# Unraveling The Impacts of Meteorological and Anthropogenic Changes on Sediment Fluxes Along an Estuary-Sea Continuum

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# Unraveling the impacts of meteorological and anthropogenic changes on sediment fluxes along an estuary-sea continuum

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## ABSTRACT

Sediment fluxes at the estuary-sea interface strongly impact particle matter exchanges between marine and continental sources along the land-sea continuum. However, human activities drive pressures on estuary physical functioning, hence threatening estuarine habitats and their ecosystem services. There is an increasing societal need to better predict the potential trajectories of estuarine sediment fluxes resulting from natural and anthropogenic pressures, but the concomitance of human-induced and meteorological-induced changes makes the responses ambiguous. Therefore, this study explores a 22-year numerical hindcast, experiencing contrasted meteorological conditions and human-induced morphological changes (i.e., estuary deepening and narrowing), in order to disentangle the relative contributions of meteorological and anthropogenic changes on net sediment fluxes between a macrotidal estuary and its adjacent coastal sea. Our results highlight that intense wave events induce fine sediment (≤100 µm) export to the sea but coarser sediment (≥210 µm) import within the estuary. Remarkably, moderate to large river flows support mud import within the estuary. Over 25 years, the reduction of intense wave and river flow events reduces fine sediment export to the sea. In addition, the estuary morphological changes due to human activities increase fine sediment import within the estuary, shifting the estuary from an exporting to importing system. We propose a conceptualization of mud flux response to river flow and wave forcing, as well as anthropogenic pressures. It provides valuable insights into particle transfers along the land-sea continuum, contributing to a better understanding of estuarine ecosystem trajectories under global changes.

## Introduction

Suspended sediments are vectors of nutrients and pollutants along the land-sea continuum[1]. However in tidal estuaries, at the interface between continental freshwaters and coastal seas, sediment may be trapped by the interaction of tide-induced and density-induced processes leading to the formation of estuarine turbidity maxima (ETM)[2-6]. Such pools of mainly muddy sediment buffer particulate and dissolved matter exchanges between terrigenous and marine sources, may alter the system morphology and thus potentially disturb these extremely productive habitats[7-11].

In situ measurements, remote satellite observations, and numerical simulations have shown that estuary sediment fluxes are driven by the combination of hydro-meteorological forcing, such as tide, waves, wind, and river flow[12-16]. Sediment export to coastal seas is usually associated with wave-induced sediment resuspension, whereas sediment import within estuaries mainly results from tidal and gravitational circulations[14]. Nonetheless, there is no consensus yet on the phasing of the gravitational circulation contribution concerning the hydrological cycle. For instance, Ganju and Schoellhamer[17] observed a density-induced sediment import within the Suisun Bay (CA, USA) during low river flow, whereas Schulz *et al.*[16] observed that it is enhanced during high river flow in the Seine Estuary (France). Measurements carried out by Sommerfield and Wong[18] in the Delaware Estuary (USA) corroborate Schulz *et al.*'s observations, highlighting that the estuary has a large capacity to buffer extreme river flow and suppress the export of suspended sediment to the Delaware Bay. Nevertheless, it remains difficult to relate sediment fluxes to external forcing due to the general concomitance of antagonist meteorological events, such as stormy (i.e., high waves) and wet (i.e., high river flow) events concurrently occurring during North-Atlantic winter seasons.

Net sediment transfers between rivers and seas depend on the estuary hydrological and hydrodynamic regimes, which are modulated by the estuary morphology and the sediment availability[19]. Human activities can drastically change the upstream river supplies (e.g., through dam construction[20]), the local sediment nature (e.g., through dredging activities[21]), and the estuary morphology (e.g., through harbor extension and channelization[22]). Guo *et al.*[23] recently investigated a centennial hydro-morphodynamic evolution of the Changjiang Estuary (China) to highlight the influence of anthropogenic pressures on estuary sediment import-export. More specifically, they observed that a narrower funnel-shaped estuary resulting from intensive human activities induced a shift from ebb to flow dominated estuary, leading to increase sediment import and channel aggradation. Such behavior was observed as well in estuaries following severe channel deepening, shifting systems from normal to hyper-turbid states [24,25]. However, despite human activities (e.g., dredging), some estuaries can keep balanced sediment budgets over hundreds of years, such as the Humber Estuary, UK[26]. Nonetheless, Townend and Whitehead[26] identified that there is a mechanism for the net export of coarse sediment and that fine material can enter and move upstream, driven by secondary circulation and density currents. This fine-grained import was also observed by Sommerfield and Wong[18] and consistent with the conclusions originally put forth by Meade[27].

