Nguyen, M. V., Nguyen, D., Hung, N. N., Kummu, M., Merz, B., Apel, H. (2015): Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. - *Global and Planetary Change*, *127*, p. 22-33.

DOI: http://doi.org/10.1016/j.gloplacha.2015.01.001

Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise

Nguyen Van Manh, Nguyen Viet Dung, Nguyen Nghia Hung, Matti Kummu, Bruno Merz, Heiko Apel

PII: S0921-8181(15)00016-8
DOI: doi: 10.1016/j.gloplacha.2015.01.001
Reference: GLOBAL 2229

To appear in: *Global and Planetary Change*

Received date: 5 August 2014
Revised date: 14 November 2014
Accepted date: 5 January 2015

Future sediment dynamics in the Mekong Delta floodplains: impacts of hydropower development, climate change and sea level rise

NGUYEN VAN MANH[1,4], NGUYEN VIET DUNG[1,2], NGUYEN NGHIA HUNG[2], MATTI KUMMU[3], BRUNO MERZ[1] and HEIKO APEL[1]

[1] {GFZ - German Research Center for Geoscience, Section 5.4 Hydrology, Potsdam, Germany}

[2] {SIWRR - Southern Institute of Water Resources Research, Ho Chi Minh City, Vietnam}

[3] {Water & Development Research Group, Aalto University, Espoo, Finland}

[4] {IWARP - Institute of Water Resources Planning, Hanoi, Vietnam}

Correspondence to: **NGUYEN VAN MANH** (donmanh2014@gmail.com)

Abstract

The Mekong Delta is under threat due to human activities that are endangering livelihood of millions of people. Hydropower development, climate change and the combined effects of sea level rise and deltaic subsidence are the main drivers impacting future flow regimes and sedimentation patterns in the Mekong Delta. We develop a sensitivity-based approach to assess the response of the floodplain hydrology and sediment dynamics in the Delta to these drivers. A quasi-2D hydrodynamic model of suspended sediment dynamics is used to simulate the sediment transport and sediment deposition in the delta, including Tonle Sap Lake, for a baseline (2000-2010) and a future (2050-2060) period. For each driver we derive a plausible range of future states and discretize it into different levels, resulting in 216 combinations. Our results thus cover all plausible future pathways of sediment dynamics in the delta based on current knowledge. Our results indicate that hydropower development dominates the changes in floodplain sediment dynamics of the Mekong Delta, while sea level rise has the smallest effect. The floodplains of the Vietnamese Mekong Delta are much more sensitive to the changes compared to the other subsystems of the delta. The median changes of the three drivers combined indicate that the inundation extent would increase slightly, but the overall floodplain sedimentation would decrease by approximately 40%, and the sediment load to the South China Sea would diminish to half of the current rates. The maximum changes in all drivers would mean a nearly 90% reduction of delta sedimentation, and a 95% reduction of the sediment reaching the sea. Our findings provide new and valuable information on the possible future development of floodplain hydraulics and sedimentation in the Mekong Delta, and identify the areas that are most vulnerable to these changes.

Keywords

Floodplains, sediment dynamics, dam impact, climate change, sea level rise.

Highlights:

We examine the future sediment dynamic in the floodplains of the Mekong Delta using a hydrodynamic model and sensitivity-based approach.

Plausible ranges of impacts are determined for the delta boundaries.

Hydropower dams are the dominant impact driver on floodplain sediment dynamics

Climate change and sea level rise acts as second-order impact effect.

The floodplains in the Vietnamese part of the delta respond most sensitive to the expected changes.

1. Introduction

The Mekong Delta (MD) sustains the livelihood and food security of millions of people in Vietnam and Cambodia. It is known as "rice bowl" of South East Asia and has one of the world's most productive fisheries (Ziv et al., 2012). This high productivity is a consequence of the annual flood pulse and large amount of suspended sediments transported by the Mekong River to its extensive floodplains (Arias al et. 2014, Lamberts and Koponen 2008). The sediment load transported by the flood pulse to the floodplains provides nutrients for agriculture and plays a major role for the high biodiversity in the whole delta system. However, recent assessments classify the MD among the most vulnerable regions in the world due to climate change related sea level rise (Watson al et., 2013) and other human activities linked to the economic development of the six countries in the Mekong River Basin (MRB) (Syvitski, 2007, Syvitski al et., 2009). The ongoing hydropower development in the MRB impacts the flow regime (Lauri et al 2012, Piman et al 2013) and changes the sediment load entering the MD (Kummu et al. 2010; Kondolf et al. 2014). Economic development within the delta induces land subsidence, which in turn enhances the effect of climate change related sea level rise (Ericson 2006, Syvitski 2008, Syvitski 2009, Doyle 2010).

In total, 136 hydropower plants are being built or planned throughout the MRB. According to the current plans, 31 dams are under construction, 82 dams will be completed within 20 years and nearly all of the 136 dams will be built within the coming 40 years (MRC 2011b). These dams will trap considerable amounts of sediments, which in turn is very likely to strongly reduce the sediment input to the delta (Kummu et al. 2010; Kondolf et al. 2014). There is a particularly strong hydropower development in the Chinese part of the MRB known as the Langcang cascade (Fig. 1), which comprises approximately only 23% of the total basin area and provides 15% of the total annual flow volume, but is responsible for 65% of the total suspended sediment load (Kummu al et. 2010). A number of studies have estimated the consequences of hydropower development in the Lancang on sediment load (Lu and Siew 2006, Fu and He 2007, Fu et al. 2008, Kummu and Varis 2007, Walling 2008, Liu and He 2012, Liu et al. 2013, Kameyama et al. 2013). The sediment load reduction of reservoirs is commonly quantified by sediment trapping efficiency (TE). These studies find TE values of the Lancang cascade being within the range of 80-90% just downstream of the cascade and of approximately 50% at the Mekong Delta. An implementation of all 136 dams across the whole Mekong Basin is likely to result in massive reduction of sediment load in the Mekong Delta. Estimated TE varies from 78-81% by Kummu et al. (2010) to 85-90% by ICEM (2010), and 96% by Kondolf et al. (2014). Hydropower development will also alter the flow regime in the lower MRB and will increase the flows in the dry season and decrease those in the wet season (Keskinen et al. 2010, Räsänen et al. 2013, Lauri et al. 2012, Piman et al. 2013).

Climate change is expected to act as another main driver changing the hydrology in the MRB (Eastham et al. 2008, Hoanh et al. 2010, Västilä et al. 2010, Kingston et al. 2011, Lauri et al. 2012), however its impact on the flow regime of the Mekong River is highly uncertain (Lauri al et. 2012, Kingston et al. 2011). Hoanh (2010) and Västilä et al. (2010) use only one Global Circulation Model (GCM) and thus their findings are not reflecting GCM uncertainty as shown in Kingston et al. (2011) and Lauri et al. (2012). Eastham et al. (2008) examine eleven GCMs but they do not, however, downscale the GCM output to the MRB and their results are thus associated with very large uncertainty. Impact studies which have used a GCM ensemble approach along with downscaling have obtained a large range in future Mekong streamflow (Kingston et al. 2011, Lauri et al. 2012), mainly as consequence of different GCMs. Kingston et al. (2011) study the uncertainty resulting from different GCMs and different global warming assumptions on the flow at the Mekong River gauge Pakse having a more reliable historical discharge record compared to the next downstream station Kratie, which indicates the upper boundary of the MD. Lauri et al. (2012) used two emission scenarios and five GCMs to illustrate effects and uncertainties of climate change projections, and compared this to the expected changes caused by hydropower development. For the period 2032-2042, they find that hydropower development is very likely to have a much larger impact on the flow regime, particularly for the lower Mekong basin, compared to projected climate change impacts.

Another important driver of changes in the hydrology and sediment dynamics of the MD is sea level rise (SLR). The flow regime, and with that the sediment dynamics of the delta, are sensitive to changes in sea level (Manh al et. 2014). Higher sea levels would cause higher backwater effects, which in turn alter the water levels and flow velocities in the river system and the floodplain inundation. As a consequence also the sediment dynamics, i.e. the erosion and sedimentation, is expected to change, with distinct spatial differences. Also the flood hazard in the delta is likely to change with higher sea levels. For deltaic regions often effective sea level rise values are defined. Effective sea level rise is a combination of sea level rise caused by climate change and deltaic subsidence. Available studies (Ericson et al. 2006, Syvitski et al. 2009, Doyle 2010, MONRE 2012, Syvitski et al. 2012) indicate that, with economic development and population growth, deltaic subsidence is increasing and playing an important role in effective sea level rise. The main anthropogenic causes for deltaic subsidence are subsurface resource exploitation (oil, gas, groundwater) and accelerated ground compaction by urban growth (Syvitski et al. 2009).

It can be summarized that climate change and hydropower development along the Mekong River and its tributaries are expected to alter the hydrological regime and the sediment load at the upper boundary of the MD, while climate change related sea level rise and deltaic subsidence influence the lower boundary. Hence, the hydrology and sediment dynamics of the MD are subject to a superposition of these drivers of change. Moreover, the delta consists of an intricate system of rivers, channels and floodplains. A large degree of human interventions in the floodplains contribute to a highly variable hydrological system (Hung et al., 2012, 2014a, 2014b) and to very heterogeneous patterns of sediment transport and deposition (Manh et al., 2013, 2014). To date, there is no study available which quantifies the cumulative effects of these drivers on future hydraulics and sediment dynamics in the Mekong Delta in a spatially explicit manner. The purpose of this paper is to close this gap.

To achieve this goal, we assess the response of hydraulics and sediment dynamics of the MD floodplains to a plausible range of changes in the upper and lower boundary of the delta. We achieve our aim by using a sensitivity-based approach for all three above identified drivers. The plausible future pathways are used to drive a quasi-2D hydrodynamic model (Manh et al, 2014), including a suspended sediment transport module, for the whole MD floodplains. The model enables a quantification of the floodplain hydrology and sediment transport, providing spatially explicit information on the sediment deposition within the delta.

