

Sedimentation strategies provide effective but limited mitigation of relative sea-level rise in the Mekong delta

Frances E. Dunn ¹✉ & Philip S. J. Minderhoud ^{1,2,3,4}✉

The Mekong delta is experiencing rapid environmental change due to anthropogenic activities causing accelerated subsidence, sea-level rise and sediment starvation. Consequentially, the delta is rapidly losing elevation relative to sea level. Designating specific areas for sedimentation is a suggested strategy to encourage elevation-building with nature in deltas. We combined projections of extraction-induced subsidence, natural compaction and global sea-level rise with new projections of fluvial sediment delivery to evaluate the potential effectiveness of sedimentation strategies in the Mekong delta to 2050. Our results reveal that with current rates of subsidence and sediment starvation, fluvial sediments alone can only preserve elevation locally, even under optimistic assumptions, and organic sedimentation could potentially assume a larger role. While sedimentation strategies alone have limited effectiveness in the present context, combined with enhanced organic matter retention and interventions reducing anthropogenic-accelerated subsidence, they can considerably delay future relative sea-level rise, buying the delta crucial time to adapt.

¹ Faculty of Geoscience, Utrecht University, 3584CS Utrecht, The Netherlands. ² Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy. ³ Soil Geography and Landscape group, Wageningen University, Wageningen, The Netherlands. ⁴ Department of Subsurface and Groundwater Systems, Deltares Research Institute, Utrecht, The Netherlands. ✉email: F.E.Dunn@uu.nl; Philip.Minderhoud@wur.nl

Relative sea-level rise (RSLR) increasingly affects the ability of societies around the world to function in coastal zones^{1,2}. These at-risk communities must find solutions to the global problem of sea-level rise which are effective in local environmental and societal contexts³. While the global sea level is rising, other factors, e.g., land subsidence, also drive coastal elevation change and can locally have a much larger impact than global drivers^{4–6}. Modern coastal river deltas share key physical characteristics which make them particularly susceptible to RSLR (Fig. 1): deltas are constructed of newly-deposited organic and inorganic sediment, which decomposes and compacts, thereby losing volume and reducing land elevation.

Modern deltas came into existence during a period of low rates of sea-level rise, no anthropogenically accelerated subsidence, and an uninterrupted supply of sediment. Deltas around the world have started to lose land because of a reversal of these favourable conditions due to anthropogenic activities^{6,7}, including the Mekong delta^{8,9}, although some deltas have gained land due to activities like deforestation¹⁰. Under pre-Anthropocene conditions, elevation loss would be (over-) compensated for by sediment deposition from flooding. However, the balance in many deltas has shifted due to increased anthropogenic activities such as dam construction in upstream basins, land-use change, and mining of sand, water and fossil fuels within deltas causing sediment starvation and accelerated subsidence^{2,11,12}.

The low-lying Mekong delta¹³, the third-largest delta in the world and predominantly located in Vietnam, has experienced severe anthropogenic disruptions in recent decades^{14–16}. The delta is under pressure from a growing population, expanding cities, and intensifying agriculture and aquaculture activities¹⁷. As the upstream Mekong river basin is shared between five other countries (Cambodia, Thailand, Laos, Myanmar, China) with their own demands on the river's resources, downstream Vietnam has little control over the fluvial fluxes reaching the delta^{18,19}. The delta suffers from reduced sediment flows from upstream^{19,20}, sediment extraction within the delta due to channel mining^{14,21}, and dyke construction that impedes natural floods by restricting connectivity between rivers and floodplains^{22,23}, as well as accelerated subsidence due to groundwater pumping^{24,25}, on top of already high rates of natural compaction²⁶ and other land-use induced subsidence processes, such as drainage or infrastructural loading^{27,28}. The resultant loss of elevation drives RSLR²⁵, coastline erosion^{9,14} and increased salinization^{16,29}, posing a serious threat to the current population and future development¹⁵.

Recent studies have revealed the existential threat of anthropogenic accelerated subsidence to the future of the delta, with subsidence rates up to a magnitude larger than sea-level rise^{24,30,31}, highlighting the urgent need for subsidence mitigation by reducing

groundwater extraction²⁵. Although in the case of the Mekong delta reducing groundwater extraction is potentially the most effective strategy to mitigate overall relative elevation loss²⁵, controlled sedimentation is receiving much more attention, both in the scientific³² and public debate^{33,34}. Increasing sedimentation through controlled flooding has been presented as a method to reduce environmental issues in the Mekong³² and other deltas³⁵. This strategy counters RSLR in deltas by encouraging sedimentation on delta land to maintain or build elevation relative to sea level^{35,36}, allowing suspended sediment to settle out of floodwaters, mimicking processes occurring in preanthropogenic deltas. Managed sedimentation has occurred in several deltas, for instance in tidal river management in the Bengal delta³⁷ and splay construction in the Mississippi³⁸. Tidal river management involves breaking dykes in tidal locations to allow river water to flow into previously poldered land at high tide, bringing with it sediment, which is deposited inside the polder area³⁹. After sufficient sedimentation, potentially over multiple years, the dykes are repaired and the polder land can continue to be used for agriculture or other purposes. In comparison, river diversions in the Mississippi use sluice gates to enable the passage of water through dykes into adjacent areas, water which carries sediment which then settles and raises elevation⁴⁰. Sluice gates allow more control over the volumes of water and sediment diverted but incur more costs⁴¹. The effectiveness of all of these strategies is highly dependent on the exact hydrodynamics and management^{42,43}.

In the Mekong delta, sedimentation in recent years has often just been a by-product of flood management for rice agriculture⁴⁴. Even though fluvial sediment supply is declining, controlled sedimentation³⁶ may still bring benefits for the delta's environment, elevation, and communities. While controlled sedimentation is being widely suggested as a solution to RSLR in the Mekong delta in advisory reports on sustainable delta management^{32–34}, its true effectiveness in the delta's context has, apart from a single preliminary study using delta-wide averages¹⁵, not been quantified. Here we examine the quantitative potential of targeted sedimentation strategies to counterbalance RSLR in the Mekong delta by evaluating and projecting the main drivers of elevation change using advanced physical process-based numerical approaches. We combine new spatially and temporally explicit quantifications and projections of delta-wide natural compaction^{26,45} and extraction-induced subsidence²⁵ from process-based numerical models together with climate change-induced sea-level rise⁴⁶ to create plausible RSLR projections. Furthermore, we use new projections of sediment delivery under dam construction and climate change scenarios, together with estimates from previous work, to evaluate future fluvial sediment availability. Our approach presents a blueprint for similar assessments of sedimentation strategy effectiveness in deltas and coastal regions worldwide.

We present four examples of potential sedimentation areas (Fig. 2) and quantify the elevation change following targeted sedimentation strategies, including organic accumulation, using new delta elevation data¹³, until 2050 under a range of environmental change scenarios. Our analyses underscore the dire situation of the delta following recent sediment flux reductions and acceleration of subsidence rates, therefore we also quantify the potential to boost sediment delivery by removing upstream dams in the Mekong catchment and restoring water and sediment flow. Restoring sediment delivery and reducing anthropogenically induced subsidence will limit relative elevation loss in the Mekong delta and allow time for adaptation to changing environmental conditions.