In addition to anthropogenic pressures, meteorological changes can induce the evolution of estuarine forcing (e.g., river flow and storminess) and can exacerbate drastic perturbations as extreme events[28-31]. Still, it is challenging to disentangle the effects of meteorological and human-induced changes on estuarine sediment transfers over decades because they concomitantly impact the system's functioning. It is however critical for better understanding and predicting particulate transfers along the land-sea continuum in the context of global changes. Therefore, this study aims at investigating the relative contributions of estuarine key forcing on net sediment transfers between a macrotidal estuary and its adjacent coastal sea, for contrasted conditions representative of anthropogenic and meteorological changes.

The analysis is based on a 22-year numerical hindcast of the Seine Estuary (France) comparing two periods with contrasted human-altered morphologies (1990-2000 and 2005-2015, Figure 1). The influence of meteorological changes on sediment transfers is investigated through a global analysis of mean differences over the two periods, but we do not specifically analyze individual extreme events, as already examined for severe tropical storms[32,33]. Although sediment import-export can depend on the occurrence between tidal phasing and meteorological forcing[13], this work focuses on fortnightly tide-averaged fluxes to draw a conceptual pattern of wave-river flow contributions to sediment transfers between estuaries and seas.

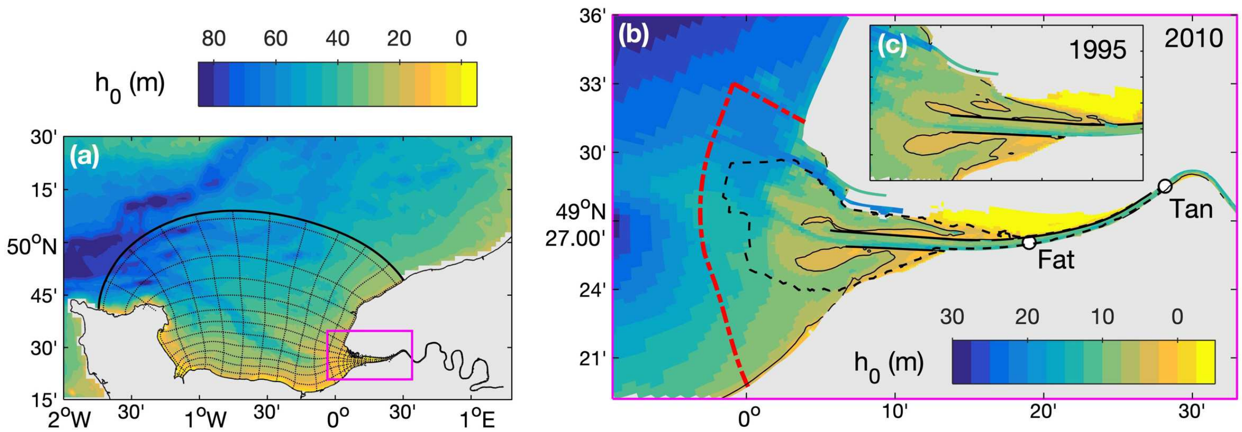


**Figure 1.** Bathymetry $h_0$ of the Seine Estuary, NW France (mean sea level chart datum). (a) Full model domain with every tenth grid cells represented, (b) focus on the lower estuary in 2010, and (c) focus on the estuary mouth in 1995. In panels (b,c), solid black contours represent 5-m isobaths, characterizing intertidal areas. In panel (b), the black dashed contour represents the comparison area between field surveys and numerical simulations, the red dash-dot line represents the estuary-sea boundary where sediment fluxes are computed, and the white circles represent Fatouville and Tancarville locations ('Fat' and 'Tan', respectively).

## Results and discussion

### Changes in forcing and environmental parameters

Changes in meteorological forcing during the last decades are analyzed through the median and extreme values (i.e., 5$^{th}$, 50$^{th}$, and 95$^{th}$ percentiles) over the two investigated periods (i.e., 1990-2000 and 2005-2015), as illustrated in Figure 2. Statistics on the river flow $Q$ are based on the Seine and its tributaries and statistics on the significant wave height $H_s$ are computed at the estuary-sea boundary (red dash-dot line in Figure 1b). River flow and wave forcing present similar trends with an increase of median values ($p_{50}$: +8% and +9%, respectively) and a decrease of the extreme values ($p_{95}$: −18% and −6%, respectively). Such changes do not corroborate our view of climate-induced changes that would increase extreme events and reduce mean river flow[28-30]. However, these forcing conditions are representative of two contrasted meteorological decades and are not directly driven by human-induced changes.

