https://doi.org/10.5194/nhess-2023-165
Preprint. Discussion started: 29 November 2023

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The contribution of diminishing river sand loads to beach erosion worldwide

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Journal: Natural Hazards and Earth System Sciences (NHESS) https://natural-hazards-and-earth-system-sciences.net/

https://doi.org/10.5194/nhess-2023-165
Preprint. Discussion started: 29 November 2023

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Abstract

The erosion of sandy beaches can have a profound impact on human activities and ecosystems, especially on developed coasts. The scientific community has, to date, primarily focused on the potential impact of changes in sea level and waves on sandy beaches. While being abundantly recognized at local to regional scales in numerous studies over the last two decades, the contribution of diminishing fluvial sediment supply to sandy beach erosion at the global scale is still to be investigated. Here, we present a model of sediment budget computed from the balance between land riverine input and coastal transport. It results in a global picture of sand pathway from land to sea. Our analysis demonstrates the massive impact of the thousands of river dams on beach erosion worldwide. Sand can be mobilized with wave-induced longshore transport over large distances, in general toward the equator, within sediment cells, often at distance from the outlets.

1 Introduction

Coastal zones are dynamic areas at the interface between land and sea. They concentrate a large part of the world's population (Maul and Duedall, 2019) as well as rich and rare ecosystems (Barbier et al., 2011; Dada et al., 2020). However, human activities severely affect the fragile equilibrium of these areas, notably by weakening ecological sustainability while increasing the exposure of populations to natural hazards (Oppenheimer et al., 2019). Luijendijk et al. (2018) showed, from satellite data, that about 31% of the world's ice-free coasts are fronted by sandy beaches, 24% of which are eroding at a rate exceeding 0.5 m/y. Where beach erosion prevails, social-ecological systems can be severely destabilized.

Sandy shoreline retreat is driven by regional and global oceanic factors such as sea-level rise and changes in wave regimes as well as local ambient processes, including fluvial sediment inputs (Vousdoukas et al. 2020; Bruun, 1962; Ranasinghe, 2021; Bamunawala et al., 2020, 2021; Warwick et al., 2022, 2023). Locally, the cross-shore temporal evolution of the coastline ΔX_{cross} can be expressed as: $\Delta X_{cross}=f(RSLR, Waves_{cross}, \Delta Q, Q_{anthrop})$, where *RSLR* is the relative sea-level rise, $Q_{anthrop}$ the amount of sediment added or removed from the beach by direct human actions (i.e., beach nourishments, sand extractions, etc...). $Waves_{cross}$ is the equilibrium term between wave energy and cross-shore shoreline location (Yates et al., 2011; Splinter et al., 2014; Roelvink et al., 2020). $\Delta Q=Q_{river}+Q_{wave,in}-Q_{wave,out}$ is the local coastal sediment budget under natural processes (even though some of these natural processes are altered by human influences such as deep-water harbours, dikes and jetties) between sediment inputs from land Q_{river}, wave-induced longshore transport input $Q_{wave,in}$ and loss $Q_{wave,out}$. A sediment imbalance in ΔQ drives a local evolution, with a negative value signifying a sediment deficit with potential shoreline retreat and a positive value an accumulation of sediment with shoreline progradation (Figure 1). Whereas the contributions of RSLR, $Waves_{cross}$, and $Q_{anthrop}$ to shoreline change have, to date, attracted most of the attention of the coastal scientific community, the present study focusses on the relatively overlooked land-sea sediment pathway contribution ΔQ.

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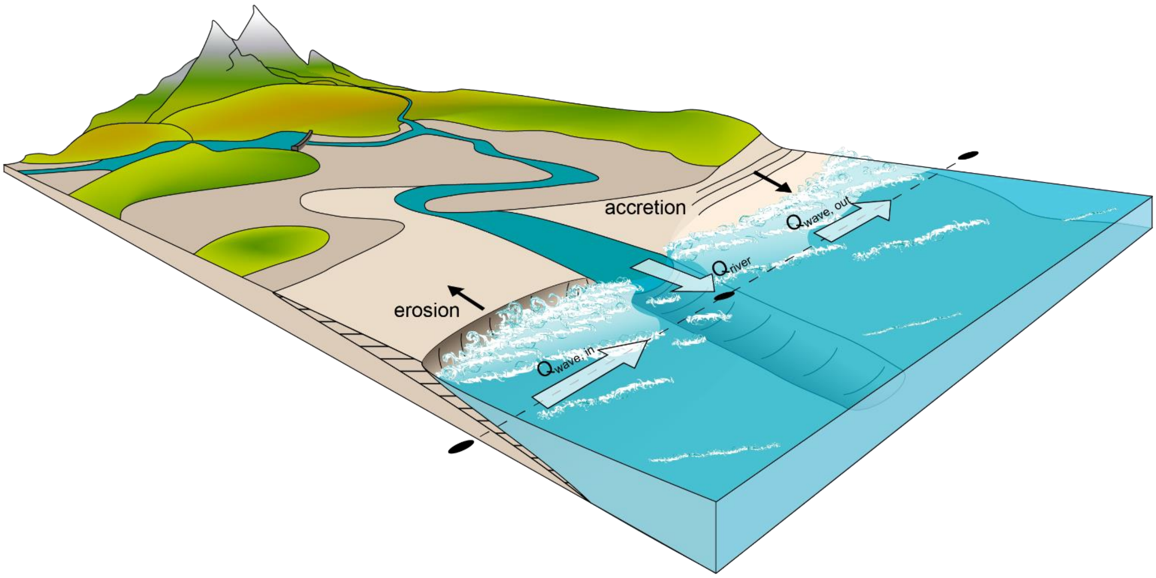

Figure 1. *Schematic representation of the river-wave sand transport. Diagram of the sand budget at the coast for one coastal cell (centred on one solid black ellipse). The sand supplied by the river (Q_{river}) is re-distributed by wave-induced longshore transport ($Q_{wave,in}$). Sand is lost or gained at any point through longshore transport ($Q_{wave,out}$). A positive or negative budget is indicative of an accreted or depleted sediment budget at the coast, respectively.*