Results and Discussion

Target areas for sedimentation strategies. We focus on the evolution of existing delta land elevation and assess whether

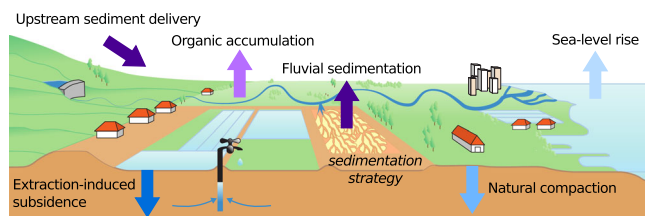


Fig. 1 The main processes driving present-day delta elevation change considered in this study. Sediment deposition through fluvial sedimentation depends on sediment delivered from the upstream river basin, and in situ organic matter accumulation raises delta elevation. Land subsidence processes such as natural compaction and extraction-induced aquifer system compaction, together with global sea-level rise, result in negative relative elevation change of the delta surface (modified from Minderhoud⁴⁵).

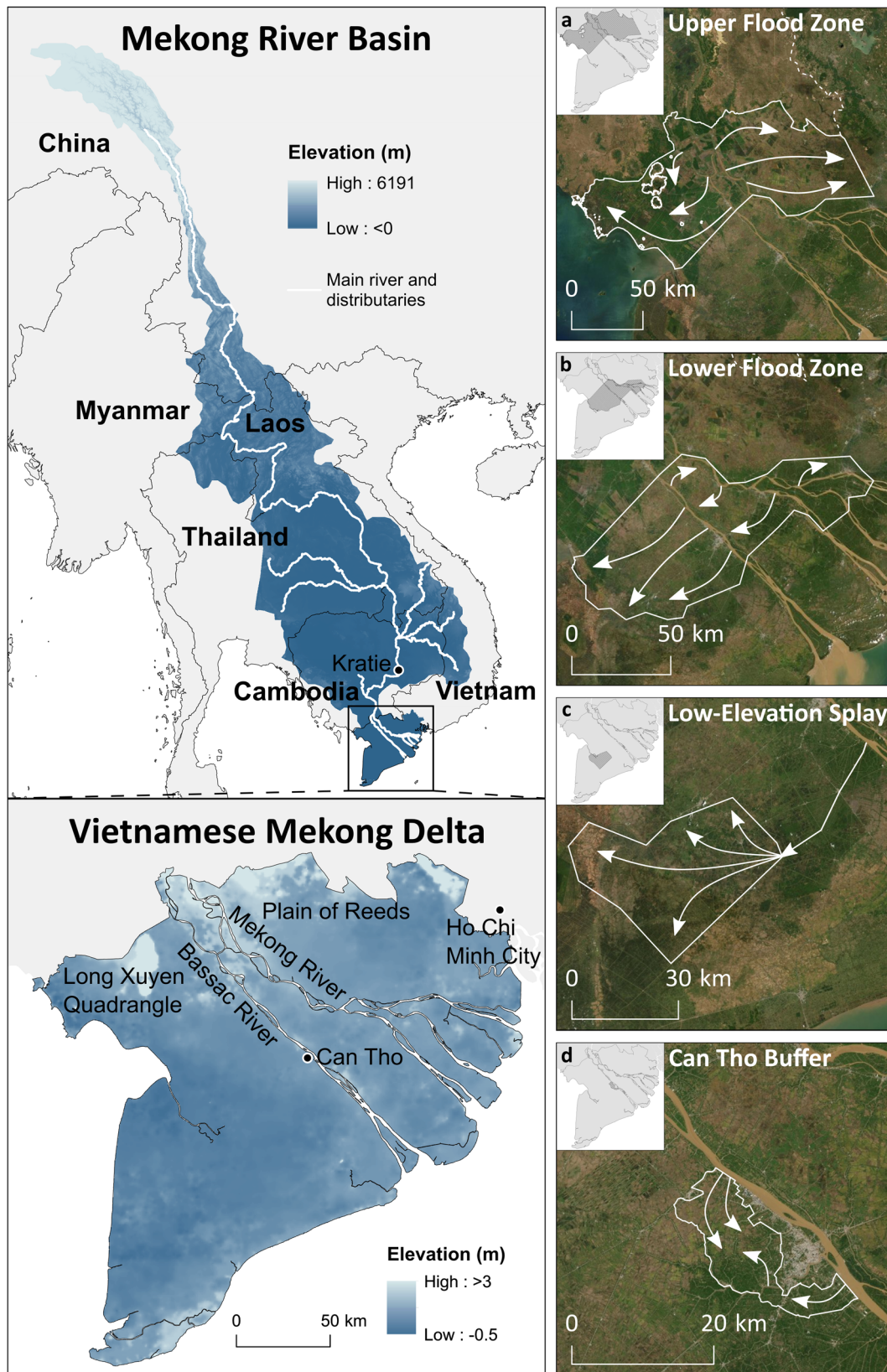


Fig. 2 Maps of elevation above sea level of the Mekong river basin and Vietnamese delta, and locations of the sedimentation scenarios in the Vietnamese Mekong delta. **(a)** Upper flood zone (12,000 km²), area that historically experienced fluvial floods; **(b)** lower flood zone (7000 km²), area which modern floods are shifting towards; **(c)** low-elevation splay (1500 km²), located in one of the lowest, predominantly agricultural, areas of the delta; **(d)** targeted sedimentation strategy to build a protective, elevated ring around the delta’s largest city, Can Tho (200 km²). See Methods for details on extent definition. Aerial imagery: Esri, Maxar, GeoEye, EarthStar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. River shapefile from the HydroSHEDS database¹⁰⁴.

sedimentation strategies may allow the surface elevation to keep up with RSLR under a range of future scenarios. We selected four sedimentation areas to showcase the potential of sediment management efforts at different scales and in different parts of the delta (Fig. 2). The example areas provide a range of sedimentation strategy scenarios, encompassing different extents, elevations and locations. Implementing the suggested strategies in the different areas would require different energy inputs, as some would be gravity-driven and others would require mechanical intervention. In each scenario we assume no sedimentation outside of the targeted area in the rest of the delta, which may not be far from reality considering the current minimal sedimentation.

The upper delta area in Vietnam (Fig. 2a), comprised of the Long Xuyen Quadrangle to the southwest of the rivers and the Plain of Reeds to the northeast, is an area which has historically experienced seasonal fluvial flooding⁴⁷ and so represents where sedimentation traditionally occurred. The lower flood zone (Fig. 2b) is experiencing increasing water levels, potentially due to water control structures in the upper delta²², as well as sea-level rise and other anthropogenically-driven environmental changes, such as increased tidal amplitude following channel bed lowering due to sand mining^{16,48}, and so shows where flood sedimentation may occur if current trends continue. The low-elevation splay scenario (Fig. 2c) is an attempt to raise elevation in one of the lowest elevated, agricultural areas in the delta¹⁴. Finally, the area around the delta's largest city Can Tho (Fig. 2d) presents a focused sedimentation strategy intended to build a protective ring around the current city which may also create areas of increased elevation to enable future urban expansion to higher-elevation areas.