Figure 2(c-e) illustrates mean changes in dominant environmental parameters – as near-bed temperature $T$, salinity $S$, and suspended sediment concentration $SSC$ – within the central salt wedge and ETM areas (i.e., at Fatouville in Figure 1b). The median temperature increased by 1 °C (+8%), whereas the mean temperature only increased by 0.2 °C. These changes are in agreement with observations of global warming in the English Channel[34]. The difference between median and mean values highlights changes in temperature distributions, but it also alerts us on the estimate sensitivity to statistic computations. The median salinity substantially increased as well ($p_{50}$: +3.4 psu, +23%), with a moderate increase of extreme values. These changes mainly result from the density-induced salinity intrusion enhanced with anthropogenic changes (i.e., channel deepening, estuary narrowing), as observed by Grasso and Le Hir[22]. Finally, changes in SSC are even stronger, both in median and extreme values ($p_{50}$: +0.06 kg/m$^3$, +52%; $p_{95}$: +0.26 kg/m$^3$, +72%). As for salinity, such an increase in SSC is mainly associated with estuary deepening and narrowing[22], which increases tide- and density-induced upstream sediment transport and potentially shifts systems toward hyper-turbid states[10,35,36].

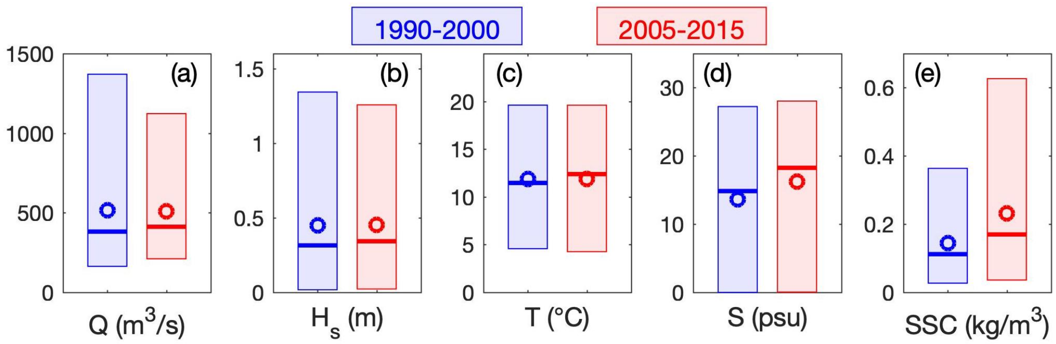


**Figure 2.** Comparison of characteristic environmental parameters between 1990-2000 (blue) and 2005-2015 (red): (a) river flow $Q$, (b) significant wave height $H_s$ at the estuary-sea boundary (red dash-dot line in Figure 1b), (c-e) near-bed temperature $T$, salinity $S$ and $SSC$, respectively, at Fatouville ('Fat' in Figure 1b). Boxes range from $5^{th}$ to $95^{th}$ percentiles; thick lines and circles represent median and mean values, respectively.

### Comparison of annual sediment fluxes between 1990-2000 and 2005-2015

At the annual time scale, total sediment fluxes present contrasted behaviors along the two periods (Figure 3), with a net sediment export in 1990-2000 ($-1.55\times10^9$ kg/year) and a net import in 2005-2015 ($+1.72\times10^9$ kg/year). These changes mainly result from the mud dynamics, representing 75% and 84% of the total fluxes in 1990-2000 and 2005-2015, respectively. The rest of the changes are attributed to very fine and fine sands, as coarser sediments (i.e., coarse sand and gravel) contribute to less than 3% of the total fluxes. Note that these coarse sediments ($d > 800$ µm) are mainly imported within the estuary, in contrast with the Humber Estuary where Townend and Whitehead[26] identified a net export of coarse sediment. Nonetheless, fine sand (210 µm) is exported from the Seine Estuary during the two periods.

The shift from total sediment export to import can result from bathymetric changes (estuary deepening and narrowing; Figure 1b and c), as observed by Guo *et al.*[23]. Nonetheless, it may also result from changes in river flow and wave forcing (Figure 2a and b). Thus, the potential explanatory factors are further investigated in the following section.

### Sediment flux response to meteorological forcing

To unravel the relative contributions of meteorological forcing (i.e., river flow and wave conditions) on sediment transfers, sediment fluxes are computed at a shorter time scale. We used a fortnightly sliding window to average sediment fluxes, river flow, and wave forcing. The $95^{th}$ percentiles of river flow and significant wave height are used to represent the forcing parameters over the fortnightly periods because they showed greater correlations with sediment fluxes rather than median or mean values. Net fluxes are analyzed through a $Q$-$H_s$ diagram for the dominant sediment classes (i.e., mud, very fine and fine sands) and the two periods (Figure 4). Sediment fluxes are averaged over $Q$ and $H_s$ bins with a spacing of 100 $m^3/s$ and 0.1 m, respectively. The corresponding occurrences (Figure 4c and h) illustrate that the 1990-2000 period experienced stronger conditions both in river flow and wave forcing than the 2005-20015 period (as observed in Figure 2a and b).