On a global basis, there is a permanent flow of sediment from watersheds to the ocean, delivered by rivers (e.g., Syvitski and Milliman, 2007; Miliman and Farnsworth, 2011; Owens, 2020; Syvitski et al., 2022a). While the finer sediment particles, including silt and clay, reaching the sea are generally trapped in estuaries, deltas and low-energy embayments or transported far offshore, bedload transported from river mouths to adjacent coasts is the main source of terrigenous sediment supply to beaches. Of the estimated 7.5 Gt/yr of current sediment supplied by rivers to the global ocean (15.5 Gt/yr in 1950), 7.2 Gt/yr are suspended sediments (14.5 Gt/yr in 1950) while bedload constituted only 0.3 Gt/yr (1.0 Gt/yr in 1950) (Syvitski et al., 2022a). Based on a simple predictive model, Cohen et al. (2022) indicate a median proportion of bedload to total terrigenous material of about 15%, with a median particle size of 0.3 mm, with a fining trend with river size. If anything, this relatively modest figure for bedload, which concerns both sand and gravel, places into a sharp perspective the relatively low global availability of fresh fluvial bedload supply to maintain the world's beaches. Sand is described as being transported to the coast as bedload. Literature shows that suspended sand transport is generally equal to or greater than bedload for littoral grains (Camenen and Larson, 2005). We may reasonably assume that much of the load actually transported alongshore concerns sand because of the propensity for gravel to accumulate in storm-dominated high-latitude beaches close to river and glacial-till sources. Sediment supply from coastal erosion, erosion or reworking of sand-rich coastal deposits such as beach-ridges and dunes, as well as poorly consolidated soft-rock coasts, has been estimated at > 0.5 Gt (Syvitski et al., 2022a; Regard et al. 2022) - undifferentiated mud and coarser sediment- and is commonly a source of gravel as much as sand. The production of sand from offshore carbonate factories (Laugié et al., 2019) is considered highly variable, with some coasts being richly supplied and others having little or no carbonate supplies (Anthony and Aagaard, 2020). Offshore sources potentially involve the reworking of relict shelf-deposited terrigenous sediments or abandoned river-delta lobes subsisting on the shoreface. The longshore transport of sand, whatever the source, is of paramount importance to the stability of beaches. Additionally, the longshore transport system can also redistribute shoreface-derived carbonate and detrital (mainly quartz) sand as well as sand inputs from coastal erosion or reworking of sand-rich coastal deposits such as beach-ridges and dunes.

Wave-driven longshore sediment transport can conceptually be viewed in terms of a sediment cell with a budget involving inputs and outputs, the latter of which can be redirected towards the building of dunes or beach ridges. Some sand can be permanently lost into submarine canyons (Mazières et al., 2014), while severe storms can lead to prolonged and even permanent offshore losses (Gillet et al., 2008; Anthony and Aagaard, 2020). A sediment cell is an area of coastline where sand generally flows alongshore in a single direction (e.g. see Vitousek et al., 2017; Van Rijn, 2011). The balance of sand available for beaches at any time is the amount of sand entering the sediment cell minus the amount leaving (Figure 1). If this sand balance is altered, the beach sand budget and morphology will change. These aspects can be viewed in terms of alongshore sediment connectivity (Pearson et al., 2020) and its potential perturbation by engineering works, for instance (Cowell et al., 2003; Anthony, in press).

The proliferation of river management schemes for various purposes (Best, 2019), notably the construction of dams for hydropower generation and irrigation, and dikes and peripheral works for navigation and flood control, is increasingly leading to river fragmentation (Grill et al., 2019). Already perturbed river sediment fluxes are further relayed by massive sand extractions in river beds (Peduzzi, 2014; UNEP, 2019). Along the coast, sediment fluxes are increasingly impacted by engineering structures to control erosion and with the development of harbours (Pilkey and Cooper, 2014; Abessolo et al., 2021; Anthony, in press), further depriving beaches distant from river outlets of an essential supply of sand (Syvitski et al., 2003; Wiegel, 1996; Milliman and Farnsworth, 2011; Yang et al., 2011). At the same time, the rate of sea-level rise is projected to accelerate over the 21st century (Oppenheimer et al., 2019; Fox-Kemper et al 2021), compounding the current problems.

While coastal sand pathways and associated sediment cells have been abundantly addressed at local and regional scales (Abam, 1999; Anthony et al., 2019; Bamunawala et al., 2021; Warrick et al., 2020), they have not received attention from the coastal engineering/scientific community at the global scale. There is, however, a need for a comprehensive consideration of global sand availability to coasts and its alongshore redistribution pathways if we are to find ways of effectively anticipating and eventually mitigating the effects of climate change on beaches as well as the consequences of increasing human interventions on alongshore sand mobility. Recent developments in remote sensing (Benveniste, et al., 2019; Melet et al., 2020) provide scope for the generation of global databases, for instance, on the distribution of sandy beaches (Luijendijk et al., 2018), sub-aerial beach slopes (Vos et al., 2020), nearshore slopes (Athanasiou et al., 2019), and shoreline change (Mentaschi et al., 2018; Luijendijk et al., 2018). However, while being part of the way forward to improve science-based coastal management strategies, these environmental databases need to be carefully considered in the light of realistic scenarios and models. The purely data-derived information in these databases needs to be carefully used, while considering physical processes as well. For a holistic consideration, it is necessary to gain insight on how the combination of terrigenous sand supply from rivers, and coastal redistribution of this supply, link with sandy beach evolution at the global scale. With that goal, we introduce here an integrated sand pathway model and

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quantify the impact of river-basin changes on modern-era coastal sand budgets often far from the rivermouth and the observed retreat affecting nearly a quarter of the world's sandy beaches.