2. Regional Setting

The Mekong River is one of the major rivers of the world. It drains a total land area of 795,000 km^2, from the eastern watershed of the Tibetan Plateau to the South China Sea. The mean annual flood volume of the Mekong is approximately 475 km^3 (MRC 2009). The annual flood pulse in response to the Western North-Pacific monsoon and partially to the Indian monsoon during July to October is the key hydrological characteristic of the Mekong River. Estimates of the mean annual suspended sediment load of the Mekong at Kratie, just above the MD (see Figure 1), vary from 50 to 160 Mt (Walling 2008, Milliman and Farnsworth 2011, Lu et al. 2014), and about 50-65% of this load is contributed by the upper part of the basin in China (Roberts 2001, Walling 2008, Wang et al. 2011).

The MD is a large-scale and complex river, channel, and floodplain system with highly variable hydrodynamic characteristics (Hung et al. 2012). The sediment load transported to the MD has a very fine grain size (Hung et al. 2014a) and contains high nutrient fractions (Manh et al. 2013). Sediment-related nutrient deposition in the floodplains is a significant source of natural fertilizers for the rice crops in the delta (Manh et al. 2014). The sedimentation rates in the floodplains show a high variability in space, caused by the interplay of the complex river and channel network, two tidal systems and human regulation of floodplain inundation (Manh et al. 2013, 2014).

In this paper we divide the MD into four subsystems (Fig. 1): Tonle Sap, Cambodian Mekong Delta, Vietnamese Mekong Delta and coastal zones. The subsystem Tonle Sap consists of the Tonle Sap Lake (TSL) and the Tonle Sap River. During the rising stage of the flood season the Tonle Sap River diverts water with high suspended sediment concentration (SSC) in northern direction to the Tonle Sap Lake (Kummu et al. 2008). During the falling stage water from the TSL flows back to the Mekong River and further downstream to the Vietnamese part of the delta. This return flow has very low SSC, and Manh et al. (2014) estimate that 5% and 10% of the total sediment load entering the MD at station Kratie has been trapped in the TSL during the low flood in 2010 and the high flood in 2011, respectively. This is supported by the findings of Kummu et al. (2008) for the period of 1997-2003.

The subsystem Cambodian Mekong Delta (CMD) comprises the entire MD in Cambodia excluding the Tonle Sap subsystem. During the flood season, overbank flow from the Mekong and Bassac Rivers inundates the Cambodian floodplains. These floodplains are mostly in a morphological natural state.

Approximately 19%-23% of the total sediment load at Kratie is deposited in these floodplains (Manh et al. 2014).

The Vietnamese Mekong Delta (VMD) stretches from the national border just north of the cities Tan Chau and Chau Doc to the stations My Thuan and Can Tho at the Mekong River (Tien River in Vietnamese) and Bassac River (Hau River in Vietnamese), respectively (Fig. 1). The VMD consists of three regions: Long Xuyen Quadrangle (LXQ) west of the Hau River, Plains of Reeds (PoR) east of the Tien River, and the region between the Tien and Hau Rivers (THA). The VMD floodplains receive flood water from the Tien and Hau Rivers with high SSC, and from the overland flow originating from the Cambodian floodplains with lower SSC. The VMD is characterized by very strong human interference. Channels, with a total length of 91,000 km and dikes on both sides, form thousands of floodplain compartments. These compartments are linked to the channels by sluice gates, which are operated according to the rice crop water demand. Hence, sediment transport and deposition are highly variable in the VMD, depending on the setup of channels and compartments, on the flood magnitude, on the operation of sluice gates, and on the height of the dikes. Further, the tidal regime influences the hydrodynamic situation and the sediment transport. The sediment deposited in the VMD floodplains ranges from 1% in a low flood year to 6% in a high flood year relative to the total sediment load at Kratie (Manh et al. 2014).

The subsystem coastal zone is strongly affected by the semi-diurnal tide from the South China Sea (East Sea in Vietnam), the diurnal tide from the Gulf of Thailand (West Sea in Vietnam) and the mixed-diurnal tide in the interference area along the Ca Mau peninsula. The tidal magnitude in the Gulf of Thailand is about 0.5-1.0 m and as such much smaller than the tidal magnitude in the South China Sea, which ranges between 2.5-3.8 m (Nguyen et al., 2000). Thus the tidal effects differ in their magnitudes in different parts of the coastal zone. The coastal zone receives approximately 48-60% of the sediment entering the MD at Kratie (Manh et al. 2014).

3. Material and methods

Given the unpredictability of actual future hydropower development in the MRB and the large uncertainties in climate change impacts, we apply a sensitivity-based impact approach instead of a scenario-based approach. As argued by Prudhomme et al. (2010), this scenario-neutral approach allows rapid appraisal of impacts for different sets of boundary conditions, for example, when new climate change or hydropower development projections are available, without the need to undertake a new impact analysis.

3.1. Sensitivity-based, scenario-neutral approach

The sensitivity-based, scenario-neutral approach proposed by Prudhomme et al. (2010) is applied to quantify possible future sediment dynamics in the MD. In our assessment we consider the complete spectrum of changes that can be differentiated into three drivers: (1) hydropower development in the MRB influencing the streamflow and sediment load at station Kratie, the upper boundary of the MD, (2) climate change impact in the MRB and associated influence on streamflow and sediment load at Kratie, (3) effective sea level rise and its impact on floodplain hydraulics and sediment dynamics at the lower boundary of the MD. For each of these drivers of change, the plausible range is derived and discretized into five levels (details are given in Sections 3.2; 3.3; 3.4; Table 1 summarizes the selected ranges). When each level of each driver is combined, considering also the baseline (no change relative to the present state), altogether 216 (6 x 6 x 6) possible combinations of upper (Kratie) and lower (sea) boundary conditions are obtained. The division into five levels is a trade-off between computational demand and the high degree of variability in suspended sediment transport in the MD (Manh et al. 2013, 2014). Hereinafter, the following notations are used: ‘D’ for the impacts of dams, ‘C’ for climate change impacts in the MRB, and ‘S’ for effective sea level rise; ‘0’ for baseline, ‘1’ to ‘5’ for the five levels from the lower bound to the upper bound of the plausible ranges.

We apply the approach proposed by Prudhomme et al. (2010) mainly because of the large uncertainty associated with future hydropower development and climate change impacts in the MRB. For example, today it is unclear whether all the dams will actually been built, and what their characteristics and date of implementation will be. Using a conventional scenario approach would require to select a number of plausible scenarios and propagate them through the MD model. New projections, new knowledge or new political boundary conditions could require undertaking the impact analysis again. In contrast, the scenario-neutral approach allows rapid appraisal of new information, as long as the drivers and their combinations are contained within the defined scenario space. Another advantage is that this approach can be based on diverse studies. All input that is needed is the plausible range for the future impact of the different drivers. This information can be taken from available studies. Hence, different assumptions and inconsistencies between studies do not play a major role, as would it be the case for the conventional scenario approach.

We select the period 2000-2010 as baseline. The MD has undergone massive changes during the last decades, such as the recent implementation of floodplain compartments in the VMD, with large consequences on the spatial distribution of inundation extent, height and duration and associated sediment transport, thus we do not consider the morphological state of the floodplains and channels before 2000. We use the MD sediment model set up by Manh et al. (2014), which represents the state of the delta during the base line time period. Also, this period encompasses a wide spectrum of floods, from the very low flood season of 2010 to the extreme flood of 2000. The year 2000, with peak discharge of 57,000 m^3s^{-1}, was taken as design flood for flood defenses in the following years (Hung et al. 2014a). In contrast 2010, the flood peak reached only 37,000 m^3s^{-1}, being the lowest flood volume in the 86-year observation period, and the flood was also six weeks shorter than on average (MRC 2011a). Thus our reference period includes a wide range of events depicting the increased variability of flood discharges in the last decades, as reported by Delgado et al. (2010). For the future time horizon we select the period 2050-2060, when all the 136 dams are expected to be in operation according to the current plans (MRC 2011b), and when projected climate change related sea level rise will significantly impact the hydraulic regime in the MD (IPCC 2014).

The peak discharge, duration and volume of the seasonal flood play important roles in the spatial distribution of sediment transport and deposition in the MD (Manh et al. 2014). Thus the baseline discharge time series for the model boundary at Kratie have to map the observed patterns of flood discharges. As usual in climate impact studies we defined a baseline period (2000-2010). The average peak discharge and flood volume was calculated for this reference period. However, the shape of the flood hydrograph, i.e. the distinct characteristic of the time series, was determined using the full historical discharge records in order to capture the full natural variability in flood generation in the Mekong basin. From this time series Dung et al. (2011) identified four typical hydrograph shapes with different number of flood peaks and time series characteristics by a cluster analysis (Fig. 2). Thus in this study the baseline discharge time series is generated from the average peak discharges over the baseline period 2000-2010 depicting the flood magnitudes in this reference period, and the four typical patterns of discharge time series derived by Dung et al. 2011, which map the full variability of flood events covered in the historical data record. In order to take the variability of flood events into account in this study, each of our 216 driver combinations is run with the four typical flood patterns. The resulting sediment transport patterns in the MD are averaged across the four patterns using their past frequencies as weight in the averaging.