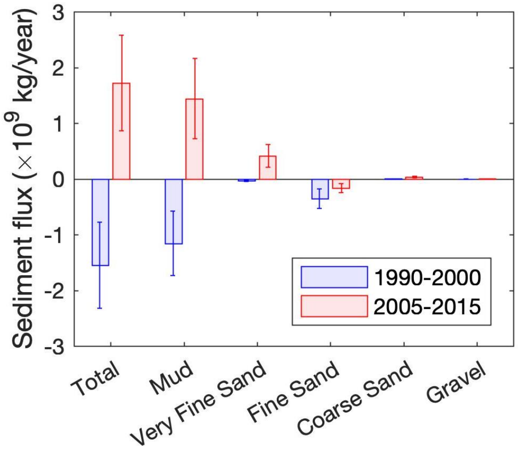


**Figure 3.** Comparison of yearly-averaged sediment fluxes at the estuary-sea boundary (red dash-dot line in Figure 1b) between 1990-2000 (blue) and 2005-2015 (red), for each sediment class and the sum (Total). Positive fluxes are directed up-estuary (i.e., import) and negative fluxes are directed seaward (i.e., export). Brackets represent inter-annual standard deviations.

In 1990-2000, the mud fluxes present a clear pattern with export increasing with wave conditions (Figure 4a), resulting from the increase sediment resuspension[13,14]. Interestingly, the mud export decreases when river flow increases and even turns out to import for moderate to large river discharges (i.e., from 400 $m^3/s$ to 1500 $m^3/s$). This is characteristic of the enhanced gravitational circulation observed by Sommerfield and Wong[18] and Schulz *et al.*[16]. Nevertheless, mud fluxes can export again for high river discharges (i.e., >1500 $m^3/s$) when the density-induced import at the bottom is not sufficiently strong to compensate for the large sediment export at the surface. In addition, it is remarkable to observe that sands present opposite behaviors depending on size. There is a tendency to export very fine sand (100 µm), similarly to mud but associated with weaker fluxes, but import fine sand (210 µm), when wave conditions are the strongest (Figure 4b and c). Such behaviors result from different erodibility thresholds and suspension durations associated with subtidal currents (i.e., ebb-flow asymmetries in both current intensity and duration; Nidzieko[37]). These results point out that different sand classes need to be considered for properly simulating the diversity of natural sand fluxes and the resulting morphological evolutions.

Sediment fluxes substantially changed in 2005-2015 with more import of mud and very fine sand, but less import of fine sand (Figure 4e, f, and g). Such differences can be related to changes in both meteorological and anthropogenic pressures, which are specifically investigated in the following section.

## Untangling the influences of meteorological and anthropogenic changes on mud fluxes

Mud fluxes represent more than 75% of the total sediment fluxes between the estuary and the coastal sea and these very fine particles largely contribute to biogeochemical processes along the land-sea continuum (e.g., adsorption and desorption mechanisms). Therefore, the present section focuses on the sensitivity of mud transfers to meteorological and anthropogenic changes. Over the 1990-2000 period, results highlighted that mud export increases with wave forcing, but moderate to large river discharges support mud import (Figure 4a). This pattern can be schematized through the $Q$-$H_s$ diagram in Figure 5. Changes in meteorological conditions between 1990-2000 and 2005-2015 are observed throughout changes in $Q$-$H_s$ occurrences (Figure 4d and e). For instance, the milder conditions experienced in 2005-2015 limit the mud export occurring for large river flow and wave events, and thus favor mud import within the estuary.