Elevation loss by land subsidence. Land subsidence is intrinsically rooted in delta elevation evolution as newly deposited sediments naturally compact over time, and anthropogenic activities can enhance rates of compaction and create new human-induced subsidence processes. In recent years, understanding of subsidence in the Mekong delta has progressed from the first InSAR-based estimates of total subsidence³⁰ towards spatial and temporal unravelling of dominant drivers and processes^{24–28}. In the youngest parts of the delta, close to the present coastline⁹, high compaction rates in the shallow subsurface could stem predominantly from natural compaction caused by the weight of overlying sediments and delayed dissipation of porewater overpressure²⁶. We used numerical quantification of natural compaction over a 2D transect in the south of the delta²⁶ combined with a new, delta-wide map of Holocene clay thickness (Supplementary Fig. 1) to arrive at a first, spatially explicit estimate of maximum (see explanation in Methods) present-day natural compaction rates throughout the delta, which gives an average, maximum delta-wide rate of 4.4 mm/y, ~1–2 mm/y for inland areas and rates as high several cm/yr²⁶ in geologically young, coastal areas (Fig. 3a).

Subsidence rates in the Mekong delta show a high spatial and temporal correlation with land use and land-use history, with higher rates associated with more human influence²⁷, revealing the strong influence of anthropogenic drivers, such as groundwater extraction or infrastructural loading on increasing subsidence in the delta. As subsidence related to infrastructural loading happens at a very local scale²⁸, this effect is neglectable at the delta scale in relation to RSLR. Groundwater extraction from the deeper aquifer system can drive subsidence in much larger areas²⁴ and is therefore an important factor in delta elevation loss.

The steady increase in groundwater extraction that fueled agro-economic development in recent decades⁴⁹ lead to overexploitation of the groundwater reserves. Consequently, water pressure in the multi-aquifer system dropped throughout the delta and

caused aquifer-system compaction³⁰. Using a delta-wide 3D hydrogeological model an accelerating trend in extraction-induced aquifer-system compaction was computed (delta-wide averages), from ~4 mm/y in the 1990s to ~11 mm/y in 2015, with rates in specific areas increasing to 25 mm/y (Fig. 3b)²⁴. This accelerating trend was recently confirmed by new InSAR-based estimates^{28,31}. An updated version of the hydrogeological model was used to quantify future extraction-induced subsidence for several plausible future extraction pathways to 2100²⁵. We use these temporally and spatially explicit projections of delta-wide, aquifer-system compaction as scenarios for future extraction-induced subsidence (Fig. 3c–e). Note that aquifer-system compaction happens in the deeper subsurface below the Holocene layer, so in addition to shallow natural compaction. The individual contribution of other drivers of subsidence, such as tectonic subsidence and isostatic adjustment, has not yet been quantified for the Mekong delta. Analysis of InSAR-based subsidence estimates and the location of primary faults revealed no evidence for fast neotectonics movements in the Mekong delta⁴⁵. For this reason, and because quantifications of normal faulting and (sediment) isostatic adjustment in other large delta systems reveal low rates <1 mm/y e.g., Mississippi delta⁵⁰, we do not consider these processes in our analyses.

Past and future fluvial sediment delivery. The sediment load of the Mekong river is undergoing drastic reduction^{18,51,52}, with only ~25% of the sediment delivered to the delta in recent years than was available in the period before substantial dam construction (pre-1992)¹⁹. The predam period may include other anthropogenic influences in the basin, making the exact value of pristine sediment load uncertain²⁰. Key drivers of recent changes in the sediment budget are upstream dam construction, which traps sediment in reservoirs and limits downstream delivery⁴⁸, and channel mining, which takes sediment from the river bed and removes it from the fluvial system⁵³. The change in river sediment load alters delta morphodynamics, and observed environmental problems caused by these changes include shoreline erosion^{8,15}, tidal amplification¹⁶, salinity intrusion²⁹, channel incision and riverbank erosion^{21,53}.

Sediment starvation is currently creating a negative total sediment budget¹⁶ due to sand mining removing coarse-grained material from river beds, resulting in the increased river bank and coastal erosion^{14,21}. Impacts of sand mining on the fine-grained suspended sediment load transported by the Mekong river are not known, but are assumed to be limited as sand mining activities target coarse-grained material which is not transported in suspension²¹. Dams, however, do have demonstrated impacts on suspended sediment loads, as reservoirs cause suspended sediment to settle rather than be transported further downstream^{18–20}. While decreased bed sediment leads to channel incision and bank erosion⁵³, salinity intrusion^{16,29,54} and shoreline erosion of coarse-grained (i.e., sandy) coastlines^{8,9,14}, decreased suspended sediment affects the amount of sediment deposition during flood events. We therefore focus here on suspended sediment availability and floodplain trapping efficiency as a key factors for the success of managed sedimentation strategies.

While the Mekong river sediment load, both historic and future, is currently a topic of considerable interest⁵⁵, it has been decreasing as rapidly as research can investigate (Fig. 4) due to the recent boom in dam construction in the Mekong basin¹⁹. Attempts to understand the current state of the system and how it might change in the future, and therefore what environmental changes the Mekong delta can expect, have involved projections of sediment fluxes in the Mekong under dam construction and

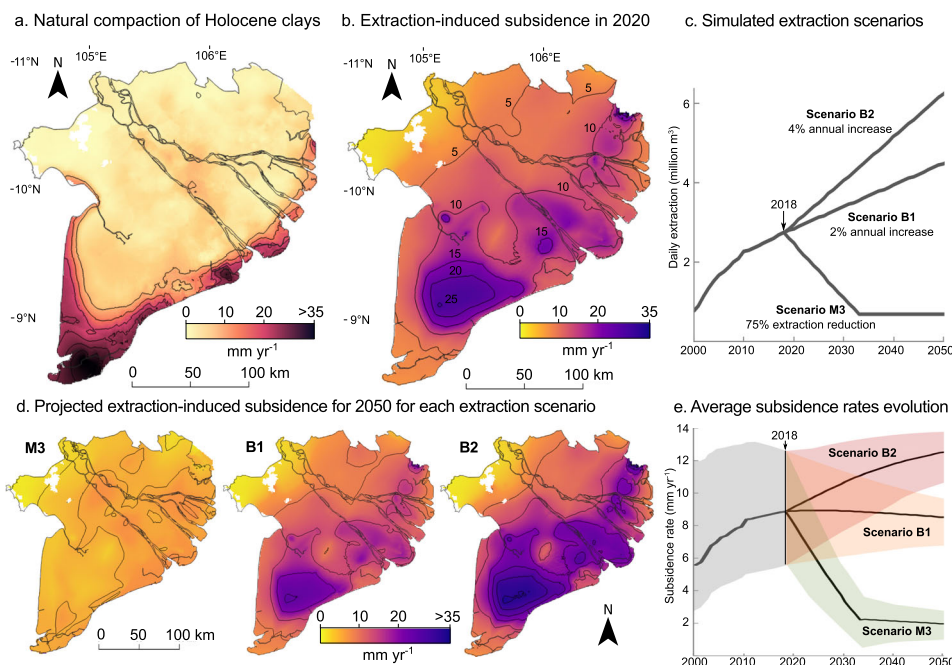


Fig. 3 Natural compaction and extraction induced subsidence projections for the Mekong delta. **a** Estimated maximum annual natural compaction in the Mekong delta, based on the spatial distribution of Holocene clays and modelled natural compaction rates following delta evolution²⁶. The maximum delta-wide average rate is 4.4 mm/yr, skewed by high rates at the coast. **b** Extraction-induced subsidence following simulated aquifer-system compaction for 2020 following scenario B1 (modified after Minderhoud et al.²⁵). **c** Simulated extraction scenarios of daily extraction evolution until 2050 in the Mekong delta. **d** Projected extraction-induced subsidence for 2050 following the three extraction scenarios in (c). **e** Temporal evolution of extraction-induced subsidence rate following the three extraction scenarios. The coloured envelopes show the minimum and maximum rate following geotechnical parameter uncertainty (modified after Minderhoud et al.²⁵), while the black line shows the best estimate rate used in the analyses.