3.2. Impact of hydropower development on the upper boundary

The impact of hydropower development on the streamflow and sediment load at Kratie, the upper boundary of the MD, is described by the sediment trapping efficiency (TE) of the reservoirs and the change in the discharge (ΔQ_D) of the flood season. The plausible range for TE is assumed to be 30-96%. The upper bound is taken from Kondolf et al. (2014), who estimated a basin wide trapping efficiency of 96% in case all 136 dams were built. The lower bound has been estimated by Kummu et al. (2010) and includes the dams already built and those currently under construction. However, both cited studies take the 1970s as baseline, i.e. when no dams existed. These values are rescaled to the baseline period 2000-2010 for which Kummu et al. (2010) estimate TE = 20%. Thus, $TE = \frac{30\%-20\%}{100\%-20\%} = 12\%$ and $TE = \frac{96\%-20\%}{100\%-20\%} = 95\%$ are the lower and upper values of the plausible TE range relative to the baseline 2000-2010, respectively (Table 1).

The upper bound of the plausible range for streamflow changes as a consequence of hydropower development is taken from Lauri et al. (2012). They simulate the MRB hydrology assuming all 136 dams were built. The difference in the daily streamflow at Kratie between this situation and the baseline (ΔQ_D) is considered as the impact of the hydropower development on streamflow. A similar simulation for the dam operation impact on streamflow assuming that only the dams built and those already under construction are realized does, however, not exist. Hence, the lower bound of the range of streamflow change had to be estimated in a different way. We use the cumulative active storage of the reservoirs in the MRB as a proxy. This storage capacity for the lower bound (only the dams built and under construction) is 55% in relation to the storage capacity of the upper bound (all 136 dams) (Kummu et al. 2010). This value is then rescaled to the baseline in Kummu et al. (2010), for which a storage value of 25% was estimated. Thus, storage for the lower bound is $\frac{55\%-25\%}{100\%-25\%} = 40\%$ of the upper bound storage. We further assume that the streamflow change is proportional to the change in active storage, and thus we multiply the result for the upper bound derived from Lauri et al. (2012) by 0.4 to obtain the streamflow change for the lower bound. Fig. 3 shows in time series of the upper and lower bounds of the change in streamflow for the flood season as a consequence of hydropower development (ΔQ_D). The maximum and minimum value of ΔQ_D are shown in Table 1. For each day of the flood season, the streamflow is averaged over the eleven years of the baseline and future periods, respectively. We assume that the five levels of TE and streamflow change apply jointly, i.e. a certain case for hydropower development is associated with the same level for TE and streamflow change.

In addition, an attempt was made to include the discussed conversion of the planned eight Mekong main stem dams in the Lower Mekong Basin (LMB) from reservoirs to run-of-river hydroplants. In this case the planned active storage would be reduced to almost zero, resulting in TE = 0 with the here applied Brune's method for the estimation of the trapping efficiency (Brune, G.M., 1953). Thus, in terms of trapping efficiency, a case assuming all main stem dams are realized as run-of-river plants is equal to a case of no main stem dams being built. This is equivalent to TE = 50-68% (Kummu et al. 2010, Kondolf et al. 2014).

3.3. Climate change impact on the upper boundary

To estimate the plausible range of discharge change in Kratie under climate change (ΔQ_C), the results from Lauri et al. (2012) are used, because this is the most comprehensive study available for the MRB to date. It considers two emission scenarios (IPCC SRES B1 and A1b) and five GCMs, and includes a downscaling procedure. Fig. 3 shows the change in daily streamflow at Kratie for the ten climate change scenarios for 2050-2060 in relation to the baseline period 2000-2010. For each day of the flood season the streamflow is averaged over the eleven years of the baseline and future periods, respectively. The upper and lower bounds of the plausible range of the climate change impact are derived by selecting the upper and lower values of the ten scenarios for each day of the flood season (Fig. 3).

3.4. Impact of sea level rise on the lower boundary

The effective SLR (ΔH_S) is a combination of deltaic subsidence (ΔH_{sub}) and climate change related SLR (ΔH_{slr}) . The ΔH_{slr} is taken from IPCC (2014), which estimates the global mean sea level rise in the range of 17-38 cm for the period 2046-2065 compared to the baseline 1986-2005. This range encloses the results of MONRE (2012), in which climate change related SLR based on IPCC (2007) is downscaled to the South China Sea and the Gulf of Thailand, surrounding the MD.

Deltaic subsidence in the MD is given by Syvitski et al. (2009) as:

$$\Delta \mathrm{H}_{sub} = -S + C_n + C_a + M$$

S: Annual sedimentation rate in the delta, $S \cong 1\ mm.y^{-1}$ in a normal flood year (Manh et al. 2014),

$\mathrm{C_n}$: Natural compaction of the soil layers in the delta, $C_n = 3\ mm.y^{-1}$ (Syvitski et al. 2008, Syvitski et al. 2009),

$\mathrm{C_a}$: Accelerated compaction due to human activities such as gas exploration, groundwater exploration, $C_a = 2\ mm.y^{-1}$ for the MD (Ericson et al. 2006),

M: Crustal vertical movement the Earth's mass, $M = 1\ mm.y^{-1}$ for the MD (Syvitski et al., 2009).

The range of deltaic subsidence for the considered future period varies from 5 cm in case only M ($1\ mm.y^{-1}$) is active to 25 cm in case all factors apply ($-\mathrm{S} + \mathrm{C_N} + \mathrm{C_A} + \mathrm{M} = 5\ \mathrm{mm.y^{-1}}$ for 50 years). Thus the plausible range of future effective SLR, i.e. the combined effect of climate change related SLR and deltaic subsidence, $\Delta H_S = \Delta H_{slr} + \Delta H_{sub}$ = 22 - 63 [cm].

3.5. Sediment transport model for the Mekong Delta

The quasi-2D cohesive sediment transport model developed by Manh et al. (2014) is used to simulate sediment transport and deposition in the MD. It is an extension of the hydrodynamic model developed and applied for the MD by Dung et al. (2011). It simulates flood propagation, inundation and associated suspended sediment transport and floodplain sediment deposition in the MD from Kratie to the coast including Tonle Sap Lake (Fig. 1). The model describes river and channel network in 1D. Floodplain compartments in the VMD are represented in a quasi-2D way. The model contains 2340 floodplain compartments enclosed by dike rings and the associated hydraulic structures consisting of weirs, culverts and sluice gates. In order to quantify sediment deposition originating from the MRB only, re-suspension within the MD floodplains is suppressed in the simulation. The model was calibrated and validated using a comprehensive dataset including water and sediment observations in rivers, channels and floodplains. It showed good agreement with measurements (Manh et al. 2014). Details about model structure and setup, calibration, validation and general model performance can be found for the hydrodynamic module in Dung et al. (2011) and for the sediment dynamics in Manh et al. (2014), respectively.

The model is driven by streamflow and SSC time series at Kratie (Fig. 1). The sediment load at Kratie is thus a very important variable for the simulation of sediment deposition in the MD. For the future conditions representing the impact of climate change and hydropower development, times series of streamflow are derived from existing models, but the impact on sediment load is either not simulated (for climate change projections) or given in an aggregated form (TE values for hydropower development projections). A catchment model simulating the sediment dynamics in the MRB does not exist to date. In order to obtain daily SSC values at Kratie we assume that the close relationship between SSC and streamflow (Manh et al. 2014) holds also for the future period. The derived sediment rating curve of Manh et al. (2014) is rescaled by TE to accommodate the reduction in sediment load. Hence, daily SSC at Kratie is derived for given streamflow and TE by:

$$\boldsymbol{SSC_t^{Krat} = [1 - \frac{TE}{100}].\,10^{\left(-494.02 \log\left(Q_t^{Krat}\right)^{-4.52} + 2.88\right)}}$$

In which SSC_t^{Krat} is suspended sediment concentration ($mg.l^{-1}$) at time t at Kratie, Q_t^{Krat} is discharge ($m^3.s^{-1}$) at time t at Kratie, TE is the basin wide sediment trapping efficiency (%).

4. Results

Future sediment transport and deposition in the MD is analyzed based on the plausible ranges of drivers shown in Table 1 and their discretization into five levels for each driver. For each case of the 216 combinations, the spatial distribution of streamflow, suspended sediment concentration and sediment deposition in the MD is simulated throughout a complete flood season. To be able to present these results in a condensed way, the changes (relative to the baseline period) in the following variables are given and discussed: (1) annual sediment load to the four subsystems of the MD, (2) annual sediment deposition in the Vietnamese floodplains (spatial distribution and deposition aggregated over all compartments), and (3) peak water level of flood season at station Tan Chau at the upper border of the VMD (Fig. 1). To understand the impacts of the different drivers, the sensitivity runs representing changes caused by a single driver only are presented first, followed by the cumulative impact.

4.1. Impacts of hydropower development

Hydropower development will reduce streamflow during the rising and high stage of the flood season, as well as sediment load to the MD. Table 2 shows the decline in annual sediment load for the different subsystems and in annual sedimentation for the VMD. For a given hydropower development level, the reduction in both variables is similar throughout the MD. However, the compartments of the VMD are proportionally most strongly affected for low to medium dam development. This is caused by the combined effect of reduced sediment input into VMD floodplains, which is already lowest among all subsystems in the baseline period, and the reduced flood peak water levels causing a reduction in the inundation extent. Fig. 4A-B shows how this reduction varies with TE. Depending on the level of hydropower development, the flood peak is reduced by 30-68 cm at Kratie and 15-35 cm at Tan Chau, respectively. Sediment load at Kratie changes by -12÷-95% and sedimentation in the VMD floodplains is reduced by 21-96%. Sediment load supplied to the sea at the river mouth diminishes by 14 - 95%.