2 Data and Methods

2.1 The global sand pathway model

A numerical 'along-coast' sand transport model has been developed and implemented on the world's coastline segmented into 0.5° alongshore cells, applied in a stationary mode (i.e. no time step). The terrigenous sand budget of each of the 11,161 coastal cells is calculated considering the sediment conservation equation 1 (Figure 1) for either side (alongshore) of the cells and from the shoreline to the depth of closure (cross-shore, see Hallermeier, 1978; Bergsma and Almar, 2020). The source term Q_{river} corresponds to the bedload discharge by rivers (1.0 Gt/yr in 1950, 0.3 Gt/yr of bedload in the present period, see Miliman and Farnsworth, 2011 and Syvitski et al., 2022a), of which only a fraction is sand (including gravel but discarding mud). The wave-induced longshore sand transport, the predominant sand transport mode along open, wave-exposed coasts, is represented by Q_{wave} (Kamphuis, 1991). This transport occurs mostly in the surf zone which generally extends offshore for tens of metres to a couple of hundreds of metres. Each of these sediment fluxes relies on different physical mechanisms and thus requires a large amount of data to be estimated. Here, Q_{river} is calculated at each coastal cell from river watershed mean inputs, in this case for the years 1980-2010, from a calibrated erosion law (BQART or Maffre's formulaes, cf. Sect 2.3) depending on the catchment area, mean annual catchment discharge, average temperature and local slope (Syvitski and Milliman, 2007; Maffre et al. 2018). To verify the soundness of this calculation, we compared our estimate to Milliman and Farnsworth's (2011) database, obtaining a good agreement (Supplementary Section S1, Figure S1). Q_{wave} is calculated from climatological ocean data (over the 1993-2015 period) such as wave height, wave period, and wave orientation relative to the coast (Kamphuis, 1991, see Sect 2.4 for a sensitivity analysis on the choice of the formulation).

This model produces patterns in coastal sand accumulation and removal, i.e. accreted or depleted volumes. We do not go on to predict sandy morphological change, i.e., coastal advance or retreat, strictly speaking, because conversion of the calculated accumulation/removal volumes into morphological change would require taking into account an additional level of complexity due to accommodation space modulated by relative sea-level changes (e.g. sea-level rise, subsidence affecting coastal bathymetries that still remains to be mapped adequately at the global scale) and morphodynamic considerations (e.g., beach profile evolution, dune accretion), which entail uncertainties not relevant to the specific question addressed here. The ability of our sand pathway model, leading to coastal sediment imbalance, and potentially to shoreline migration, is tested against shoreline change observations by Luijendijk et al. (2018).

2.2 Global coastal cells

For the coastline grid points, we use the Global Self-consistent Hierarchical High-resolution Geography Database (GSHHG version 2.3.6 August 17, 2016; Wessel and Smith, 1996). The GSHHG coastline is further segmented into coarser points with a 0.5° alongshore (~50-km) resolution and called cells (Almar et al., 2021). Locations at latitudes above 50° north and south were excluded as they correspond to areas such as Patagonia or Northern Canada where the model fails to properly represent sand transport, probably due to the multitude of closely interspaced islands. Also ERAInterim wave model struggles with ice caps.

2.3 River sediment supply

2.3.1 BQART

The annual river sediment discharge, represented by the variable Q_{river}, was calculated over the 1979-2015 period from river watershed coastal points and interpolated at each coastal cell using the widely used BQART formula (Syvitski and Milliman, 2007, see Equation 3). We used it for every watershed connected to the ocean, as defined in the HydroBASIN database (Lehner et al., 2013). Regarding the size of watersheds for which BQART is valid, recent work indicates that BQART may not be applicable to small watersheds more exposed to singular behavior such as extremes (Warwick et al., 2022, 2023). Of note, Syvitski et al. (2022b) indicate that small basins contribute only very little fluvial sediments. In the HydroBASIN database, small streams that drain directly to the coast are aggregated into larger entities of the order of 100 km^2 (max 500 km^2). In the absence of a better solution, we applied BQART on these surfaces.

$$Q_{river} = \omega B Q^{0.31} A^{0.5} R \times \max(T,2) \tag{3}$$

where ω = 0.0006 (Syvitski and Milliman, 2007), Q_{river} is the sand river discharge in *Mt/year*, T is the average ambient temperature (°C), Q is the liquid river discharge (km^3/*year*), A is the drainage area of the catchment (km^2) and R is the relief (i.e. the difference in elevation from highest catchment point and its outlet, in *km*). In addition, $B = IL(1-Te)E_H$ accounts for geological as well as human factors (Syvitski and Milliman, 2007). In the formulation of B, I is a modulation from glacier erosion: $I = 1+0.09A_g$ where A_g is the percentage area covered by glaciers. L is a lithological factor usually in the range of 0.5 (low erodibility lithology) to 3 (high erodibility lithology). Te is the fraction of potential sediment retention in plains, lakes, whether natural or anthropogenic – i.e. dams); it ranges between 0 and 1, with 1 representing complete retention. This parameter is poorly constrained. Due to missing regional information, here the same value was used for all the catchments and corresponds to a worldwide mean of 0.2 (Syvitski and Milliman, 2007). Last, E_H is an anthropic factor, and can have one of three possible values (Syvitski and Milliman, 2007) : E_H = 0.5 for areas with conservative human footprints (density < 200 *inh./km*^{2}, and gross domestic product per capita> 15000 \$/*yr*) ; E_H = 2 for areas with high human footprints (density > 200 *inh./km*^{2}, and gross domestic product per capita< 1000 \$/*yr*); or E_H = 1, for areas with low human footprints.

In order to calculate Q_{river} at the coast for all catchments with the BQART formula, we extracted the values of Q, A, R, T, A_g, population density, and gross domestic product per capita from the HydroBASIN database (Lehner et al., 2013). L is determined from the *lit_cl_smj* categories in the GLiM database (Hartmann and Moosdorf, 2012). A validation to this BQART model was conducted with data from Milliman and Farnsworth (2011) and discussed in Supplementary Section 2.

2.3.2 Maffre's model

Alternatively to the BQART, and in order to better evaluate the potential impact of terrestrial retention such as with dams on the sand flux in different catchments, we used a model where the sediment flux can be calculated on every pixel and either summed or partially removed by dams in order to calculate the sediment outflux to the ocean Q_{river}. This model was proposed by Maffre et al. (2018) on the basis of a 3.75◦ longitude by 1.9◦ latitude grid of cells:

$$E = kq^{0.2}s^{1.3} \times max(T,2)^{0.9} \quad (4)$$

where E is the pixel erosion rate in *m/year*, k is a constant parameter adjusted to obtain a global sediment outflux of 19 Gt (as predicted by the BQART model), s is the local slope, q is the run-off (*mm/year*) and T is the ambient temperature in (°*C*). Erosion rates are summed within catchments in order to predict the sediment flux Q_{river} at their outlet. The results of BDART and Maffre models illustrated present a good agreement (Figure S2).