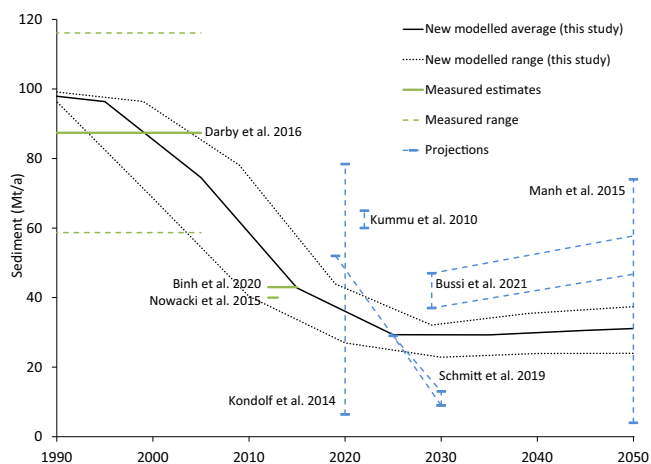


Fig. 4 Estimated and projected sediment delivery to the Mekong delta. Data are taken from published measured estimates^{19,52,56}, published modelled projections^{20,55,75,105,106} and new modelled projections (see Methods for model details). Historical Holocene sediment loads are estimated to be around 160 Mt/a¹⁹.

other environmental change scenarios such as climate change (Fig. 4). Projections of future sediment loads have given a large range of potential sediment delivery to the delta, as they take into account uncertainty both in future anthropogenic activities (predominantly dam construction) and the physical response of the system to changes.

Considering recently published suspended sediment load estimates^{19,52,56}, we have undertaken updated scenario modelling of potential future sediment delivery to the Mekong delta to 2050, accounting for the newest reservoirs, to produce new projections

more aligned with recent measured estimates. The future scenarios consider the range of potential dam construction (from no further dams to all planned dams constructed) and three climate change scenarios (RCP2.6, 4.5, 8.5). See Methods for details of the model and scenarios. Averages of the new projections are used as best estimates for suspended sediment available for managed sedimentation strategies in the Mekong delta, while the maximum and minimum projected values from the literature are taken as extremes.

Projected delta elevation change factors. Land surface elevation change relative to sea level in the Mekong delta depends on three main factors (Fig. 5): i) accumulation of new sediments through fluvial sediment deposition and in situ organic matter production increases surface elevation, ii) land subsidence, at delta scale predominantly caused by natural compaction of shallow sediments and aquifer-system compaction following groundwater overexploitation, results in surface elevation lowering, and iii) global, or climate change-induced, sea-level rise⁴⁶. Recent process-based, numerical model projections of subsidence and sea-level rise in combination with newly modelled estimates of future fluvial sediment supply and in situ organic sedimentation enable the evaluation of present and potential future elevation evolution of the Mekong delta. Under past conditions before considerable anthropogenic influence (‘Pristine’ in Fig. 5a), sedimentation processes exceeded RSLR, which enabled the Mekong delta to grow to its modern size. Anthropogenic subsidence and climate change-induced sea-level rise recently moved the elevation balance of the Mekong delta past its tipping point from delta-wide average positive to negative elevation change. Our new assessment suggests that loss of delta plain elevation could cause the average elevation of the Mekong delta to decrease by half a meter relative to local mean sea level by 2050 (Fig. 5b).

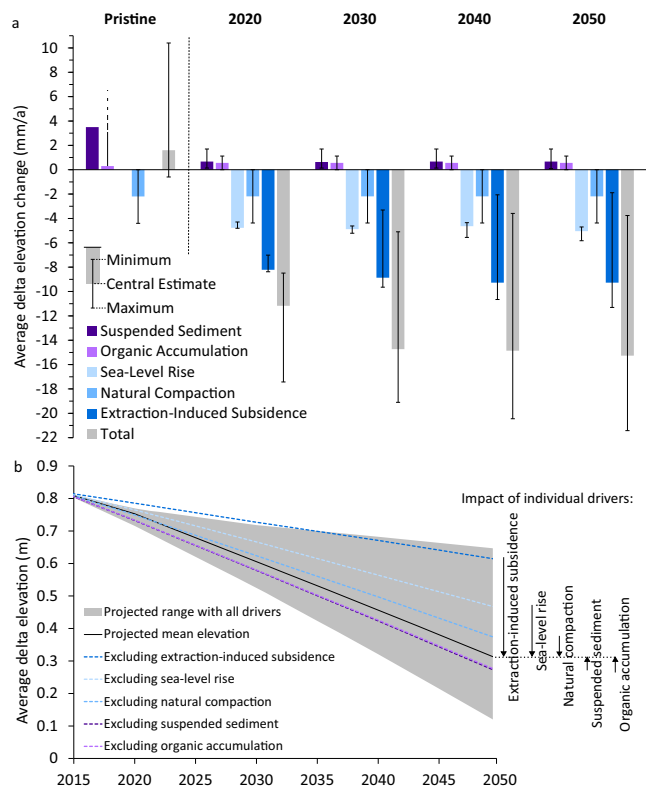


Fig. 5 Contribution of individual drivers to the mean elevation of the Mekong delta over time. **a** Changes in five main drivers affecting delta elevation, with values pre-anthropogenic influence ('Pristine') and modelled projections (2020–2050); **b** projections of the mean elevation of the Mekong delta under future scenarios, showing the influence of the individual drivers. For suspended sediment, central estimates are the average of new modelled scenarios, while minimum and maximum are from the range reported in the literature. For organic accumulation, the range is calculated using an equation giving the maximum values, the minimum is assumed to be 0, and the average of these is taken for the central estimates. For sea-level rise, RCPs 2.6, 4.5, and 8.5 were used to provide the minimum, central, and maximum values⁴⁶. For natural compaction, the maximum is the maximum delta-wide average rate of 4.4 mm/y (Fig. 3a), the minimum was assumed to be zero, and the average is taken for the central estimate. For extraction-induced subsidence, the M3, B1, and B2 scenarios from Minderhoud et al.²⁵ were taken as a minimum, central, and maximum values respectively. See Methods for details.

Traditionally, fluvial sediment deposition is considered to be the main driver of delta elevation gain^{6,7} and organic accumulation is considered less important for deltas globally⁵⁷. Our results reveal, however, that given the extreme decreases in fluvial sediments in the Mekong river in recent decades, in situ organic matter accumulation (for example organic residue from rice agriculture¹⁵) could contribute more to elevation gain in the delta than fluvial sediments. This could mean a substantial shift in sustainable delta management, from a primary focus on fluvial sediments towards additionally stimulating in situ organic sediment production and retention. Next to the potential to raise elevation, increasing organic sedimentation will also lead to other beneficial effects like soil carbon sequestration⁵⁸.