Fig. 5 (D-panel) shows the change in spatial distribution of annual sedimentation in the VMD for three hydropower development levels (minimum D, medium D, maximum D), excluding the effects of climate change and sea level rise. Sedimentation is significantly reduced at all three levels. In general, the sedimentation rates but also the sedimentation area are reduced with increasing TE. Already under the medium D level conditions the floodplain sedimentation is largely reduced compared to the baseline. Maximum sedimentation is reduced to just 14 $kg.m^{-2}.y^{-1}$ (cf. 40 $kg.m^{-2}.y^{-1}$ in baseline), occurring in close vicinity of the main rivers only. In the maximum D level, these rates are reduced even further to 1.3 $kg.m^{-2}.y^{-1}$, which is equivalent to an almost complete loss of floodplain sedimentation for most parts of the VMD floodplains.

4.2. Impacts of climate change

Climate change impacts in the MRB affect the flood magnitude and volume, and associated sediment transport during the flood season. The plausible range of climate change may decrease or increase flooding and associated sediment transport. However, the majority of climate change scenarios used points to an increase with higher average flood discharge, prolonged inundation duration and larger inundation areas. These changes in hydraulic characteristics are associated with higher sediment concentration, sedimentation rates and larger sedimentation extent, as illustrated in the difference maps of Fig. 5 (C-panel).

Table 2 illustrates that, similar to the hydropower development levels, the floodplains in the VMD show the highest sensitivity to changing boundary conditions. The change in annual sediment load varies from -12% to +36% at Kratie and from -12% to +40% in the VMD floodplains, leading to changes in annual sedimentation in the VMD floodplains from -30% to +137%. The range of the future change in flood peak at station Tan Chau extends from -30 cm to +80 cm and from -60 cm to +150 cm at Kratie relative to the baseline level (Fig. 4C-D). Sediment load to the sea varies from -10 to +30%.

The change in spatial sedimentation patterns in the VMD floodplains varies considerably depending on the level of climate change (Fig. 5C-panel). The annual sedimentation changes from 4.1 million tons for the baseline period to 2.9, 5.6 or 9.7 million tons for the minimum, medium or maximum climate change level, respectively. The median climate change level predicts an increase in sedimentation rates and areas with a net gain in sedimentation. The latter point is most prominent in the remote parts of the VMD floodplain, i.e. eastern parts of the PoR. But also the remaining parts of the PoR receive larger amounts of sediment. This increase is much less visible in the LXQ, which is a direct consequence of the already present high number of high dike compartments and the current management scheme, as well as the significant backwater effects from the tide in the Gulf of Thailand, which limits flow and thus sediment transport into the LXQ. For the maximum climate change level a similar pattern can be observed, only with higher sedimentation rates and an even further extent of the sedimentation into the remote parts of the PoR. In the minimum level with decreasing flow and sediment load, the sedimentation pattern is similar to the baseline with moderately reduced sedimentation rates.

4.3. Impacts of effective sea level rise

Sea level rise mainly impacts the sediment transport into the VMD floodplains and the sedimentation in the dike compartments of the VMD. A higher sea level results in higher water levels of Tien River and Hau River which increase the sediment load into the VMD floodplains by 2-6% and sedimentation in the dike compartments by 7-23% (Table 2; Fig. 4E-F; Fig. 5 S-panel). The higher sedimentation in the VMD floodplains without increase of sediment supply from upstream reduces the sediment transport into the coastal area by 1- 3% (Table 2), and sediment load to the sea changes by -1% to -3%.

Sea level rise leads to additional dike compartments being flooded and thus expands the sedimentation area compared to the baseline level (Fig. 5 S-panel). Most of these additional sedimentation areas show very low sedimentation and are located in the remote parts of PoR where the tidal influence is limited by the larger distance to the coast. LXQ is much closer to the coast than PoR and thus directy influenced by the tide from Gulf of Thailand restricting the flow of SSC into the area. Thus hardly any changes in sedimentation can be observed in this area. The areas of higher future sedimentation are mostly located close to the main channel at the border of Cambodia and Vietnam.

4.4. Cumulative impacts on sediment transport and deposition

An overview of the possible future changes in sediment dynamics due to the combination of the three drivers is presented in Fig. 6, where annual sediment load to the different subsystems of the MD and annual sedimentation in the Vietnamese floodplains are plotted for all 216 combinations. These results are grouped according to TE, representing different levels of hydropower development. It can be observed that the reduction of sediment load by sediment trapping of reservoirs drives the change in sediment dynamics in all subsystems, from Kratie through the entire delta down to the sea. Climate change has a second-order effect. It has, however, a large effect on the sedimentation in the Vietnamese floodplains. For most of the levels, climate change increases the sediment load and deposition, thus partly compensating the sediment trapping by reservoirs. Sea level rise has the smallest effect. It has impact only on the lower areas and, in addition, induces changes that are smaller than those by climate change. The results further reveal that the VMD floodplains are most sensitive to changes caused by the considered drivers.

Medium level of hydropower development (TE = 53%) is equivalent to the case of all planned dams being built without the implementation of the mainstream dams along the Lower Mekong River or with the mainstream dams realized as run-of-river hydropower plants (Kummu et al. 2010). For this level of hydropower development, the annual sediment transport to the MD is reduced by 39-61% (Table 2). This reduction in sediment load propagates downstream and leads to similar reductions in the other subsystems. However, due to the large sensitivity of the Vietnamese floodplains to climate change and sea level rise, the sediment deposition in VMD varies from -73% to +8% (Fig. 6, Table 2).

For the condition of all dams built with the current design, the sediment load to the MD is dramatically reduced (TE = 95%), and sedimentation in the MD is very low due to the low suspended sediment concentration in the main rivers. Even the combined effect of the highest levels of climate change and sea level rise does not strongly change this result: the reduction in sedimentation in the VMD is 96% for the case where only maximum hydropower development is considered (S0D5C0), while it is 89% for the case where all three drivers have their strongest impact (S5D5C5) (Table 2).

If only those dams will be implemented which are under construction as of today, the case TE = 12% applies. In this condition the impacts on the sediment dynamics are small for the subsystems with low sensitivity to climate change and sea level rise. However, climate change and sea level rise may have a large impact on the sedimentation in the VMD. Depending on the levels, sedimentation may vary between -52% and +105% (Fig. 6). In case of TE = 0%, i.e. no further hydropower development, climate change and sea level rise have a mild impact on the sediment transport to the upper subsystems (e.g. from -12% to +35% at Kratie). However, a stronger impact is found on sedimentation in the VMD floodplains, ranging from -30% to + 137% in case of C only (Table 2, Fig. 4), and from -33% to +158% in case of C and S together (Fig. 6).

To have a more detailed view on the impacts of the three drivers on the VMD floodplains, Fig. 7 shows the peak flood [m] at Tan Chau, the upper border of the VMD, and the annual sedimentation in the floodplain compartments for the complete scenario space. The plausible ranges of the three drivers lead to a large range of sediment deposition and flood peak levels. Annual sedimentation varies from 0.1 million tons to 11.2 million tons while maximum water level varies from 3.9 m to 5.5 m. Again, the dominant role of hydropower development on sedimentation is visible, leading to strongly decreasing sediment deposition with increasing TE. Climate change and sea level rise have a very small effect on sedimentation in case of total hydropower development. This is different for smaller TE values (0%, 12%, 33%). For example, for TE = 33%, annual sedimentation varies from 1.5 million tons to 6.5 million tons depending on the level of climate change and sea level rise. The effect on flood peak shows, however, a different behavior, as climate change is the dominant control on flood peak.

Hydropower development or sea level rise reduces or increases, respectively, the maximum water level in the flood season but to a much smaller extent than climate change.

The aggregated results of the 216 levels can be described by curves fitted to the data of different TE values. The respective equations (compiled in Table 3) can be used to predict annual sedimentation in the compartments of the VMD for given TE and flood peak at station Tan Chau.

Fig. 5 (ALL-panel) shows the combined spatially explicit impacts of the three drivers on sedimentation in the VMD. As discussed above, sediment trapping by dam construction is the dominant driver for floodplain sedimentation resulting in an overall sedimentation decrease across the VMD. However, the most significant changes are expected for the PoR, depicted by the high differences in sedimentation to the baseline. The effects are much less visible in the LXQ, which is mostly caused by the lower sedimentation in general in this area due to lower SSC reaching the area compared to PoR, the tidal impacts of the Gulf of Thailand, and the high number of high dike compartments blocking floodplain inundation (assuming that the current management practices do not change in future). The latter factor is the main reason for the negligible changes compared to the baseline in large parts of the LXQ (Fig. 5 ALL-panel).

5. Discussion and conclusions

In this study we quantified the impacts of climate change and hydropower development in the Mekong River Basin (MRB) and effective sea level rise on the sediment dynamics in the Mekong Delta (MD) for the future time period 2050-2060. A particular focus was a spatially differentiated quantification of the impacts of these drivers on floodplain sedimentation in the Vietnamese Mekong Delta (VMD). Currently, the uncertainties about the future evolution of these three drivers and consequently their impacts on the hydrology and sediment transport over the MRB are very high. Hence, we adopted a sensitivity-based approach and investigated the impacts on the MD for plausible ranges of these drivers. The combination of six different levels development for each driver, including the present state as baseline, leads to 216 driver combinations, which are assumed to cover the entire range of possible future pathways based on the current knowledge.

This study is the first to assess the response of floodplain hydraulics and sediment dynamics in the Mekong Delta to a plausible range of change drivers for the upper and lower boundary of the delta. Existing studies assess the impact of the drivers on streamflow and/or sediment load reduction in the MRB only, i.e. excluding the MD. Thus possible changes in sediment dynamics and hydraulics in the rivers and particularly the floodplains of the MD are still largely unknown. The findings presented in this study thus extent the current knowledge in many aspects.