2.3.3 Dam impact

To quantify the impact of dams in Q_{river}, we used the GOODD dam database (Mulligan et al., 2020), which provides the location of the dams as well as the associated upstream watersheds. We calculated $Q_{river,dam}$ by masking the area upstream from the dams, so that it mimics total sediment retention in dam reservoirs assuming that 100% of the sediment is trapped. Overall, $Q_{river,dam}$ fits Q_{river} calculated by using the BQART with a correlation coefficient of R = 0.76. To investigate the influence of potential impact on river catchments, we also calculated an unrealistic pristine potential $Q_{river,p}$ assuming a world without artificial river catchments (i.e. dams) and using Equation 3, so that we can compare the two situations with respect to the sandy coast evolution. Because our model focuses on sand, we consider that only a fraction (e.g. an arbitrary 35% value was used here, but values as low as 10% are found in the literature) of the total riverine sediment input is sand reaching the coastal zone (Wright and Nittrouer, 1995). A sensitivity analysis is shown in Figure S5 and discussed in Supplementary Section S4 and shows that our conclusions are rather insensitive to this fraction, and also to sediment grain size, which may vary with water shed and soil/land characteristics.

2.4 Longshore wave-induced sand transport

Q_{wave} is calculated at every single cell, in a stationary model. To do so, there are several bulk longshore sand transport formulations that are widely applied by coastal engineers. These are, among others, the CERC (1984), Kamphuis (1991), and the more recently developed Kaczmarek et al., (2005) formulae. There are continuous research efforts on the improvement of bulk longshore sediment transport equations (see for example, Mil-Homens et al., 2013) yet there is no general consensus on the choice of a formulation. The sensitivity analysis of our results to the choice of the formula in Supplementary Section 3 shows no clear difference on a global basis (Figure S2). Here, the empirical wave-induced longshore sediment transport is based on hydrological and topographic data and calculated using the Kamphuis formula (Equation 5) which shows a good agreement when compared with ground truth at several sites worldwide (Figure S3):

$$Q_{wave} = 2.33T_p^{1.5}tan(\beta)^{0.75}d_{50}^{-0.25}H_{break}^2 sin(2\theta_{break})^{0.6} \quad (4)$$

We consider a single grain size of d_{50} = 400 μm (see the sensitivity test in Figure S5) which corresponds to intermediate medium-sized sand (ranging from fine – 60 μm up to coarse 1000 μm d_{50}, e.g. see Flemming, 2011), with a surf zone of $tan(\beta)$ = 0.1 (Ardhuin and Roland, 2012; Melet et al., 2018). More advanced foreshore slope data are becoming available all over the world (e.g. from Almar et al., 2021b; Athanasiou et al 2019), but still with substantial discrepancies relative to ground truth in the surf zone. In Eq. 5, T_p is the peak wave period in s, H_{break}

the wave height at the breaker line (in *m)* and ϑ_{break} the wave angle at the breaker line in degrees. The average wave regime was derived from ERA-Interim (ECMWF) over the 1993-2015 period. We did not account for the transformation of waves from offshore deep waters to the continental shelves and coastal zones, a process that can be substantial with wide continental shelves (Passaro et al., 2021). The sensitivity of our global model and the longshore sand transport to sediment grain size and coastal slope is discussed in Supplementary Section S4. Figure S5 indicates no substantial change of model score and when varying d_{50} and coastal slope, as the model looks at patterns not the values themselves that might be influenced.

According to the relative angle between the waves and shoreline, transport occurs in one direction or the other. A set of consecutive cells where the transport moves in the same direction constitutes a coastal cell. Within a cell, each cell receives sand from the previous cell and supplies sand to the next cell. A positive/negative ΔQ_{wave} across a cell is indicative of accretion/erosion. When Islands are considered as isolated coastal systems, there is no sand flux from one island to another. The model provides results in one iteration starting from a hypothetical initial situation where sandy beaches are infinite reservoirs of detached sand and non-sandy stretches of coast are empty reservoirs. Here, the sandy cells were delineated as in the database of Luijendijk et al. (2018).

3 Coastal sand mobility potential and Equator-ward convergence

The quantification of Q_{river} is well documented locally at the outlets of the world's major rivers (Milliman and Farnsworth, 2011; Besset et al., 2019). It is then possible to integrate this output over large areas (e.g. a continent) and at the global scale (Milliman and Farnsworth, 2011, Syvitski and Milliman, 2007). Using the widely used BQART model (calibrated with rivers data Supplementary data S1), here with pristine watersheds without human dams, at the global scale gives a total annual sediment flux of ΣQ_{river} = 15.1 Gt/yr (over the 1980-2010 period), which is within the already estimated pristine range of 10 to 20 Gt/yr (Syvitski and Kettner, 2011; Dedkov and Gusarov 2006 ; Peucker-Ehrenbrink, 2009). ΣQ_{river} corresponds thus to 5700×10^6 m^3/yr considering ρ_s = 2650 kg/m^3. Integrated over all the coastal cells, this gives an average of 1,050,000 tons per year per cell, or 400,000 m^3/yr per cell. All this global sediment flux can be reconsidered and brought down to bedload, and sand only, discarding the finer fraction of suspended sediment such as mud (Figure 2).

Q_{wave} is an estimate of the potential (i.e. maximum) annual flux of sediment transport along the coast driven by waves. On a global basis, the longshore sediment transport potential per cell is approximately 155,000 cubic meters (410,000 tons) per year, when averaged over the 1993-2015 period. The value closely aligns with terrestrial discharge, unveiling significant potential for wave-driven remobilization and redistribution along the coast. In Figure 2, the global latitudinal averages of Q_{wave} show a tendency for waves in the northern and southern hemispheres to transport sediment southward or northward, respectively. Around the Equator, the reversal of the direction of the longshore sediment transport potential represents a global convergence zone of these transport potentials. On average, at a global scale, waves appear to induce sediment transport from higher latitudes to the equatorial zone with notably high sediment deposition in tropical areas where there is a pronounced decrease in wave energy (Figure 2). Figure 2c shows that the relative importance of Q_{wave} and Q_{river} depends on latitude. Between 15°N and 5°S, Q_{river} dominates over Q_{wave} whereas Q_{wave} dominates south of 10°S and north of 35 °N.