Elevation projections. Drivers of elevation change are spatially and temporally variable across the delta. Therefore, we used a spatially explicit quantification of natural compaction, and spatial-temporal

explicit numerical model quantifications of extraction-induced subsidence to project future elevation change. Projections of sea-level rise and organic accumulation are temporally variable and were spatially uniformly distributed across the delta. On top of these baseline elevation projections, scenarios of fluvial sediment deposition were considered in four areas to demonstrate potential sedimentation strategies (Fig. 6). The two spatially smaller scenarios (i.e., low-elevation splay and Can Tho) use not the entire Mekong river load but the sediment load measured for the Bassac River (Sông Hậu) at Can Tho (43% of the total⁵⁹) as this distributary would be the sediment source. The scenarios assume enabling conditions resulting in an optimistic 50% trapping of the total available suspended sediment in the river (with 25 and 75% taken for the minimum and maximum scenarios respectively, see Methods), which is the total amount of sediment that is extracted from the river and retained in the diversion area, proportional to the available suspended sediment in the river. In this research, we combine the two processes of sediment diversion from the river and sediment retention in the diversion area as they both modulate the proportion of the total fluvial sediment contributing to elevation gain. Both processes are also dependent on the exact method of operating the diversion. If in reality less sediment is diverted (e.g., 10% as modelled for the Mississippi^{42,43}) and retained, the resulting elevation gain will logically also be lower, therefore the results should be regarded as optimal scenarios under enabling conditions of sediment trapping.

Our quantifications (Fig. 6) reveal that even under optimistic assumptions of sediment trapping efficiency, the projected sedimentation is not enough to compensate for the elevation loss over large areas, and only when sedimentation strategies are focused on a small area can they make a noticeable difference and result in relative elevation gain (i.e., Scenario D, Can Tho). Even with 30 years of continued sedimentation strategies, the three areas covering the largest spatial area (Strategy A–C, Fig. 6) are projected to have lower average elevations in 2050 than in 2020 in the central scenario (see Data Availability for other scenario results⁶⁰). This clearly demonstrates that in the vast majority of the delta, the current and projected wildly unsustainable practices leading to major elevation loss cannot be compensated for entirely by sedimentation management, even under optimistic projections. In case of Strategy D, in which all efforts are focused on the surroundings of Can Tho, a sedimentation strategy can successfully result in an elevation gain.

Our quantifications show that sedimentation strategies will not solve the problem of RSLR in the Mekong delta; however, this does not mean they should not be implemented. First, vegetation growth in designated fluvial sedimentation areas can further stimulate the accumulation of in situ organic sediment, which under effective management will increase elevation gain. Second, flood deposits deliver nutrients to the land. Third, as the upper limit of each scenario shows, the combination of different environmental preservation measures, i.e., building elevation with sediments while reducing elevation loss by mitigating extraction-induced subsidence, will have considerable effects on projected elevation in 2050. This way sedimentation strategies can become part of a larger integrated delta management plan which in turn increases the effectiveness of the strategies themselves. So even though the effect of sedimentation strategies may be limited in mitigating relative sea-level rise, reconnecting the river with the delta plain and reinstating flooding processes is a recommendable management approach.

Impact of potential dam removal. To examine the entire spectrum of potential futures, we also considered several scenarios in which the future sediment load in the Mekong river increases

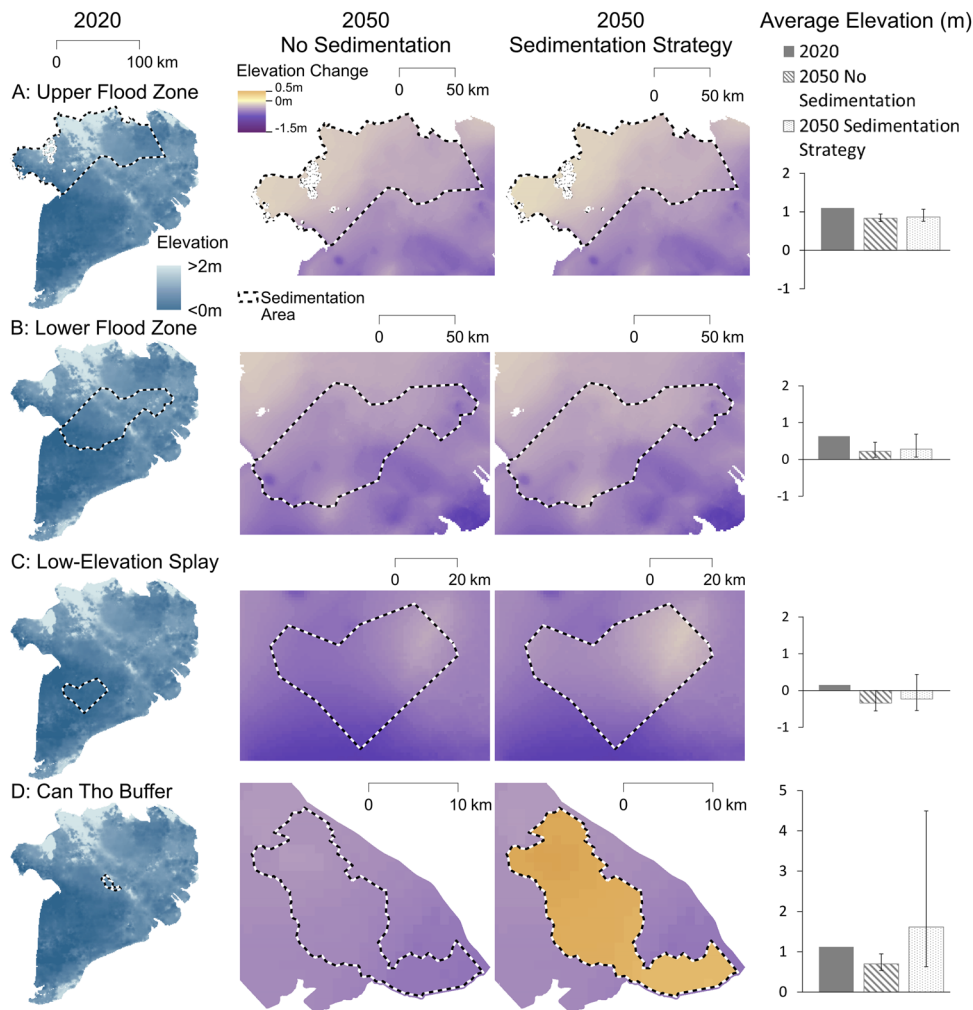


Fig. 6 Elevation projections in the Mekong delta. These projections account for sedimentation strategies, central estimates of extraction-induced subsidence, natural compaction, sea-level rise and organic accumulation. Graphs give the average elevation for the selected areas and the error bars give the min-max range using all elevation drivers (Fig. 5b). See Data Availability for elevation maps of other scenarios⁶⁰.

instead of declines further. As dams are the main cause of fluvial sediment reductions⁵⁵, we explored the potential effect of several dam removal scenarios. If we assume no further dams are built from 2020 and existing dams are removed 50 years after construction, the fluvial sediment delivery could return to pre-Anthropocene levels (160 Mt/a)¹⁹ by the end of the 21st century, as all dams will have been removed by 2070. In case new dams continue to be built along with the condition of removal after 50 years, by the end of the century sediment flux could increase 3–4 fold compared to current levels to over 120 Mt/a. If we assume a longer dam lifetime of 100 years instead of 50, as 50 years would be considered a short lifetime for many dams, noticeable effects on the sediment load are not seen this century due to the very recent boom in dam construction. Another dam removal strategy could focus on only removing the largest dams which trap the most sediment. If, for example, the largest 10% of dams in the database (25 dams) are removed in 2050 and no further dams are built after 2020, this dam removal strategy could see sediment delivery to the delta rebound to almost half of the pre-Anthropocene value (66 Mt/a) by the end of the 21st century (Supplementary Table 1, see Methods for details).