We found that hydropower development dominates the changes in the sediment dynamics of the MD in case of medium to high hydropower development. Under these circumstances sediment trapping by the reservoirs reduces dramatically the provision of sediment to the MD, with climate change acting as a second-order effect. Even the highest level of climate change, which increases the flood peak and the sediment input to the MD, does not significantly counteract the hydropower sediment reduction effect. Overall, sea level rise has the smallest effect on sediment dynamics. If median changes of all factors are assumed as the most likely pathway for sediment dynamics in the MD for the period 2050-2060, our findings indicate that the inundation extent would slightly increase in the VMD, particularly in the PoR, but the overall floodplain sedimentation is likely to be reduced significantly.

We further found that the floodplains in the VMD respond much more sensitive to changes in the drivers compared to the other subsystems of the MD. The observed changes include changes in sediment deposition, but also the spatial extent of floodplain sedimentation. Within the VMD floodplains, the Plain of Reeds (PoR) sees the largest changes, while changes in the Long Xuyen Quadrangle (LXQ) are much less mainly due to the current practice of blocking floodplain inundation by numerous high dike floodplain compartments.

5.1. Possible environmental consequences of high hydropower development

The presented results put the existing studies on basin wide sediment trapping by hydropower dams (Kummu et al., 2010, Kondolf et al., 2014) into the context of impacts on the MD. In case all 136 planned dams will be built, drastic reductions of sediment input to the MD and floodplain sedimentation are expected. This is very likely to have dramatic consequences for ecology, agriculture and fishery in the MD. For example, Manh et al. (2014) showed that floodplain sedimentation can provide on average 50% of the nutrient requirements for rice crops, which is one of the reasons for the high agricultural productivity. This would be reduced to negligible amounts already with a basin wide sediment trapping efficiency of 53%. The important fishery sector is likely to suffer from sediment starvation because fish productivity is adapted to the nutrient and turbid conditions (Kummu and Varis 2007; Valbo-Jørgensen et al., 2009), and dams would block essential fish migration routes (Ziv et al., 2012). The high impact of sediment and flood pulse could be mitigated, to some extent, by designing hydropower plants as run-of-river type plants. Another important aspect with possibly severe environmental consequences is the increased erosion of the MD when sediment loads are decreasing. This is already observable (Tamura et al., 2010, Anthony et al., 2013), but will be most likely aggravated by extended dam construction.

5.2. Uncertainties and future research directions

When using our results, one has to consider that the likely increased erosion within the riverbeds after damming is not considered explicitly. Particularly for the case of all 136 dams being built (TE = 95%), reduction in sediment load to the MD subsystems and in floodplain sedimentation could be smaller in the first years after dam closure due to ‘cannibalism’ of the river on its bed (Kondolf et al. 2014). However, after stabilization of the riverbeds to a new equilibrium, sediment loads will be inevitably reduced in the long run. The effect might also be stretched over a long time period and thus be less strong, because the dam construction and closure of the all dams swill not be simultaneously, but stretched over a few decades. But nevertheless, a dedicated morphological study of the Mekong River would be useful to reduce the uncertainty of this driver in our assessment. The presented combination set provides, however, estimates also for smaller sediment trapping rates, which can be used in case it becomes clear that bank erosion compensates sediment trapping significantly.

Another uncertainty source in this study is the link of SSC to discharge at Kratie derived through a sediment rating curve and the assumed linear reduction of SSC with future increased sediment trapping. However, we expect that the sediment dynamics of the whole Mekong system are described realistically, although the absolute values contain an, from our point of view, acceptable amount of uncertainty (as always when sediment rating curves are used). A watershed model for the MRB, which would include all major processes, such as sediment trapping of reservoirs and riverbed deposition/erosion, could reduce this uncertainty. But given the low quantity and quality of SSC measurements in the Mekong Basin (Walling 2008), uncertainties would definitively remain due to insufficient or equifinal model calibration.

We used the climate change impacts on hydrology of Lauri et al. (2012), which showed high uncertainty in the projection of the future flow regime. However, GCMs are developing fast and using the most recent runs of the GCMs might reduce this uncertainty. Therefore, the climate change impacts on the Mekong hydrology should be regularly updated to reflect the most up-to-date projections.

These future research directions could provide more information on the drivers, and thus the span of the plausible ranges could be reduced. This would lead to a smaller scenario space of sediment dynamics in the MD. However, as long as the ranges of the drivers defined here are not exceeded, appropriate future pathways are already at hand by the presented approach.

Another possible application of the model and results might be the study of erosion and deposition in the estuary, i.e. the river reaches influenced by salt water intrusion and tidal sediment pumping, and the sediment dynamics in the subaqueous delta and along the coasts. The model could provide boundary conditions for more sophisticated 2D/3D models required for these kinds of studies. Using such an extension of the model chain would enable the assessment of the impacts of dam development and climate change to the morphology of the estuary and coasts of the Mekong Delta.

5.3. Concluding remarks

Given the high pace of dam development in the basin and projected climate change impacts on hydrology and sea level, the Mekong Delta is most likely facing significant changes in the foreseeable future. These changes might have severe impacts on the nature of the delta and on the livelihoods of millions of people. Our results call for urgent reconsideration of the future pathways in the Mekong River Basin. If the development continues with the current pace, our findings deliver valuable information on how and where the impacts on sediment dynamics are largest and they might be used as a starting point for mitigation measures.

Acknowledgements

This work was performed within the project WISDOM – Water related Information System for a Sustainable Development of the Mekong Delta (www.wisdom.eoc.dlr.de). Funding by the German Ministry of Education and Research (BMBF) under FKZ 033L040DN and support by the Vietnamese Ministry of Science and Technology (MOST), within the framework of National project coded KC08.21/11-15, are gratefully acknowledged. Additional funding by GFZ Potsdam, University of Potsdam and Academy of Finland funded project SCART (grant no. 267463) is also appreciated.

References

Anthony, E. J., Goichot, M., Brunier, G., Dussouillez, P., Provansal, M. and Dolique, F.: Widespread erosion of the Mekong River Delta: from construction to destruction phase? Mekong Environmental Symposium. 2013, Ho Chi Minh city, Vietnam, 2013.

Arias, M. E., Cochrane, T. a., Kummu, M., Lauri, H., Holtgrieve, G. W., Koponen, J. and Piman, T.: Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland, Ecol. Modell., 272, 252–263, doi:10.1016/j.ecolmodel.2013.10.015, 2014.

Brune, G. M.: Trap efficiency of reservoirs, Trans. Am. Geophys. Union, 34(3), 407–418, 1953.

Delgado, J. M., Apel, H. and Merz, B.: Flood trends and variability in the Mekong river, Hydrol. Earth Syst. Sci., 14(3), 407–418, doi:10.5194/hess-14-407-2010, 2010.

Doyle, T. W., Day, R. H. and Michot, T. C.: Development of Sea Level Rise Scenarios for Climate Change Assessments of the Mekong Delta, U.S. Geol. Surv., Open-File(1165), 110 [online] Available from: http://pubs.usgs.gov/of/2010/1165/, 2010.

Dung, N. V., Merz, B., Bárdossy, A., Thang, T. D. and Apel, H.: Multi-objective automatic calibration of hydrodynamic models utilizing inundation maps and gauge data, Hydrol. Earth Syst. Sci., 15(4), 1339–1354, doi:10.5194/hess-15-1339-2011, 2011a.

Eastham, J., Mpelasoka, F., Ticehurst, C., Dyce, P., Ali, R. and Kirby, M.: Mekong River Basin Water Resources Assessment : Impacts of Climate Change, CSIRO Water a Heal. Ctry. Natl. Res. Flagsh., 153 [online] Available from: http://wacc.edu.vn/vi/wp-content/uploads/2013/06/wfhc-MekongWaterResourcesAssessment.pdf, 2008.

Ericson, J., Vörösmarty, C., Dingman, S., Ward, L. and Meybeck, M.: Effective sea-level rise and deltas: Causes of change and human dimension implications, Glob. Planet. Change, 50(1-2), 63–82, doi:10.1016/j.gloplacha.2005.07.004, 2006.

Fu, K. D. and He, D. M.: Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the Lancang River, Chinese Sci. Bull., 52(S2), 134–140, doi:10.1007/s11434-007-7026-0, 2007.

Fu, K. D., He, D. M. and Lu, X. X.: Sedimentation in the Manwan reservoir in the Upper Mekong and its downstream impacts, Quat. Int., 186(1), 91–99, doi:10.1016/j.quaint.2007.09.041, 2008.

Hoanh, C. .: Impacts of climate change and development on Mekong flow regimes First assessment - 2009, MRC, (29), 104 [online] Available from: http://www.mrcmekong.org/assets/Publications/technical/tech-No29-impact-of-climate-change.pdf, 2010.

Hung, N. N., Delgado, J. M., Tri, V. K., Hung, L. M., Merz, B., Bárdossy, A. and Apel, H.: Floodplain hydrology of the Mekong Delta, Vietnam, Hydrol. Process., 26(5), 674–686, doi:10.1002/hyp.8183, 2012.

Hung, N. N., Delgado, J. M., Güntner, A., Merz, B., Bárdossy, A. and Apel, H.: Sedimentation in the floodplains of the Mekong Delta, Vietnam. Part I: suspended sediment dynamics, Hydrol. Process., 28(7), 3132–3144, doi:10.1002/hyp.9856, 2014a.

Hung, N. N., Delgado, J. M., Güntner, A., Merz, B., Bárdossy, A. and Apel, H.: Sedimentation in the floodplains of the Mekong Delta, Vietnam Part II: deposition and erosion, Hydrol. Process., 28(7), 3145–3160, doi:10.1002/hyp.9855, 2014b.

ICEM: Strategic environmental assessment of hydropower on the Mekong mainstream-Final report, Mekong River Comm., (October), 1–198 [online] Available from: http://www.mrcmekong.org/assets/Publications/Consultations/SEA-Hydropower/SEA-FR-summary-13oct.pdf (last access 4/5/2014), 2010.

IPCC: Climate Change 2007: The Physical Science Basis, Intergov. Panel Clim. Chang., (Technical Summary), 19–91, 2007.