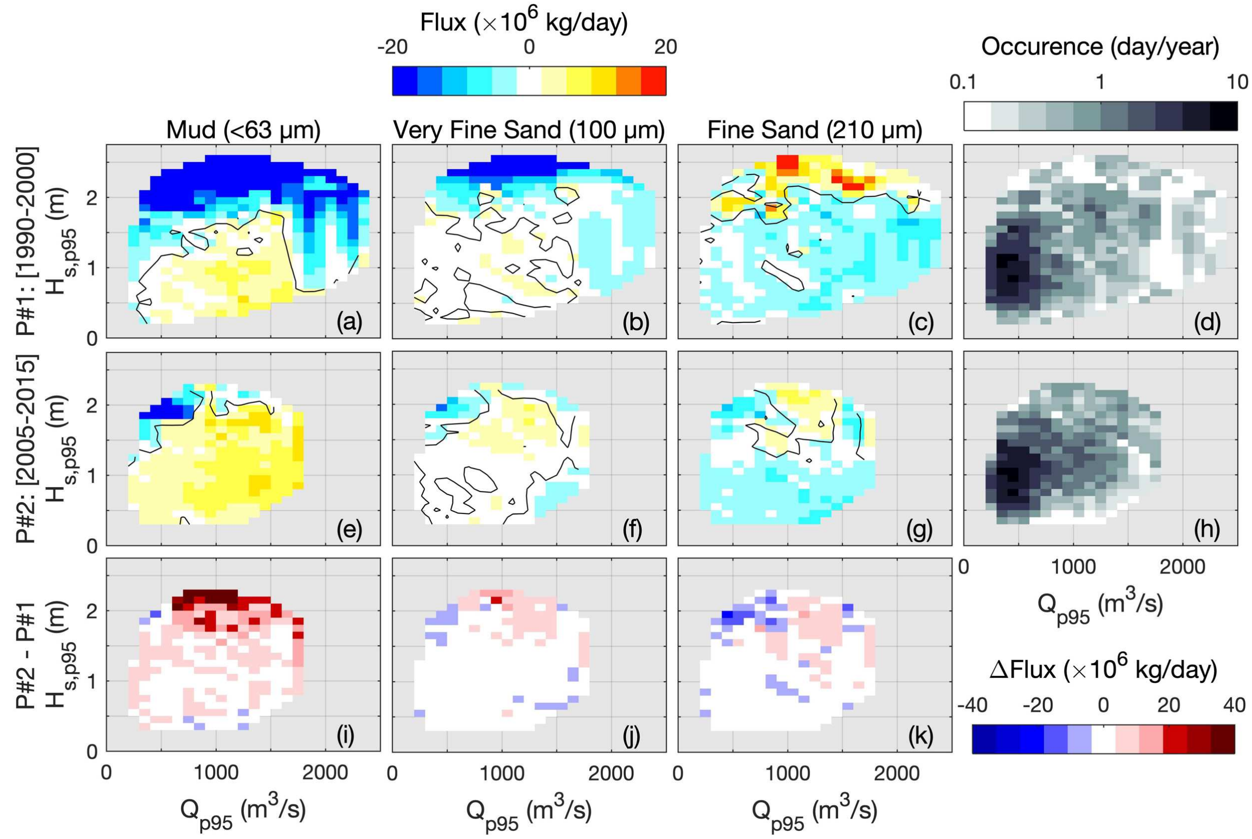


**Figure 4.** Comparison of fortnightly-averaged sediment fluxes at the estuary-sea boundary (red dash-dot line in Figure 1b) between (top panels) the first period P#1 [1990-2000] and (middle panels) the 2nd period P#2 [2005-2015], in function of the fortnightly-95th percentiles of river flow ($Q_{p95}$) and significant wave height ($H_{s,p95}$) forcing, for the three dominant sediment classes (a,e) mud, (b,f) very fine sand and (c,g) fine sand. Positive fluxes are directed up-estuary (i.e., import) and negative fluxes are directed seaward (i.e., export). Bottom panels (i-k) represent the flux differences $\Delta Flux$ between P#2 and P#1. Panels d and h represent the occurrence of $Q$-$H_s$ forcing in 1990-2000 and 2005-2015, respectively.

Within the same $Q$ and $H_s$ ranges, i.e., for the same meteorological conditions, the mud flux pattern changes between the two periods (Figure 4a and e). For instance, the isoline delimiting mud import-export at $Q = 1000$ m$^3$/s is close to $H_s = 1.5$ m in 1990-2000 and rises around $H_s = 2$ m in 2005-2015. These changes in mud flux contours are illustrated through the positive flux difference in Figure 4i (i.e., 2nd period minus 1st period), characterizing more import (or less export) of mud in 2005-2015 than in 1990-2000. Such a behavior can be attributed to human-induced changes, which impacted the system functioning via the estuary deepening and narrowing, as observed by Guo *et al.*[23]. Thus, anthropogenic pressures ($P_{ant}$) would affect the mud pattern schematized in Figure 5 by shifting the $Q$-$H_s$ diagram isolines. In other words, the mud fluxes would respond differently to similar meteorological forcing due to human-induced morphological changes.