The above quantification shows the potential for dam removal to boost fluvial sediment supply and increase the effectiveness and feasibility of managed sedimentation for elevation maintenance in the Mekong delta. However, as sedimentation strategies are

evaluated here to 2050, the example dam removal scenarios would have minimal effect on their efficacy because any increases in sediment flux are small for all scenarios before 2050. Apart from the benefits for delta sedimentation, dam removal could have other positive consequences e.g., restoring the flood regime and ecological connectivity of the Mekong river⁶¹. However, there is no precedent for such dam removals in the Mekong basin, and such projects would be challenging considering international relations between the riparian countries. Additionally, given the current and near-future rates of RSLR, dam removal strategies that increase sediment flows decades from now will be too late to sustain a large part of the current delta. These strategies could, however, contribute to long-term future sustainability, particularly considering the other benefits of dam removal.

Implications for delta sustainability. The Mekong delta is experiencing unprecedented high rates of RSLR, dominated by anthropogenic accelerated subsidence^{25,31}. Although sedimentation strategies are promoted as the solution to RSLR in the Mekong delta³², they will not save the delta alone. If current environmental trends in the Mekong delta continue, with high demand for groundwater extraction causing accelerated subsidence, as well as low sediment availability, it will be nearly impossible to use natural delta-building processes to maintain the delta through the 21st century. It is therefore crucial to also

engage in strategies to minimise RLSR by other means such as reducing groundwater extraction and increasing fluvial sediment delivery⁶².

Our results show that under current conditions managed fluvial sedimentation strategies will likely not be sufficient to result in a net elevation gain when applied to large areas under current environmental trajectories of subsidence and sea-level rise, even under optimistic assumptions of sediment trapping. In addition, if more of the available fluvial sediment is effectively rerouted and deposited on the delta plain, this will allow less sediment to reach the downstream coastal area. Attempts to increase the sustainability of the delta plain may therefore come at the expense of similar efforts downstream where coastal erosion is already occurring due to sediment starvation¹⁵, which undermines protective ecosystems such as mangroves^{63,64} and could thereby hinder antierosion efforts. This underscores the fact that there is simply not enough fluvial sediment present to sustain the Mekong delta at its current spatial extent.

This research presents the first combination of the physical factors affecting RSLR in the Mekong delta in such numerical detail. The results should be regarded as first step toward more advanced solution strategies in which sedimentation is planned with delta residents and combined with mitigation of e.g., extraction-induced subsidence. The results presented here were modelled under assumptions of extremely optimistic enabling conditions, on a spatial scale which has never before been implemented, which highlights the magnitude of the effort that would be required to make sedimentation strategies effective for even a small part of the existing Mekong delta. Additional uncertainties on the feasibility of implementing such sedimentation strategies which require further research are the effects of sand mining causing bank erosion²¹ and channel deepening amplifying tidal amplitudes¹⁶ on the morphodynamics and suspended sediment availability in the river system. In the current situation, the most effective way to reduce RSLR and preserve elevation in the Mekong delta is to not focus on a single factor controlling delta elevation but to combine strategies that address multiple components simultaneously. The largest gains in elevation preservation lie in mitigating subsidence²⁵, and combined with sedimentation strategies explored in this study the highest results can be achieved. However, even under the most optimal scenario, RSLR still occurs in the Mekong delta and will require additional adaptation measures. The popular alternative to sediment-based adaptation is hard engineering to prevent widespread flooding and land loss¹. Considering the massive size of the Mekong delta and high projected rates of RSLR, protective engineering to preserve the entire delta will eventually become economically if not technically infeasible. Looking for solutions to this crisis will mean exploring alternative strategies and considering alternative scenarios, including a managed retreat⁶⁵.

One novel option that follows from the insight of this study is that currently the potential for organic matter accumulation from rice agriculture residue is now on par with or greater than the potential of fluvial sediment to build elevation. This situation has not been recognised before because historically fluvial sediment was far more important for delta-building than organic accumulation^{6,7,15}. Rapidly changing environmental conditions in recent years mean that management strategies stimulating in situ organic matter production and deposition are increasingly viable for elevation maintenance. The strategy to raise land using organic matter, for example, by using agricultural waste or modifying environmental conditions to stimulate biomass accumulation and deposition, requires extensive further research into implications for water management, efficiency, cost, distribution, societal acceptance, and environmental health

among other factors, but considering the limited alternatives in the Mekong delta it should be seriously considered. Moreover, effective burial and preservation of organic material also contributes to soil carbon sequestration⁵⁸ which aligns with sustainability targets of the Vietnamese government, expressed in their Resolution 120: 'Sustainable and Climate-Resilient Development of the Mekong Delta of Viet Nam'³³. While it is vital for the sustainability of the Mekong delta to reduce land subsidence e.g., by reducing groundwater extraction²⁵, such sedimentation strategies could effectively delay the rate of relative elevation loss and buy the delta more time to adapt to the future⁶⁶.

Methods

Fluvial sediment modelling. The projections of suspended sediment delivery to the Mekong delta of Dunn et al.⁶⁷ have been improved by using more basin-specific data such as additional planned dam data (Supplementary Fig. 2) and different dam construction scenarios, which was not possible in the previous work due to the global nature of the modelling. The new sediment projections use water discharge from the WBMsed model⁶⁷ to drive the BQART equation⁶⁸ on an annual timestep, as well as annual trapping efficiency considering the volume of additional reservoirs constructed in the basin each year. The dam data used here is a combination of the GRanD (Global Reservoir and Dam) database^{69,70} for existing dams plus the MCR (Mekong River Commission) and WLE (Water, Land and Ecosystems) databases for planned dams^{71–73}. It is assumed, as shown by Dunn et al.⁶⁷, that other direct anthropogenic influences change minimally over the modelled time period 1980–2050 so the anthropogenic factor was considered constant (1), as was glacier cover (622 km²), lithology (1), basin area (656,364 km² at the delta apex), and relief (5612 m). Temperature data was taken from Jones et al.⁷⁴ for consistency with the hydrological projections. The updated model gives favourable results when compared to measured values from Nowacki et al.⁵⁶, Darby et al.⁵², and Binh et al.¹⁹ (Fig. 4).

The central fluvial sediment scenario used in this research and presented in the paper is the average of the new sediment projection scenarios, using 3 climate projections (RCP 2.6, 4.5, 8.5) and 2 dam construction scenarios: existing dams only, and all planned dams constructed. This results in the assumption that some of the planned dams are built and some of them are not, without deciding which individual dams are constructed. This averaging avoids the complex decision-making processes related to dam construction, which is determined by political, social, economic, and environment factors among others. The range given in the literature is used for the minimum^{20,75} and maximum^{15,20} fluvial sediment scenarios (Fig. 4, Supplementary Table 2). Minimum values may occur if dams have a higher trapping efficiency than assumed here, additional dams are planned and constructed, or there are minimal erodible sediment deposits downstream of dams. Maximum values may occur if dam management lowers trapping efficiencies, less dams are built, dams are removed, or there are erodible deposits downstream of dams.