IPCC: Climate Change 2013: The Physical Science Basis, Intergov. Panel Clim. Chang., (Technical Summary), 33–115, 2014.

Kameyama, S., Shimazaki, H., Nohara, S., Sato, T., Fujii, Y. and Kudo, K.: Hydrological and Sediment Transport Simulation To Assess the Impact of Dam Construction in the Mekong River Main Channel, Am. J. Environ. Sci., 9(3), 247–258, doi:10.3844/ajessp.2013.247.258, 2013.

Keskinen, M., Kummu, M., Käkönen, M. and Varis, O.: Mekong at the crossroads: next steps for impact assessment of large dams., Ambio, 41(3), 319–24, doi:10.1007/s13280-012-0261-x, 2012.

Kingston, D. G., Thompson, J. R. and Kite, G.: Uncertainty in climate change projections of discharge for the Mekong River Basin, Hydrol. Earth Syst. Sci., 15(5), 1459–1471, doi:10.5194/hess-15-1459-2011, 2011.

Kondolf, G. ., K, R. Z. . and J.T, M.: Dams on the Mekong: Cumulative sediment starvation, Water Resour. Res., 50, 1–12, doi:10.1002/2013WR014651, 2014.

Kummu, M., Lu, X. X., Wang, J. J. and Varis, O.: Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, Geomorphology, 119(3-4), 181–197, doi:10.1016/j.geomorph.2010.03.018, 2010.

Kummu, M., Tes, S., Yin, S., Adamson, P., Józsa, J., Koponen, J., Richey, J. and Sarkkula, J.: Water balance analysis for the Tonle Sap Lake-floodplain system, Hydrol. Process., 28(4), 1722–1733, doi:10.1002/hyp.9718, 2014.

Kummu, M. and Varis, O.: Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River, Geomorphology, 85(3-4), 275–293, doi:10.1016/j.geomorph.2006.03.024, 2007.

Lamberts, D. and Koponen, J.: Flood pulse alterations and productivity of the Tonle Sap ecosystem: a model for impact assessment., Ambio, 37(3), 178–84 [online] Available from: http://www.ncbi.nlm.nih.gov/pubmed/18595272, 2008.

Lauri, H., de Moel, H., Ward, P. J., Räsänen, T. a., Keskinen, M. and Kummu, M.: Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge, Hydrol. Earth Syst. Sci. Discuss., 9(5), 6569–6614, doi:10.5194/hessd-9-6569-2012, 2012.

Liu, C., He, Y., Walling, E. and Wang, J.: Changes in the sediment load of the Lancang-Mekong River over the period 1965–2003, Sci. China Technol. Sci., 56(4), 843–852, doi:10.1007/s11431-013-5162-0, 2013.

Liu, X. and He, D.: A new assessment method for comprehensive impact of hydropower development on runoff and sediment changes, J. Geogr. Sci., 22(6), 1034–1044, doi:10.1007/s11442-012-0981-7, 2012.

Lu, X., Kummu, M. and Oeurng, C.: Reappraisal of sediment dynamics in the Lower Mekong River, Cambodia, Earth Surf. Process. Landforms, 39(14), doi:10.1002/esp.3573, 2014.

Lu, X. X. and Siew, R. Y.: Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams, Hydrol. Earth Syst. Sci., 10(2), 181–195, doi:10.5194/hess-10-181-2006, 2006.

Manh, N. V., Dung, N. V., Hung, N. N., Merz, B. and Apel, H.: Large-scale suspended sediment transport and sediment deposition in the Mekong Delta, Hydrol. Earth Syst. Sci., 18(8), 3033–3053, doi:10.5194/hess-18-3033-2014, 2014.

Manh, N. V., Merz, B. and Apel, H.: Sedimentation monitoring including uncertainty analysis in complex floodplains: a case study in the Mekong Delta, Hydrol. Earth Syst. Sci., 17(8), 3039–3057, doi:10.5194/hess-17-3039-2013, 2013.

Milliman, J. D. and Farnsworth, K. L.: River Discharge to the Coastal Ocean: A Global Synthesis (book), Cambridge Univ. Press, doi:10.5670/oceanog.2011.108, 2011.

MONRE: Climate changes and sea level rise scenarios for Vietnam, Minist. Nat. Resour. Environ., 112, 2012.

MRC: The Flow of the Mekong, Mekong River Comm., (2), 1–12 [online] Available from: http://www.mrcmekong.org/assets/Publications/report-management-develop/MRC-IM-No2-the-flow-of-the-mekong.pdf (last access: 15/04/2014), 2009.

MRC: Annual Mekong Flood Report 2010, Mekong River Comm., 1–76 [online] Available from: http://www.mrcmekong.org/assets/Publications/basin-reports/Annual-Mekong-Flood-Report-2010.pdf (last access: 15/04/2014), 2011a.

MRC: Basin Development Plan Programme, Phase 2: Assessment of Basin-wide Development Scenarios, Mekong River Comm., 1(Main report), 254 [online] Available from: http://www.mrcmekong.org/assets/Publications/basin-reports/BDP-Assessment-of-Basin-wide-Dev-Scenarios-2011.pdf, 2011b.

Nguyen, V. L., Ta, T. K. O. and Tateishi, M.: Late Holocene depositional environments and coastal evolution of the Mekong River Delta, Southern Vietnam, J. Asian Earth Sci., 18(4), 427–439, doi:10.1016/S1367-9120(99)00076-0, 2000.

Piman, T., Lennaerts, T. and Southalack, P.: Assessment of hydrological changes in the lower Mekong Basin from Basin-Wide development scenarios, Hydrol. Process., 27(15), 2115–2125, doi:10.1002/hyp.9764, 2013.

Prudhomme, C., Wilby, R. L., Crooks, S., Kay, a. L. and Reynard, N. S.: Scenario-neutral approach to climate change impact studies: Application to flood risk, J. Hydrol., 390(3-4), 198–209, doi:10.1016/j.jhydrol.2010.06.043, 2010.

Räsänen, T. a., Koponen, J., Lauri, H. and Kummu, M.: Downstream Hydrological Impacts of Hydropower Development in the Upper Mekong Basin, Water Resour. Manag., 26(12), 3495–3513, doi:10.1007/s11269-012-0087-0, 2012.

Roberts, T. R.: Downstream ecological implications of China ' s Lancang Hydropower and Mekong Navigation project, Int. Rivers Netw., 1–14, 2001.

Syvitski, J. P. M. and Higgins, S.: Going under: The world's sinking deltas, New Sci., 216(2893), 40–43, doi:10.1016/S0262-4079(12)63083-8, 2012.

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L. and Nicholls, R. J.: Sinking deltas due to human activities, Nat. Geosci., 2, 681 – 686, doi:10.1038/ngeo629, 2009.

Syvitski, J. P. M.: Deltas at risk, Sustain. Sci., 3(1), 23–32, doi:10.1007/s11625-008-0043-3, 2008.

Syvitski, J. P. M. and Saito, Y.: Morphodynamics of deltas under the influence of humans, Glob. Planet. Change, 57(3-4), 261–282, doi:10.1016/j.gloplacha.2006.12.001, 2007.

Tamura, T., Horaguchi, K., Saito, Y., Nguyen, V. L., Tateishi, M., Ta, T. K. O., Nanayama, F. and Watanabe, K.: Monsoon-influenced variations in morphology and sediment of a mesotidal beach on the Mekong River delta coast, Geomorphology, 116(1-2), 11–23, doi:10.1016/j.geomorph.2009.10.003, 2010.

Valbo-Jørgensen, J., Coates, D. and Hortle, K.: Fish Diversity in the Mekong River Basin in: The Mekong : biophysical environment of an international river basin, Acad. Press. San Diego, 161–196, 2009.

Västilä, K., Kummu, M., Sangmanee, C. and Chinvanno, S.: Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains, J. Water Clim. Chang., 01(1), 67, doi:10.2166/wcc.2010.008, 2010.

Walling, D. E.: The changing sediment load of the Mekong River., Ambio, 37(3), 150–7, 2008.

Watson, J. E. M., Iwamura, T. and Butt, N.: Mapping vulnerability and conservation adaptation strategies under climate change, Nat. Clim. Chang., 3(11), 989–994, doi:10.1038/nclimate2007, 2013.

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I. and Levin, S. a: Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin., Proc. Natl. Acad. Sci. U. S. A., 109(15), 5609–14, doi:10.1073/pnas.1201423109, 2012.

Tables and table captions

Table 1: Plausible ranges of the three drivers of changing boundary conditions. Percentages indicate changes relative to the baseline period 2000-2010. The ΔQ_D and ΔQ_C are only the minimum and maximum value of daily lower bound and upper bound, the full values of ΔQ_D and ΔQ_C are shown in fig. 3.

Drivers	Variable (unit)	Plausible range			No. of model runs
		Lower bound	Upper bound	No. of equal intervals	
Hydropower development (D)	TE (%)	12	95	5	216 runs x 4 typical discharge patterns at Kratie
	ΔQ_D (%)	-19	+34		
Climate change (C)	ΔQ_C (%)	-21	+42	5	
Effective sea level rise (S)	ΔH_S (cm)	+22	+63	5	

Table 2: Change in sediment load (SL) in different subsystems of the Mekong Delta and sediment deposition in the Vietnam Mekong Delta (VMD) relative to the baseline for single impacts and selected cases of cumulative impacts. (Notation: S = effective sea level rise, D = dam development, C = climate change; 0-5 denote the levels, 0: baseline, 1: lower bound of plausible range, 5: upper bound; CMD stands for Cambodian Mekong Delta; TSL for Tonle Sap Lake; VMD for Vietnamese Mekong Delta).