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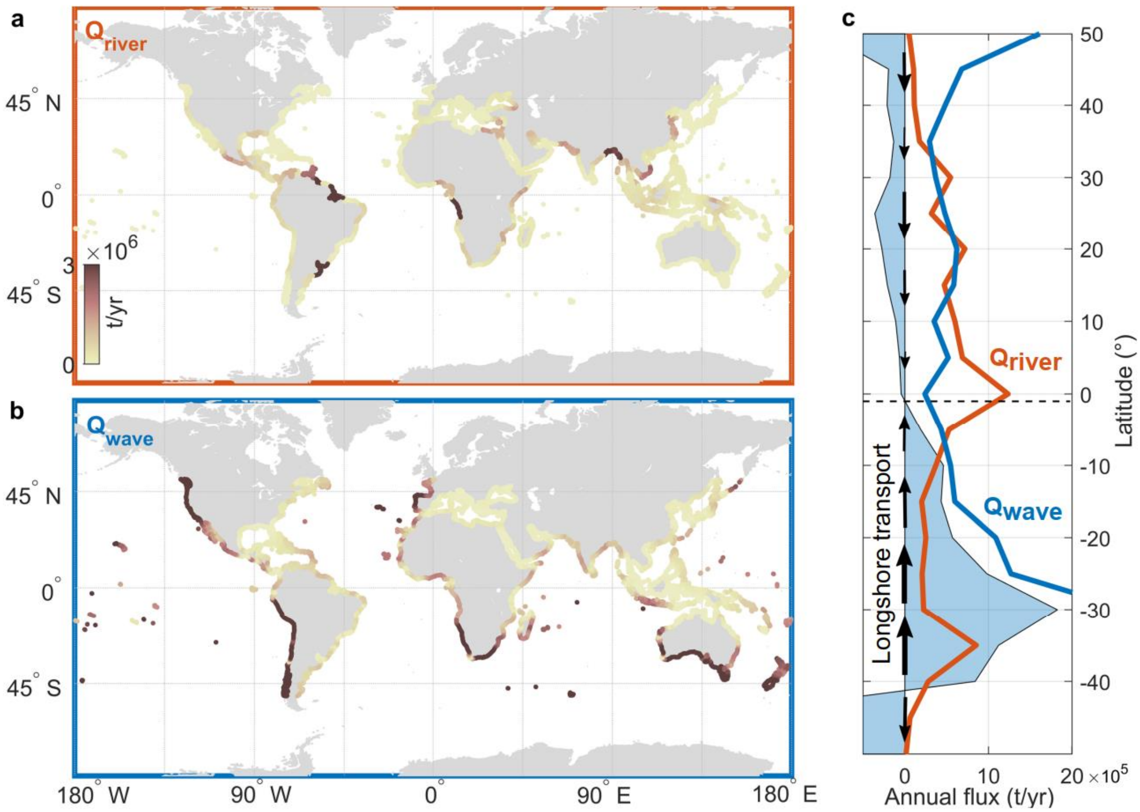

Figure 2. *A global view of fluvial sediment sand supply and longshore sediment transport. (a) Global geographic distributions (along the set of cells delineated by GSHHG i) of the river sediment discharge (Q_{river}) and (b) absolute longshore sediment transport potential (Q_{wave}), with blue arrows indicating the general direction of transport. (c) 5° resolution latitudinal averages of Q_{river} (red line), absolute Q_{wave} (blue line) and directional Q_{wave} (blue polygons - positive for northward-oriented, negative for southward-oriented). Black arrows show the directions and intensities of the longshore sediment transport.*

When $Q_{river} < Q_{wave}$, the river sediment supply is easily transported by Q_{wave}. Sediment deposition, and consequently, beach (if any) accretion, is expected where Q_{wave} diminishes alongshore. On the contrary, areas where $Q_{river} > Q_{wave}$ may be dominated by large river bedload discharge, locally outweighing Q_{wave}, which means that most of the sediment supplied is either deposited near the river mouth (sequestered in river deltas, for instance, including subaqueous delta fronts that may protrude far offshore). From 25°N to 0°, there is a consistent decrease in the mean southward (northward) coastal sediment transport, whereas from 30°S to 0° the northern component of sediment transport tends to decrease. This gradient of transport capacity leads to a progressive deposition of sediments, especially in tropical areas where this trend is most pronounced.

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The impact of river discharge is often discussed locally, specifically around the outlets and in particular at deltas (Nienhuis et al., 2020). However, sediment has the potential to travel across the entire sediment cell, which can span thousands of kilometers along the coast. A sediment cell represents a coastal stretch that shares common characteristics in terms of sediment nature and how it moves over space and time. Any disturbance occurring upstream of the sediment flux will affect the downstream portion. Figure 3 illustrates the computed sediment cells, showcasing their shared temporal variability with a 0.8 correlation threshold value. Large sediment cells are observed at open and continuous stretches of coast such as Pacific coast of South America and Atlantic coast of South Africa till the Congo plain meanwhile smaller cells are observed at more rugged coasts such as in Indonesia archipelago, Caribbean and Europe. Meanwhile, the length of these cells is sensitive to the chosen threshold with average values up to 2000 km. This sensitivity is attributed to the variation in convergence/divergence points, such as headlands and bays, in the longshore sediment transport, which tends to increase with higher resolution and a decrease in the threshold value.