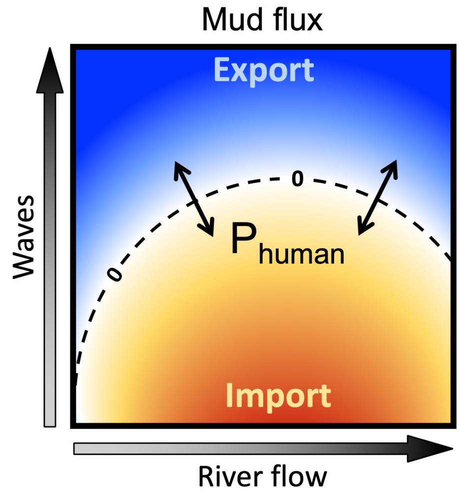


**Figure 5.** Schematic of mud fluxes in function of river flow and wave forcing. Warm colors represent up-estuary fluxes (i.e., import) and cool colors represent seaward fluxes (i.e., export). $P_{human}$ denotes the human-induced pressures impacting the diagram isolines.

## Conclusions

A 22-year numerical hindcast (1990-2000 and 2005-2015) of the Seine Estuary sediment dynamics has been analyzed to investigate the relative contributions of meteorological and anthropogenic changes on sediment import-export between the estuary and its adjacent coastal sea. From 1990-2000 to 2005-2015, human pressures induced substantial morphological changes leading to a deeper and narrower estuary; meteorological conditions (i.e., river flow and wave forcing) changed with larger median conditions but smaller extreme events. These changes resulted in increasing salinity intrusion and SSC within the estuary.

Net sediment fluxes at the estuary-sea boundary are related to river flow and wave forcing. Increasing wave conditions enhance the export of very fine sediments (≤100 µm) and import of coarser sediments (≥210 µm). Remarkably, moderate to large river flow conditions support very fine sediment import. The reduction of extreme conditions in the most recent period (2005-2015) reduces mud export to the coastal sea. In addition, human-induced morphological changes perturbated the estuary sediment dynamics and enhanced mud import. Consequently, in less than 25 years, meteorological and anthropogenic changes shifted the estuary from an exporting to an importing system.

The mud flux response to meteorological and anthropogenic changes is schematized through a "river flow-wave diagram" where meteorological conditions determine the estuary forcing, and human pressures affect the system's functioning. Such a schematic has to be challenged over other tidal estuaries. Nevertheless, it represents an excellent tool to investigate potential trajectories in estuary sediment import-export, directly impacting other compartments of the estuarine ecosystem (e.g., biogeochemistry, biology, and ecology).

## Methods

### Study area

The Seine Estuary (NW France) is a semidiurnal macrotidal system with a tidal range varying from 3 to 8 m at the estuary mouth. It is one of the largest estuaries on the Northwestern European continental shelf and stretches from the Bay of Seine open to the English Channel to the weir of Poses upstream, the tidal influence limit (Figure 1). The Seine River flow ranges from 100 to

2300 $m^3/s$ with a mean annual flow around 450 $m^3/s$ and a mean sediment supply around $0.7\times10^9$ kg/year[16,38].

The funnel-shaped estuary is exposed to western winds so that the intertidal regions at the mouth are subject to erosion under the combined effect of waves and currents[39,40]. Waves enter the bay from the northwest with typical significant wave heights of 0.5 m and peaks of more than 3.5 m in front of the estuary mouth. It is characterized by the presence of an ETM that has a pronounced control on the sedimentation patterns of subtidal areas and intertidal mudflats from the estuary mouth up to the upstream freshwater limit, which is few kilometers upstream of Tancarville ('Tan' in Figure 1b)[6,41-43].

During the last century, the Seine Estuary has been vastly altered by human activity[41]. As a result, it was changed from a dominantly natural system to a human-controlled system[22]. In the last decades, i.e., from the 1990s to the 2010s, extensive engineering works induced a deepening and narrowing of the lower estuary. It mainly resulted from the large extension of the Grand Port Maritime du Havre (GPMH) at the estuary mouth (named as "*Port 2000*") and the main channel deepening and dredging to access the Grand Port Maritime de Rouen (GPMR) approximately 120 km upstream of the mouth (Figure 1b and c).

## Numerical model set-up

The ARES hindcast simulations are based on the process-based hydrodynamic and sediment dynamic model developed and validated by Grasso *et al.*[6]. This model has been used by Schulz *et al.*[16] to investigate sediment response to idealized hydro-meteorological forcing and by Grasso and Le Hir[22] to investigate the influence of contrasted morphologies on ETM dynamics. The model set-up is extensively detailed in the above-mentioned studies; nonetheless, the main model characteristics are reminded hereafter.