Simulation		SL at Kratie	SL to CMD	SL to TSL	SL to VMD	SL to VMD floodplains	Sedimentation in VMD floodplains	SL to the sea
S0D0C0 [million tons]		83.8	23.9	-7.5	52.5	12.4	4.1	40.1
D impacts	S0D1C0	-12%	-12%	-15%	-14%	-17%	-21%	-14%
	S0D2C0	-33%	-35%	-38%	-37%	-41%	-46%	-36%
	S0D3C0	-53%	-55%	-57%	-57%	-60%	-64%	-56%
	S0D4C0	-74%	-76%	-77%	-77%	-79%	-81%	-76%
	S0D5C0	-95%	-96%	-94%	-95%	-96%	-96%	-95%
C impacts	S0D0C1	-12%	-11%	-13%	-12%	-19%	-30%	-10%
	S0D0C2	0%	0%	0%	-1%	-1%	0%	-1%
	S0D0C3	12%	10%	13%	12%	21%	37%	9%
	S0D0C4	24%	17%	27%	26%	46%	84%	20%
	S0D0C5	36%	28%	40%	40%	70%	137%	30%
S impacts	S1D0C0	0%	0%	0%	0%	2%	7%	-1%
	S2D0C0	0%	1%	0%	0%	3%	11%	-2%
	S3D0C0	0%	1%	0%	0%	4%	14%	-2%
	S4D0C0	0%	1%	0%	-1%	5%	18%	-2%
	S5D0C0	0%	2%	0%	-1%	6%	23%	-3%
Cumulative impacts	S1D1C1	-25%	-24%	-26%	-25%	-31%	-40%	-23%
	S2D2C2	-37%	-35%	-38%	-38%	-39%	-39%	-37%
	S3D3C3	-51%	-50%	-50%	-51%	-48%	-41%	-52%
	S4D4C4	-71%	-71%	-69%	-71%	-67%	-58%	-72%
	S5D5C5	-94%	-94%	-92%	-94%	-92%	-89%	-94%
	S1D3C1	-62%	-62%	-63%	-62%	-66%	-73%	-60%
	S2D3C2	-56%	-55%	-57%	-57%	-58%	-59%	-57%
	S4D3C4	-45%	-45%	-44%	-45%	-36%	-19%	-48%
	S5D3C5	-39%	-41%	-37%	-39%	-24%	8%	-43%

Table 3: Annual floodplain sedimentation S [million tons] in diked compartments of the VMD floodplain as function of annual flood peak H [m] at gauge Tan Chau for given values of hydropower trapping efficiency TE [%].

Group	Fitted equation	Goodness of fit
$TE = 0$	$S_{fp} = 1.99\,H^2 - 12.61\,H + 20.44$	$R^2 = 0.998$
$TE = 0.12$	$S_{fp} = 1.86\,H^2 - 12.12\,H + 20.54$	$R^2 = 0.997$
$TE = 0.33$	$S_{fp} = 1.43\,H^2 - 9.41\,H + 16.12$	$R^2 = 0.997$
$TE = 0.53$	$S_{fp} = 1.06\,H^2 - 7.13\,H + 12.53$	$R^2 = 0.998$
$TE = 0.74$	$S_{fp} = 0.61\,H^2 - 4.18\,H + 7.47$	$R^2 = 0.998$
$TE = 0.95$	$S_{fp} = 0.12\,H^2 - 0.84\,H + 1.51$	$R^2 = 0.997$

Figures and figure captions

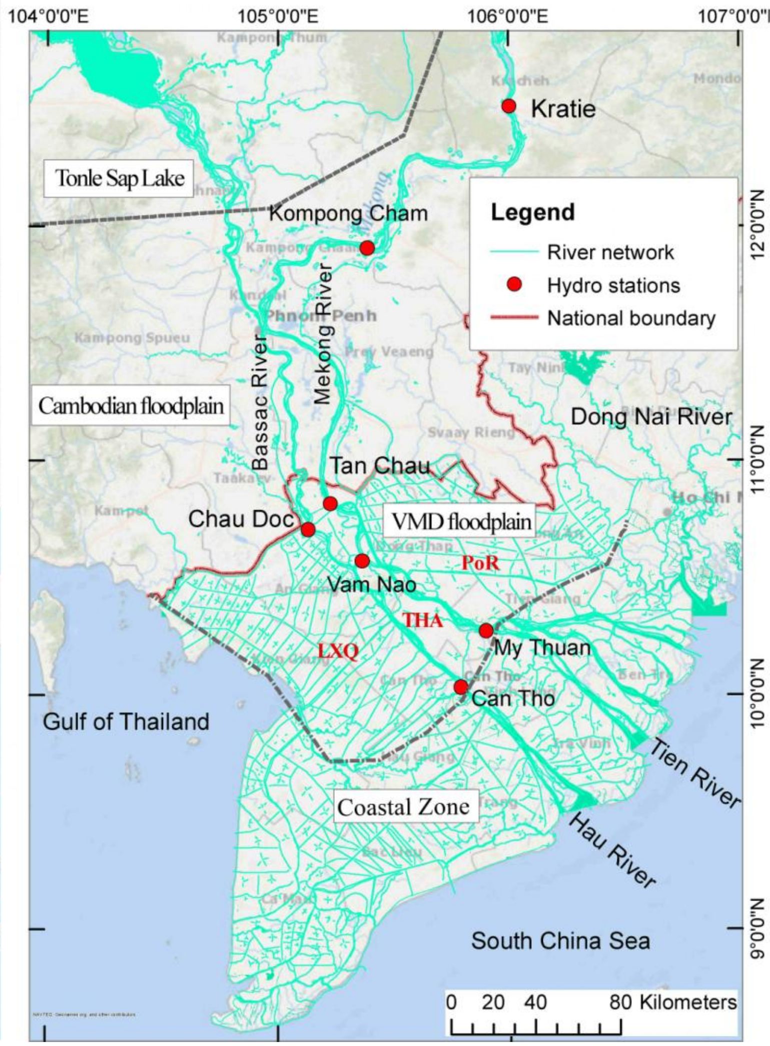

Figure 1: Left panel: The Mekong River Basin including the hydropower dam locations (MRC 2011b). Right panel: The Mekong Delta (MD) from Kratie to the seas including the main hydrological stations, the subsystems of the MD and the floodplain areas in the VMD.

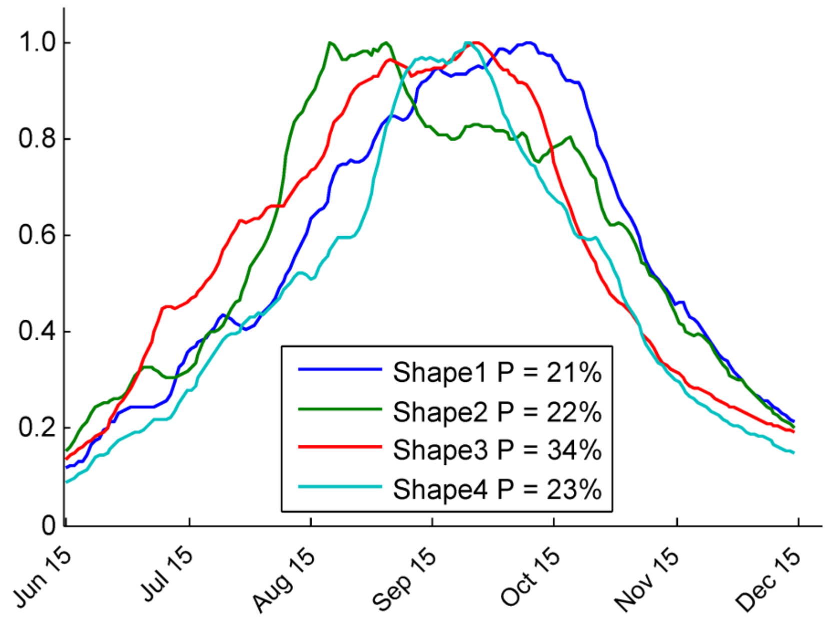

Figure 2: Four typical flood season discharge time series at Kratie gauge station resulting from a cluster analysis. The percentages show the empirical probabilities associated to the time series for the 86-year observation period (adapted from Dung et al. 2011).

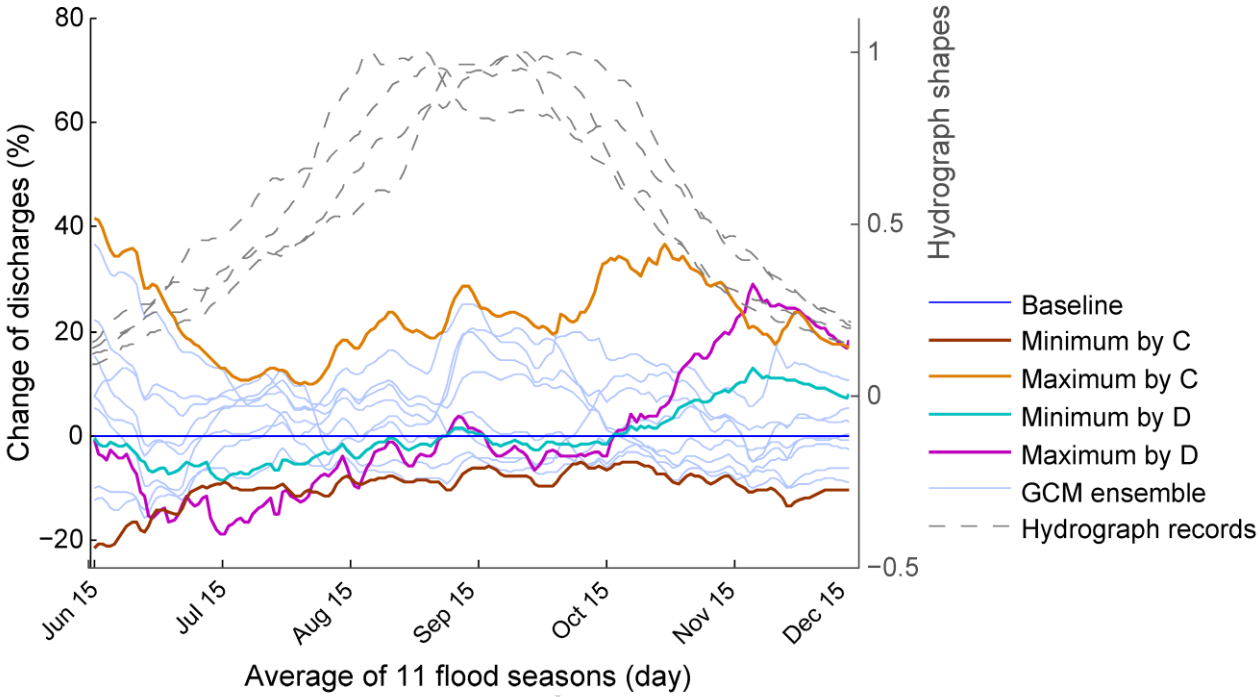

Figure 3: Change in daily streamflow during the flood season for the period 2050-2060 in relation to the baseline period 2000-2010 as consequence of climate change and hydropower development, respectively (based on Lauri et al. 2012).