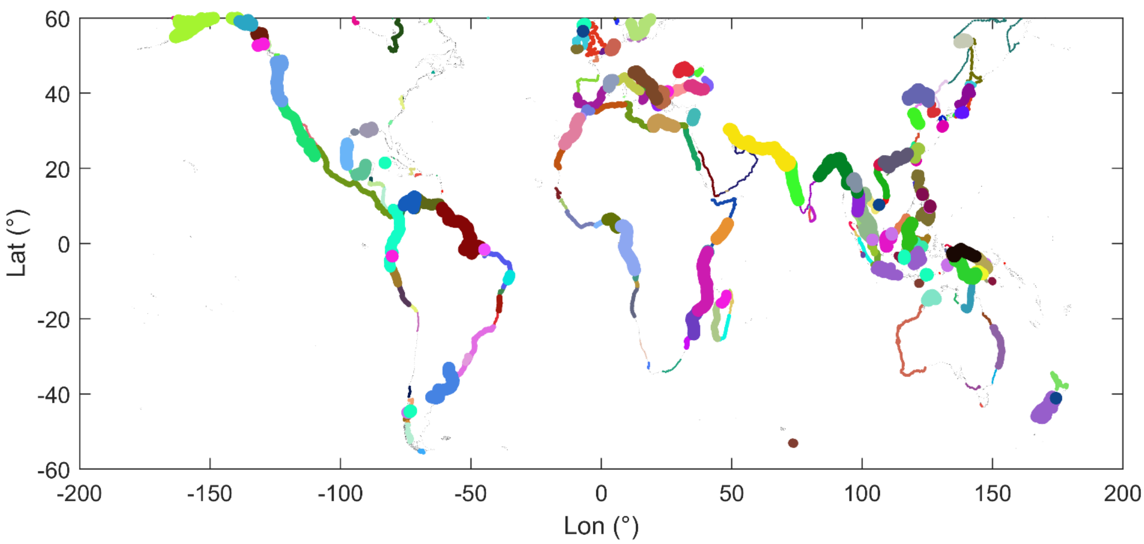

Figure 3. *Distribution of coastal sediment cells based on the continuity of longshore sediment transport. Colours are illustrative to visually distinguish the different zones and do not reflect a particular value. Line width is proportional to fluvial sediment income in each coastal sediment cell.*

4 Potential reduction of terrestrial sediment supply by rivers: the key influence of dams

In the above analysis, pristine natural watersheds were used (as in Syvitski and Milliman, 2007). This is arguably a large simplification of the problem. Significant emphasis has been placed on the impact of

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anthropogenic activities on river sediment supply (Syvitski and Milliman, 2007; Milliman and Ren, 1995; Ranasinghe et al., 2019). The effect of human-induced modifications of river loads has also been recognized in numerous individual beach studies worldwide (Bamunawala et al., 2020, 2021). Note that dam trapping is only part of the problem and that river-bed mining is also a very important activity (Peduzzi, 2014; UNEP, 2019), with deleterious effects on the coastal sediment budget. Changes in precipitation and land have been reported to have also an important contribution to sediment discharges.

In order to move beyond case studies, here we assess specifically the global picture of anthropogenic effect of dam trapping. In the BQART formula, dam trapping anthropogenic effect can be reflected by the *Te* term. However, BQART is not suited to account for the influence of river dams because it is integrated over all the watersheds, and we preferred the Maffre's model (see Sect 2.3.2) where the sediment flux can be calculated on every pixel of the catchment and either summed or partially removed by dams in order to calculate the sediment outflux to the ocean Q_{river}. In the dam scenarios adopted here, the two models are end-members with full or no dam trapping. The model with dams retaining 100% of sediment is extreme, as, in reality, the sediment trapping efficiency is quite variable, mainly depending on the water residence time (Maneux et al., 2001; Tan et al., 2019), and only sometimes up to 100% (example of the Aswan Dam on the Nile; Walling and Webb, 2009). The difference between these two scenarios is shown in Figure 4. Figure 4 shows that a potential dam retention capacity of 100% of sand would reduce the overall Q_{river} by half, from 600,000 cubic metres per year per cell in a pristine world to 270,000 cubic metres per year per cell on average in a world where dams retain all the bedload, thus depriving sandy coastal systems of half of their natural terrigenous sediment supply. Note that these extreme values bracket the current value estimated (400,000 cubic metres per year per cell). In this tested scenario, 18 % of the sandy cells (i.e. approximately 180,000 km of coastline) with a neutral or positive sand budget in a pristine situation become sediment-deficient once total retention by dams is assumed (orange/red locations in Figure 5), often far from the outlet. Although extreme, this scenario illustrates the potential effect of dams and provides pertinent information on the locations of coastal areas affected (or that may be affected) by fluvial sediment input losses (Figure 5).

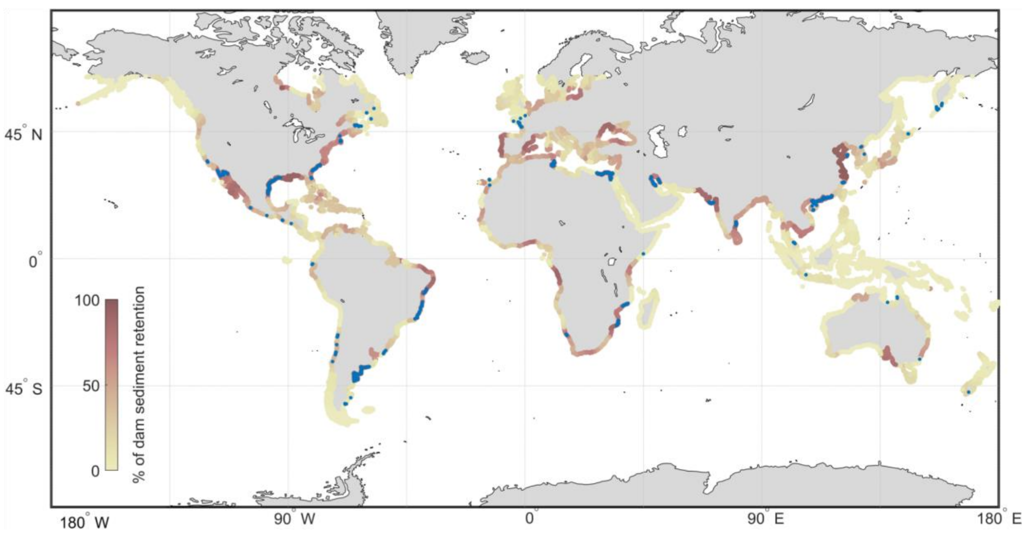

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Figure 4. *Potential dam-induced reduction of fluvial sediment supply to the world's coasts from pristine world, here shown in percentage of decrease in Q_{river} induced by dams, assuming that dams retain 100% of the bedload coming from upstream using Maffre's model and GOODD dam database (Mulligan et al., 2020). The blue dots represent cells where the sand budget balance turns from positive to negative when dams are taken into account.*