For the scenarios of dam removal, the only difference to the above modelling was to change the number of dams in the basin over the 21st century based on age and size criteria. Timelines were created both assuming that no further dams are built, and that all the planned dams are constructed. On top of these timelines, scenarios were created on dam removal assuming: dams >50 years old removed, dams >100 years old removed, largest 10% of dams removed, largest 1% of dams removed. Numbers given in the text are based on the 2070–2099 averages of three climate scenarios (RCP2.6, 4.5, 8.5). See Supplementary Table 1 for decadal results.

Considering the sedimentation scenarios, we assumed a sediment trapping efficiency of 50% for the central scenario presented in the paper, following optimistic enabling conditions, with scenarios of 25 and 75% available as data downloads⁶⁰. The percentages are the total amount of sediment that is diverted from the river and retained in the diversion area, proportional to the available suspended sediment in the river. While in reality sediment trapping naturally varies spatially over delta plains⁷⁶, and artificial sedimentation management strategies would not accumulate sediment uniformly, here we assume a uniform sediment retention in each scenario within each sedimentation area as the spatial morphodynamics depend on exact strategies, management and local conditions, the modelling of which is beyond the scope of this study. The maximum trapping efficiency was calculated from the estimated sediment export to the sea of 40 ± 20 Mt/a 2009–2016^{56,59} along with our fluvial sediment estimate of 30–81 Mt/a at Kratie over the same period, which gives a maximum retention of 75%. This maximum retention value was selected assuming the favourable conditions which would be created under scenarios of active sedimentation management. This retention estimate also allows for sediment deposition in between Kratie (location of sediment projections) and the delta, primarily assumed to be in Tonle Sap lake in Cambodia (up to 10% of load at Kratie^{75,77}). For scenarios A and B (Fig. 2) the total fluvial sediment load of the Mekong river was used (after considering trapping efficiency) as the sedimentation strategy areas are located adjacent to the main river branches, granting access to the full sediment load of the river. Scenarios C and D are located in the southwest of the delta and only have access to the Bassac/Hâu River for sediment delivery. Therefore we only considered the fraction of the total

sediment load carried by this river branch (43% of the total load at Kratie⁵⁹) for these two scenarios.

Organic Accumulation. In addition to elevation gain from fluvial sediments, there is the potential to gain elevation from in situ organic matter production and accumulation. Historically organic matter came from ecosystems such as mangroves, so for estimating 'pristine' organic matter contribution we use values of modern mangrove contribution⁷⁸. The current main potential for organic accumulation is assumed to come from rice agriculture waste because of the dominance of rice agriculture in the Mekong delta (Supplementary Fig. 3), as also suggested in the previous work¹⁵. Previous research has focused on the effects of incorporating rice straw and compost on agricultural productivity (e.g. it has been shown to increase rice yields⁷⁹) and therefore predominantly monitored crop yield and soil properties important for plant growth^{80–82}. Incorporating composted rice straw into rice paddies increases soil organic carbon⁸¹, and does so more effectively than uncomposted⁸³. Composting is also required to mitigate environmental health hazards¹⁵. We anticipate rice litter to be composted for several months^{81–84} on site after harvesting and ploughed several decimeters into the paddy soil before planting following suggested best-practices^{81,84}. In this research, we assumed that organic matter comes from rice straw from local agriculture within each respective sedimentation area.

The potential volume of organic matter is calculated as follows:

$$\text{available organic matter} = \text{straw yield} \times \text{rice agriculture area} \\ \times \text{composting loss} \times \text{volume conversion}$$

The rice agriculture area was calculated from the 2010 national land use map as $2 \times 10^4 \text{ km}^2$ for the whole delta. Mass loss during composting is assumed to be 19%⁸⁵. To convert the mass to volume 0.6 t/m^3 is assumed for the compost, as measured for in the Sacramento-San Joaquin delta⁸⁶. As the bulk density value used was measured in deposited sediments, it is not the value for the compost as it is incorporated into the topsoil but rather takes into account some compaction postdeposition. Compaction due to decomposition will reduce compaction and therefore elevation loss through decomposition once it is incorporated into soils, and can also be reduced by effective water table management, keeping it high enough throughout the year to inhibit aerobic respiration and therefore decomposition. Straw yield is measured in t/ha/a of rice agriculture, and a range is taken from the literature (minimum 9 t/ha/a ⁸⁷, maximum 15.4 t/ha/a ⁸⁸). For the whole delta area, these calculations result in $19\text{--}32 \text{ Mt/a}$ total uncomposted rice straw (Supplementary Table 2), which compares favourably with estimates of $24\text{--}29 \text{ Mt/a}$ from the literature^{15,87–89}.

Natural compaction. Natural compaction mainly occurs in the shallow subsurface as young, fine-grained deposits such as clays, silts and organic sediments become increasingly compressed and lose volume with time under the weight of the overburden. The rate at which this natural compaction happens at present is dependent on the depositional history of the sediments during delta evolution in recent millenia²⁶. Measurements of shallow natural compaction are scarce and limited to only a few locations where relative surface elevation tables are installed^{90,91}.

Zoccarato et al.²⁶ used a novel 2D tool to simulate natural compaction of Holocene sediment in the south part of the delta (see transect Supplementary Fig. 1a) and validated the relative surface elevation table-measured rates as a function of delta evolution. We took the 100-y-averaged (21st century) natural compaction rate in the transect as the central estimate for the present annual natural compaction rates of the 18 m Holocene clay cover (Zoccarato et al.²⁶ scenario B). We extrapolated this transect to create a first delta-wide natural compaction map in the Mekong delta by combining it with estimates of Holocene coastline progradation quantifying the delta surface age (based on Nguyen et al.⁹², Ta et al.⁹³, Tamura et al.⁹⁴), for the theoretical situation in which the entire Holocene delta existed of a homogeneous clay layer of 18 m thickness (Supplementary Fig. 1a). This map of natural compaction rates was divided by 18 to create a spatially explicit estimate of depth-averaged natural compaction per meter clay present in the Mekong delta. This map of average natural compaction rate of 1 m clay was subsequently multiplied with a map of the actual total thickness of Holocene soft clay occurrence created based on 1243 borehole descriptions^{45,95} (Supplementary Fig. 1b) to arrive at the first delta-wide map of annual natural compaction rate estimates of Holocene clays for the entire Mekong delta (Fig. 3a).

On average the delta experiences 4.4 mm/a , a value which is dominated by the high rates of annual compaction ($>35.0 \text{ mm/a}$) in the recently formed southern coastal part of the delta. These estimates should be considered as maximum potential natural compaction rate at present in the Mekong delta as delayed overpressure dissipation in fine-grained deposits (the driving process in model quantifications of Zoccarato et al.²⁶) may have occurred faster in reality than in the model (for example, through hydraulic shortcuts of coarser sediments present in nature). For this reason, we took our newly estimated natural compaction as the maximum in the elevation quantifications. As the minimum estimate, we consider the situation in which all overpressure dissipation has occurred in the past and also no meaningful creep (i.e., time-dependent compression) occurs anymore (for example as a result of heavy preloading of the subsurface in the past), in which case

natural compaction will be zero. As the central estimate, we assume half the maximum natural compaction rate.

