that erosion dynamics can be modelled as a Poisson process. However, this offers only a partial picture, as it does not provide any insights into the possibility of modelling depositional dynamics as a stochastic process. Indeed, SSC is not necessarily linearly related to the local BSS (see for example Eq. 9 in the main text) and it is not solely influenced by local factors because of advective and dispersive processes occurring at the basin scale, and, hence, must be analyzed independently. Therefore, the novelty of Part 2 lies in demonstrating that spatio-temporal dynamics of SSC can also be modelled as a random process, a concept not addressed in Part 1.

Characterizing both BSS and SSC as Poisson processes is necessary to test the feasibility of implementing a synthetic modelling framework that accounts for erosion and deposition. This highlights the difference and the complementarity of the results and clearly demonstrates that Part 2 is not a mere repetition of Part 1, but rather a fundamental component of our research.

To further substantiate this concept, we modified the introduction of Part 1 as follows:

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waves in shallow tidal systems (Green and Coco, 2014). Instead, deposition, D, is linked to the suspended sediment concentration (SSC). However, SSC is largely affected by advection and dispersion processes at a larger scale and, therefore cannot be solely determined by local resuspension. Consequently, to effectively model bed-level variations, it is essential to accurately describe both BSS and SSC. This contribution focuses on characterizing BSS, while the analysis of SSC is presented in the companion paper (Tognin et al., 2023).

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RC2.2: Secondly, as the core concepts, author state that the peak-over-threshold theory (POT) can be applied to suspended sediment concentration (SSC). In my opinion, this "threshold SSC" lacks physical meaning. Although this concept looks similar to the critical shear stress, the critical shear stress has a clear definition and is linked to the soil property. The SSC, however, is linked linearly to the shear stress from the entrainment formula, and it is also determined by local flow conditions, wind, wave and so on. There are too many elements that can impact the SSC. The benefit of introducing a threshold SSC concept is not clear, and the definition will not be universal. As a conclusion, the methodology of this paper is no longer new after its companion paper, and the fundamental concept of this paper is not well defined. As a result, I recommend the author put more work and thoughts on this second paper.

AR: The peak-over-threshold (POT) analysis is a statistical method used to analyze a timeseries and, if possible, derive a statistical characterization of overthreshold events. In general, the threshold does not have a direct physical meaning.

As an example, in hydrology, the POT is widely adopted to describe rainfall events, which usually are characterized by a Generalized Pareto distribution, considered the most suitable for modelling extreme events. The threshold for rainfall intensity lacks a physical meaning and it is not universal. Indeed, it is identified in each specific site in order to separate high-magnitude events from the background noise.

From this perspective, the BSS analysis may be considered particularly fortunate because the BSS threshold can be linked to the concept of critical shear stress for erosion. Nevertheless, even in this case, the threshold value is not unique and site-specific, because several factors (such as grain size, cohesion, compaction, bio-stabilization, etc) make it extremely variable both in space and time.

As explained in our reply to RC2.1, to set up the modelling framework describing both erosion and deposition, the same analysis must be applied to both BSS and SSC. However, in the case of SSC, the threshold may not have a strict physical meaning. Still, this does not contradict the assumption of the POT analysis. Similarly to the threshold selection reported here for rainfall intensity, the SSC threshold is selected to isolate the intense events from the baseline concentration available in suspension related to pseudo-deterministic tidal oscillations. For sure, this threshold is not universally applicable and may vary, but the sensitivity analysis outlined in the paper demonstrates that the differences are limited when selected within a reasonable range.

To better clarify these concepts, we modified the text as follows:

(line 323) In the POT analysis, the threshold value plays a critical role and its choice deserves careful attention. *As already noted for BSS (D'Alpaos et al., 2023), also SSC is locally influenced by many factors, making the threshold non-universal and highly site-specific. In the case of erosion dynamics, the identification of the threshold with the critical shear stress for erosion seems to be relatively straightforward, offering the advantage of preserving a physical meaning related to the process. Instead, when dealing with SSC, the absence of a clear physical threshold mechanism might complicate the identification of the threshold value.*

Nonetheless, even though a threshold on SSC may lack a physical meaning, the POT analysis can be performed to statistically characterize the bulk effect of morphologically meaningful SSC 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~~, *To this aim, the choice of a threshold value, C_0, has to meet two opposite requirements.* ~~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 pseudo-deterministic, 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.