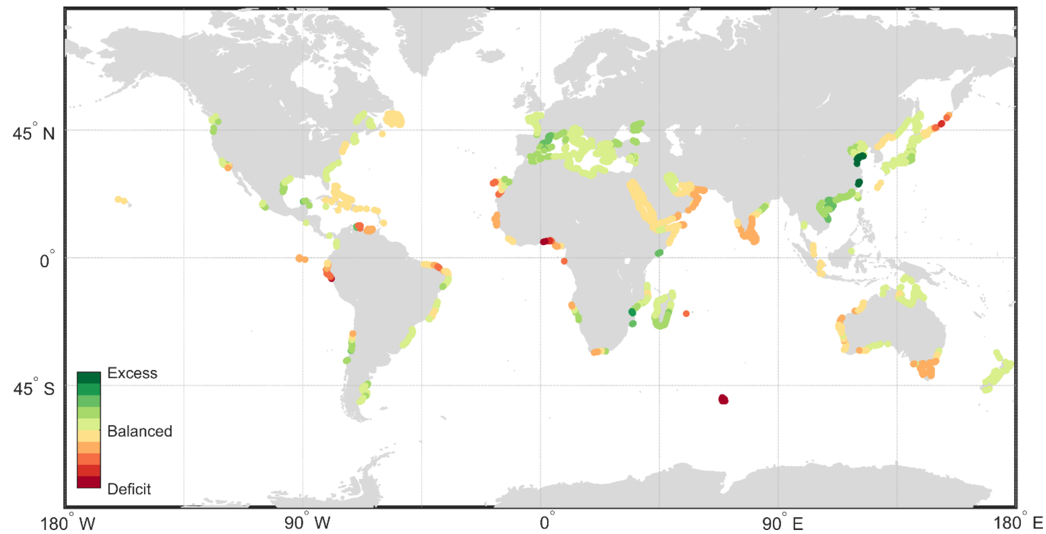

Figure 5. *Coastal sand budget change for all sandy locations, between no retention and total retention scenarios. Traffic light system representation from potential large deficit (-500,000 t/yr) to large excess (+500,000 t/yr).*

In order to evaluate our sand pathway model, we compare the pattern given by several scenarios of coastal sediment balance results with available observations for global coastline mobility; pristine sediment ($\Delta Q_{pristine}$) and dam (ΔQ_{dam}) pattern. Here, we tested the correlation (R) between the observed annual coastline evolution trend υ_{obs} and our calculated ΔQ. Sandy points are categorized using Luijendijk et al. (2018) and the dominance of not sandy/sandy is explored regionally (length scale of 4°~ 400 km). For all sandy points (31% of the total coastal points), the correlation coefficient between υ_{obs} and ΔQ_{dam} is $R = 0.49$ for sandy coastline, showing the preponderant influence (34% on a global basis) of river damming alone on explaining current sandy beaches evolution trend. The significant correlation between ΔQ_{dam} and υ_{obs} for a majority of global sandy beaches shows that our sand budget model captures, to first-order, the current cross-shore mobility of sandy shorelines, only due to the local imbalance between fluvial sediment supply and the sediment-carrying capacity of wave-induced longshore currents. Thus, the fate of river sand supply cannot be neglected when considering the cross-shore evolution of sandy beaches, especially at decadal time scales as considered here, and even at distance from outlets.

Fluvial sediment loss has in fact already been shown to be critical to deltas, especially large deltas, which are becoming increasingly vulnerable as a result of sediment depletion compounded by anthropogenic subsidence

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(Syvitski et al., 2009; Besset et al., 2019; Dunn et al., 2019; Ranasinghe et al., 2019). Large rivers deliver much of the fluvial load to the oceans, with only 1052 rivers delivering 95% of the total (Syvitski et al., 2022b). Thus, the construction of dams that essentially trap bedload has extremely deleterious effects by undermining not only the stability of sandy beaches adjacent to deltas but also the rest of the world's sandy beaches sourced by terrigenous sediment transiting through river mouths.

5 Beach conservation

Our results show that a primary global threat to sandy coasts may arise from fluvial sediment supply deficit. A number of examples have shown that sandy coasts can be rapidly reconstructed after river dam removal (Warrick et al., 2019). However, such actions must be based on conservation and integrated management policies, a trade-off at the nexus of sustainable coastal areas (Nittrouer and Viparelli, 2014; Dada et al., 2021).

Past experience has shown that effective, site-specific coastal planning can mitigate beach erosion and result in a stable coastline; the most prominent example of this is the Dutch coast (Mulder et al., 2011). While sea-level rise is projected to result in shoreline retreat almost everywhere in the world (IPCC, 2021), many locations have ambient erosive trends related to human interventions that could theoretically be avoided by more sustainable coastal and watershed management practices (Morris et al., 2020; Lincke and Hinkel, 2021; Vousdoukas et al., 2020, Luijendijk et al., 2018). At the same time, projected sea-level rise implies unprecedented pressure on our coasts, requiring the development and implementation of informed and effective adaptation measures (Pörtner et al., 2022). At local scales, human activities can also directly affect the coastline, both in terms of erosion and accretion. Some countries such as the Netherlands or China are undertaking large-scale works to gain ground on the sea. Others use their beaches as sand quarries to supply the construction industry. Land subsidence due to agriculture, mining, or urban development (Nicholls et al., 2021; Marchesiello et al., 2019), as well as coastal infrastructure, can be a dominant factor in coastal evolution (Cao et al., 2021). This was recently highlighted by the decision to move the capital city of Jakarta due to the perceived impossibility of sustainably protecting it from marine flooding (Cao et al., 2021).