It is important to realise the existing relation between natural compaction and newly deposited sediments. In case of the implementation of a sedimentation strategy, the new sediments will increase the overburden, which in turn will increase natural compaction rates and thus create an additional negative effect on surface elevation change. In simple words, more sedimentation means higher rates of subsidence. The quantifications done by Zoccarato et al.²⁶ include this relation between the sedimentation and compaction, and assume a dynamic balance between sediment deposition and natural compaction. Here we use the range between zero natural compaction and this first order, delta-wide estimate of maximum natural compaction of Holocene sediments (with the central estimate being the average of the two) to cover the potential effect of additional natural compaction created by overburden loading. Note that this effect will be stronger, and therefore more skewed towards the maximum estimate, with more overburden. Therefore in the sedimentation strategy for the Can Tho buffer, in which a lot of new sediment is deposited over a small area, this effect will be much larger and our estimates may therefore underestimate natural compaction. However, we lack the data to quantify this dynamic feedback explicitly for each sedimentation strategy. This would require a fully coupled numerical model like Zoccarato and Teatini⁹⁶ as applied in Zoccarato et al.²⁶ and future work may benefit from this. For this study, we assume and expect that the large range used for natural compaction covers the uncertainty created by this additional overburden loading.

In addition to compaction of already existing sediments, the new sediments that are deposited during the sedimentation strategy will also compact over time with dewatering and additional overburden. This effect is implicitly accounted for by our way of calculating volume (m^3) from the amount of sediment (Mt) using the average, measured density of shallow delta sediments. These measured sediments have already undergone some natural compaction. For our projections, we assume the same degree of compaction for the newly deposited sediments and this way compaction is included in the final volume (elevation) gain calculations.

Extraction-induced subsidence. To quantify present and potential future groundwater extraction-induced subsidence, we use the best-estimate quantifications following three extraction scenarios in the Mekong delta computed by Minderhoud et al.²⁵ using the updated 3D hydrogeological model. The scenarios start from the year 2018, in which the simulated extraction-induced subsidence for the Mekong delta is on average of 8.9 mm/yr (Fig. 3b)²⁵. As the central scenario, we selected the business-as-usual extraction pathway that follows a moderate linearly increase of annual extracted volume with 2% of the total extracted volume in 2018 (scenario B1²⁵). In this scenario, delta-average extraction-induced subsidence stays more or less constant throughout the modelling period with a delta-average rate of 8.5 mm/y in 2050. As the maximum scenario, we use an extraction pathway in which the annual extracted volume increases linearly with 4% of the 2018 volume (scenario B2²⁵). In this scenario, delta-wide average subsidence rates will further increase until 12.5 mm/y in 2050. For the minimum scenario, we adopt the mitigation scenario (scenario M3²⁵) in which groundwater extraction is gradually reduced by 75% of the 2018 volume over the course of 15 years (Fig. 3c). As a result, extraction-induced subsidence also considerably decreases to 1.9 mm/yr in 2050 (Fig. 3d). For more details on the modelled extraction scenarios see Minderhoud et al.²⁵.

Sedimentation Strategy Areas. For our sedimentation strategy scenarios, we selected four areas where we quantified the potential effect of sedimentation on future elevation development. As the focus of the sedimentation strategies is to maintain (vertical) delta plain elevation, we do not consider scenarios to maintain or build new land at the coastline. The selected sedimentation strategy areas are presented as examples of what may be possible considering projected physical processes, not suggestions for desirable solutions. Optimal sedimentation strategies for the Mekong delta must also account for human dimensions, such as livelihoods, land management and economics, to ensure that they address all aspects of delta sustainability. Furthermore, our approach does not include morphodynamical analyses of water and sediment flow to create spatially variable sediment deposition within the strategy areas, as this is well beyond the scope of this study. Hence, the effects of flood pulses, tides and/or other marine processes on sediment distribution are not included, but form topics for future research. The presented areas instead provide a range of example sedimentation strategies, from a larger area, lower intensity (considering energy, capital, and engineering) scenarios (A and B) to a smaller area, higher intensity scenarios (C and D).

Scenario A (Fig. 2a) encompasses the area of the 'traditional' flood extent, delineated by combining maps from Triet et al.²², Hung et al.⁹⁷, Manh et al.⁹⁸, and Kuenzer et al.^{47,99}. The area uses the Cambodia-Vietnam border as the northern boundary and the Saigon delta as the eastern boundary, as we only consider the area influenced primarily by the Mekong river and its distributaries in Vietnam. The area also excludes bedrock areas in the west ($>10 \text{ m}$ according to SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) data), as these areas would not experience sediment deposition from flooding (areal selection similar to the approach and extent of the TopoDEM by Minderhoud et al.¹³). The sedimentation area of Scenario B (Fig. 2b) was delineated considering

that water levels and therefore potentially flooding are increasing in the seaward parts of the delta, attributed to factors such as subsidence, channel siltation, sea-level rise, tidal range amplification, and dyke construction to prevent flooding in the upper part of the delta^{16,22,23,47,48,99–102}. This area is also restricted in the east to the Saigon delta boundary.

The area of scenario C (Fig. 2c) is an example of managed sedimentation targeting one of the lowest parts of the delta. The area was delineated based on elevation (on average 0.15 m above local mean sea-level in 2020), water infrastructure and land use (using aerial imagery from Google Earth, Esri, Maxar, GeoEye, EarthStar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community), selecting the lowest, preferably agricultural areas, within dykes which could either be breached to allow flooding for sedimentation or used to prevent floods spreading outside of the chosen area. The areal extent of Scenario D (Fig. 2d) is much smaller and involves a targeted intensive sedimentation strategy. The goal of this strategy would be to create a protective ring of higher elevated land around the existing urban area of the largest city in the delta, Can Tho. This measure may increase flood protection for the city while also providing higher elevation land for the growing city to expand onto in the future. This final strategy represents a novel logistical challenge, as existing strategies have relied on gravity-driven flows whereas the suggested sedimentation area will eventually be elevated above the surrounding landscape. This strategy would therefore be much more resource-intensive than the others, but it is assessed here in terms of the elevation and sediment budget rather than economic feasibility or desirability.

Projected elevation scenarios. To create the elevation projections following the scenarios we used the recent TopoDEM of the Mekong delta, derived from elevation points from the 2014 topographical map with a 1 km × 1 km resolution^{13,103} for Scenarios A–C. For scenario D we used a LiDAR-based DEM with a resolution of 50 × 50 m interpolated (median value) from LiDAR data acquired in 2009 and 2010. Sea-level rise values were taken from spatially explicit projections and averaged for the cells immediately adjacent to the coast of the Mekong delta⁴⁶. We calculated the minimum, maximum, and central projections for organic matter (constant and spatially uniform, Supplementary Table 2), sea-level rise (temporally explicit and spatially uniform, Supplementary Table 2), natural compaction (constant and spatially explicit, Fig. 3a), and extraction-induced subsidence (temporally and spatially explicit, Fig. 3d) (see previous sections) and combined them with the DEMs to get minimum, maximum, and central elevation projections for 2050. The maximum, minimum, and central fluvial sediment values are then used to create a range of scenarios for each of the four potential sediment areas. The central scenarios are presented in the paper, and the others can be downloaded⁶⁰ (see Data Availability).

Data availability

The spatial datasets generated during this study are available from <https://doi.org/10.5281/zenodo.5645494>. The TopoDEM used in the work is available at <https://doi.org/10.1594/pangaea.902136>.

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Author contributions

FED performed the fluvial sediment modelling and the data analysis of the elevation change factors and PSJM performed the quantifications of natural compaction and extraction-induced subsidence. Both authors jointly designed the study, interpreted the results and wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Frances E. Dunn or Philip S. J. Minderhoud.

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