A non-orthogonal curvilinear mesh extends from the Bay of the Seine to the weir at Poses (Figure 1a) with a resolution around $30\times100$ m² in the lower estuary (i.e., from the mouth to Tancarville; Figure 1b), corresponding to the main ETM excursion area. The hydrodynamic model is based on the hydrostatic model MARS3D[44] discretized with 10 equidistant sigma layers. The circulation model is forced by the main tidal components at the sea boundary (CST France, SHOM), the wind stresses and pressure gradients provided by the meteorological ARPEGE model (Meteo-France), and the measured daily discharges from the Seine River and its tributaries. Waves are simulated from the WAVEWATCH III® model[45] based on a series of embedded computational grids, from a large-scale model of the Atlantic Ocean down to a local model with the same resolution as the circulation model.

The hydrodynamic model is coupled with the MUSTANG sediment model for cohesive and non-cohesive mixtures[46-48]. This multi-layer model accounts for the spatial and temporal variations of sand and mud content in the sediment, as well as for consolidation processes, and resolves advection/diffusion equations for different classes of particles in the water column. This model considers five classes of sediment representative of the Seine Estuary sediment modes[49]: one gravel (diameter $d = 5$ mm), three sands (coarse: $d = 800$ µm, fine: $d = 210$ µm, and very fine: $d = 100$ µm) and one mud. Sediment is initially distributed over a 1-m thick bed according to a realistic bed coverage[49]. The mud advection is calculated using a complete 3D scheme with a variable settling velocity accounting for flocculation processes[50]. The riverine sediment supplies (defined as mud) are imposed at the river flow locations and vary with the freshwater discharges[38]. In addition, the model simulates the dredging and dumping activities related to the maintenance strategy of the GPMH and GPMR access channels[6].

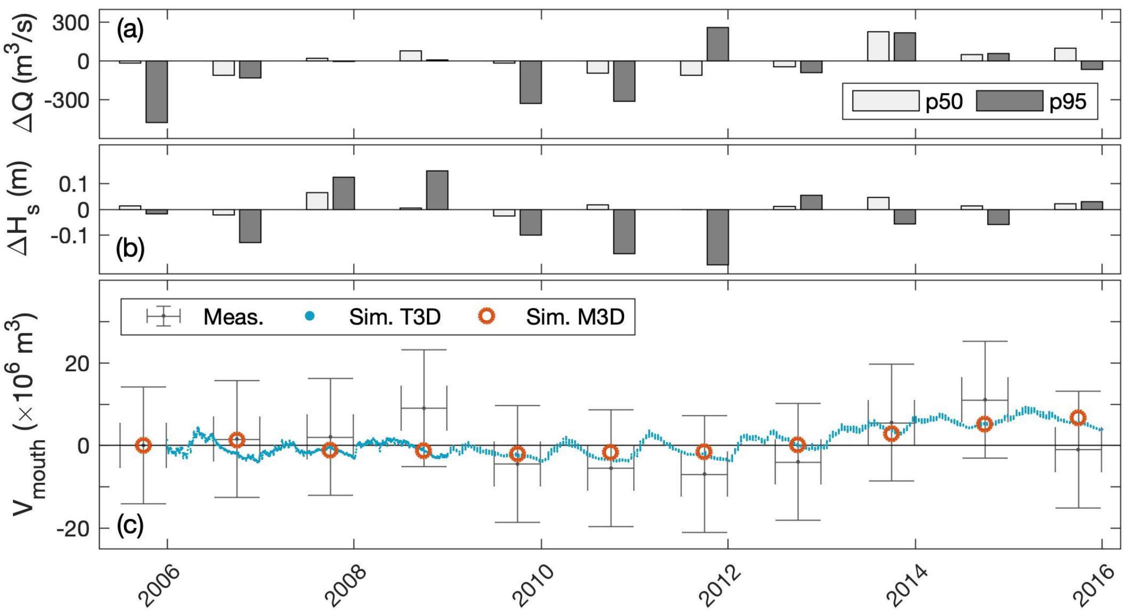


**Figure 6.** Annual anomalies from 2005 to 2015 of 50th (white) and 95th (gray) percentiles in (a) river flow $\Delta Q$ and (b) significant wave height $\Delta H_s$. (c) Sediment volume $V_{mouth}$ in the estuary mouth (black dashed contour in Figure 1b), measured from bathymetric surveys (gray brackets), and simulated from the morphodynamic model TELEMAC3D 'T3D' from ARTELIA (blue dots) and the morphostatic model MARS3D 'M3D' used in this study (brown circles).

Hindcast simulations over the 1990-2000 and 2005-2015 periods were run through independent years following a morphostatic approach (i.e., no morphodynamic coupling), which is relevant for analyzing sediment dynamics at time scales of few years (<5-10 years) when morphological changes remain relatively small to hydrodynamic processes. The 1995 and 2010 bathymetries were used to simulate the 1990-2000 and 2005-2015 hindcast, respectively. Each year was run twice to consider a 1-year spin-up period before analyzing the half-hourly outputs[6,16,22]. Moreover, simulations ran from October to October to respect annual hydrological cycles and not to cut down wet and dry periods.