However, most of these site-specific mitigation efforts have neglected the sediment imbalance that results from larger-scale, often regional, sediment redistribution (Almar et al., 2015). Our study strongly suggests that efficient management strategies cannot be limited to just coasts but should consider entire river basins within a more holistic treatment of the problem. Modification of the sediment supply by a river, which may even run across several countries, can have repercussions along the coast for up to more than a thousand kilometres (e.g. the Namibian coast), depending on the size of the coastal sediment cell. For example, the Bight of Benin, located in the Gulf of Guinea, West Africa, is under the influence of sediment supplied by the Volta and Niger rivers, and this sediment is redistributed along hundreds of kilometers of coast (Anthony et al., 2019; Abessolo et al., 2021). However, several agriculture and hydro-power dams have been constructed along these rivers, as well as deepwater harbours, blocking both river-to coast sediment transport as well as alongshore transport (Anthony et al., 2019). Although some countries are implementing expensive management strategies locally, a collaborative regional international effort would certainly deliver more benefits (Dada et al., 2021; Alves et al., 2020) at a reduced cost (Rocle et al., 2020). Current legislation does not take the integrated analysis of continental and offshore sources of sediments into account, but our study suggests that it is possible to act on saving sandy coasts by assuring the sediment balance, for example, via implementing innovative strategies of sediment management in the wake of retention by dams, better control of riverbed mining, and adapting land-use policies at a regional-to-continental scale, an approach that requires particular coordination for trans-boundary rivers (De Stefano et al., 2017) . National initiatives, mainly founded on dam removal, have already been launched, notably in the United States, Japan and Europe (Warrick et al., 2019; Noda et al., 2018; Habel et al., 2020). The need for a stronger dialogue between the scientific and public domains on the impacts of dams has been advocated (Flaminio et al., 2021). Such knowledge transfer and exchange are not only beneficial regarding, for example, perceptions of 'renewable energy' and 'green energy,' but also in terms of consideration of alternative modes of governance regarding dams. Given that the change in sediment outflow from one river may impact the shorelines of another country, we anticipate that integrated and comprehensive approaches such as advocated here could have major benefits both for national coastal management policies and for regional international legislation.

6 Discussion

In this global study, we have necessarily made approximations and assumptions. We limited our analysis to the potential sand pathway from land to sea and the alongshore redistribution by waves, and did not consider offshore sediment export beyond the depth of closure, nor sand inputs from offshore sources, which are out of the scope and reach of our study. The analysis used both sandy locations and shoreline change metrics from Luijendijk et al. (2018) which is a first-pass pioneering estimate and can be obviously refined using new classification tools, including machine learning (Vos et al., 2019).

Regarding the direct influence of dams, a river sand flux dropping to nearly zero can be attributed primarily to the impact of dams. However, the effect of water extraction from the reservoir also plays an important role on downstream erosion. For example, due to water extraction, the Nile river water discharge to the sea has decreased to nearly zero after the construction of the Aswan dam (Wiegel, 1996). No water discharge means no sediment delivery. But no water discharge also means no downstream erosion. In the Yangtze River, the sediment flow to the sea after the closure of the Three Gorges Dam remained at about 25%, as the water flow was hardly affected and river erosion downstream of the dam was still considerable (Yang et al., 2018). However, consideration of such phenomena is beyond the scope of our study. The reality lies in between our two extreme scenarios (0% or 100% retention of sediments in the dams). The temporal evolution of coastlines and its feedback on waves and the longshore sediment transport was not accounted for in our study. Numerous articles document this feedback by waves in reshaping the delta coastline (Anthony, 2015; Nienhuis et al., 2015), for instance at the Mekong (Marchesiello et al., 2019) and the Volta river deltas (Anthony et al., 2016). We believe this aspect, which involves coastline evolution and its feedback on waves, is currently out of the reach of our methodology, especially at global scale.

Although the sand budget plays a primary role in the evolution of the coastline on a global scale, other phenomena, natural or not, can influence this evolution on different spatial and temporal scales. The contribution of these phenomena is difficult to quantify because global databases (e.g. high-resolution offshore bathymetric data or a subsidence map) are still lacking. Among these various phenomena, the global rise in sea level over the last 100 years has had a visible impact on beaches, especially along gently sloping low-lying coasts. With a ~ 20 cm rise in the sea level since 1900 (Oppenheimer et al. 2019), the sea has gained up to 15 metres on land for

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beaches with a slope of 1 degree. Local subsidence due to sediment compaction following freshwater pumping can reach several metres as in Japan or Indonesia (Cao et al., 2021; Tay et al., 2022), greatly exceeding any other cause for coastline evolution. Abrupt, or progressive or transient vertical uplift or subsidence on the scale of centimetres to metres over a period of years can locally influence the relative sea-level rise substantially (e.g., Jeanson et al., 2021), and consequently the coastline position (Farías et al., 2010). These phenomena are not quantified everywhere and may explain the remaining variance in the current sandy beach trend υ_{obs} that is not explained by ΔQ.

Nevertheless, our study constitutes a major breakthrough by providing the first evidence that the current trend in sandy coastal evolution is controlled by the local imbalance of sand transport in a predictable way. Sediment supplied by rivers plays a crucial role in this imbalance and any variation in this supply, caused by dams or aggregate extractions for example, can affect sediment redistribution along continental cells. Variations in the river sediment supply are also affected by climate change. The rise in temperature (Hoegh-Guldberg et al., 2018) will increase the sediment transport potential of rivers as temperature directly affects the capacity of the river to erode the bed (Syvitski and Milliman, 2007). The intensification (reduction) of precipitation in temperate (arid) zones will lead to an increase (decrease) in Q_{river} (Greve et al., 2018). Last, the multiplication of extreme climatic events (i.e. droughts, extreme precipitation, extreme sea levels etc.) will increase vulnerability to erosion and thus influence sediment transport; for example, monsoon rains after a strong drought mobilizes large quantities of sediments. Dams are not the only anthropogenic factor to be considered with regards to the evolution of Q_{river}. Land use changes also have a critical role to play in the delivery of river sediment supply to the coast. Urbanization can hamper sediment transport, particularly through the increase in infrastructure along rivers and coasts. Conversely, deforestation and land use in general may also help increase Q_{river} by increasing the exposure of deforested soils to precipitation and the erodibility of soils that do not have enough tree roots to provide support (Restrepo et al., 2015; Ribolzi et al., 2017; Owens, 2020).

Code availability

The raw data that support the findings of this study are already available online. Calculated data (e.g. sediment outfluxes) are provided as tables. The Matlab Code will be made freely available through gitlab repository.

Author contributions statement

Conceptualization by VR and RA. MG carried out early stage study and wrote an initial draft under supervision by VR, RA and SC. VR and SC, and RA calculated the sediment supply from rivers at the global scale, and LST, respectively. PM brought his expertise on riverine fluxes. RA and VR directed the manuscript preparation. RR and EA strengthened the presentation through their external and wide expertise. All authors discussed the results and contributed to the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

RR is partially supported by the AXA Research Fund

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