## Validation of sediment budgets and fluxes

Simulations of sediment transfers between estuaries and coastal seas are prone to large uncertainties associated with both validation dataset and numerical model parameterization[51]. Grasso *et al.*[6] validated the Seine Estuary model in terms of hydrodynamics, salinity, and SSC from tidal to annual time scales at different stations within the estuary. However, Ganju and Schoellhamer[17] recommend using bathymetric surveys for evaluating the capabilities of a model to properly reproduce sediment budgets and fluxes. Therefore, the model simulations were compared to annual bathymetric changes measured in the lower estuary by the GPMR (black dashed contour in Figure 1b) during the second period (2005-2015, Figure 6c), with regard to annual anomalies of river flow and wave forcing (Figure 6a and b). The large uncertainties associated with bathymetric changes are due to both the vertical uncertainties of bathymetric surveys (±0.1 m) and the timeframe to cover the entire estuary mouth (~6 months). Thus, these measurements have to be considered as a qualitative view of sediment volume changes in the estuary mouth. In addition, these large uncertainties inform us that: (i) errors on "ground-truth" measurements can be very large; and (ii) field measurements are still needed to more accurately assess estuarine morphological changes.

The present simulations result from morphostatic modeling, so no bathymetric changes in the hydrodynamic model are computed. However, the bed sediment thickness can change with erosion, deposition, and consolidation processes. Hence, sediment volume changes can be computed from differences in bed thickness over the same area as the GPMR bathymetric surveys. While the simulations do not exactly match the measurements, they prove to be in a good capacity to reproduce the main volume changes observed in the estuary mouth over 11 years.

To extend the validation, the simulated volume changes from our MARS3D 'M3D' model are compared to volume changes resulting from morphodynamic modeling carried out by ARTELIA, based on the finite element TELEMAC3D 'T3D' model[52]. T3D continuously simulated ten years, starting from the 2006 bathymetry and with bathymetric adjustment via morphodynamics coupling, whereas M3D simulated 11 independent years considering the 2010 bathymetry. The interest in such a model intercomparison is twofold: (i) both models present very similar results although hydrodynamics and sediment dynamics are differently parameterized and resolved, which provides confidence in the simulation reliability; and (ii) the morphostatic modeling 'M3D' used in this study is shown to be relevant for investigating sediment volume changes up to 5 years around a given bathymetry.

The capacity to properly simulate changes in sediment volumes provides confidence in the ability to simulate sediment budgets and fluxes. However, changes in sediment volumes do not exactly correspond to changes in sediment mass. For instance, consolidation processes induce a decrease in sediment volume (i.e., sediment compaction), but the sediment mass does not change[47]. Moreover, changes in sediment porosity due to changes in mud-sand mixtures affect the bed volume and not the mass[53]. Thus, while bathymetric surveys are limited to analyze sediment budgets and fluxes, simulations provide adapted knowledge as changes in sediment mass are explicitly computed.

## Sediment flux computation

The net sediment fluxes are computed at the estuary-sea boundary (red dash-dot line in Figure 1b), in agreement with the 'offshore' boundary used by Schulz *et al.*[16]. It represents a suitable limit beyond which seaside morphological changes are small compared to estuarine changes[16,22] and properly characterizing sediment transfers between the estuary and the bay. The fluxes $F_{i,\Delta t}$ during a period $\Delta t$ are computed for each sediment class $i$ as the difference in sediment mass $M_i$ (i.e., sediment budget) in the lower estuary area, which is defined between the estuary-sea boundary and Tancarville (Figure 1b), and considering the incoming sediment fluxes at Tancarville $F_{i,Tan}$:

$$F_{i,\Delta t} = \Delta M_{i,\Delta t} + \int_0^{\Delta t} F_{i,Tan} dt \quad (1)$$

with a positive flux oriented up-estuary (i.e., import) and a negative flux oriented seaward (i.e., export). $F_{i,Tan}$ is integrated online at every time step across the channel section[16] and $M_i$ is the sum of sediment masses in both water and bed compartments.

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## Author contributions
F.G., E.B., and R.V. jointly conducted the study. F.G. developed the idea for the study and performed the supervision. E.B. carried out the 22-year numerical hindcast used in this study. F.G. wrote the main part of the manuscript and R.V. provided substantial contributions. All authors read and approved the final manuscript.

## Competing interests
The authors declare no competing interests.

## Additional information
The ARES hindcast dataset used in this study is available via the following link:
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