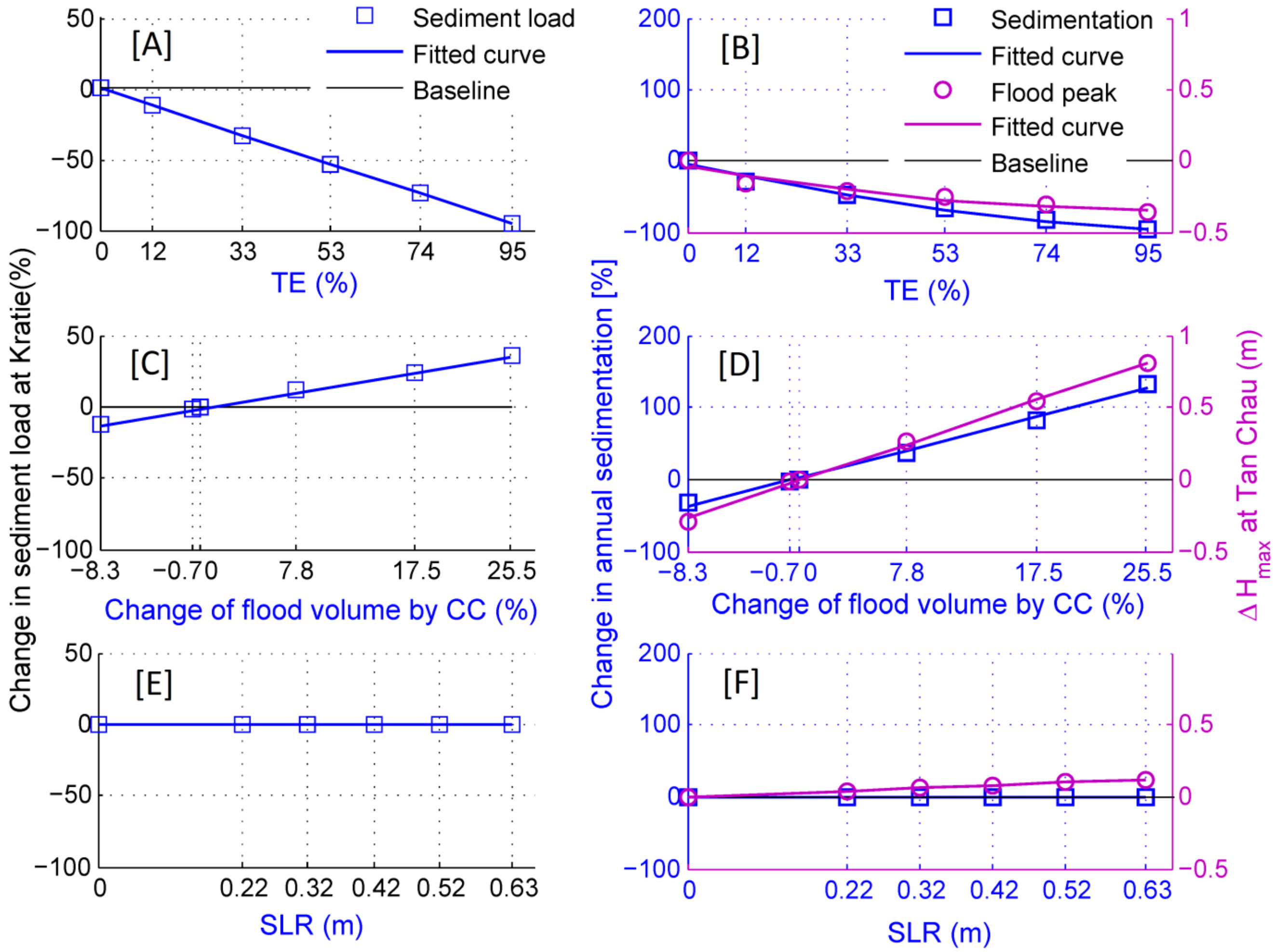

Figure 4: Single impacts of drivers. Changes in sediment load at Kratie (left column), and changes in annual sedimentation in the VMD and annual flood peak at station Tan Chau (right column) caused by A-B: hydropower development (TE), C-D: climate change (CC) impact in the MRB, and E-F: sea level rise (SLR).

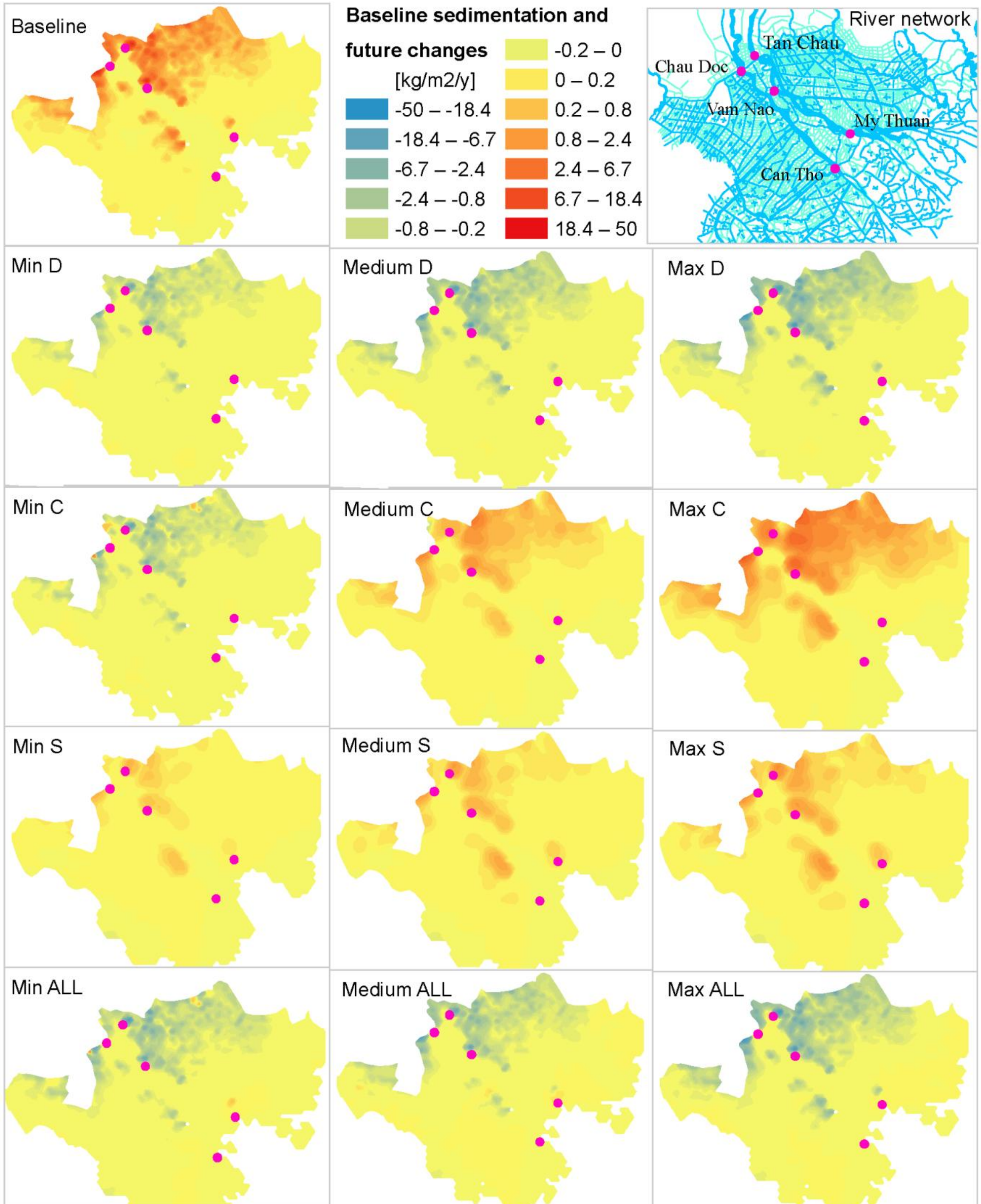

Figure 5: Spatial distribution of annual sediment deposition in the floodplain compartments of the Vietnam Mekong Delta (VMD) for the baseline condition, and the minimum, medium and maximum conditions of single drivers (hydropower development: D, climate change: C, sea level rise: S) and of combined drivers (ALL). The baseline map shows the simulated annual deposition, while all other maps show the differences in deposition to the baseline. The dots indicate the main gauging stations in the VMD for spatial reference.

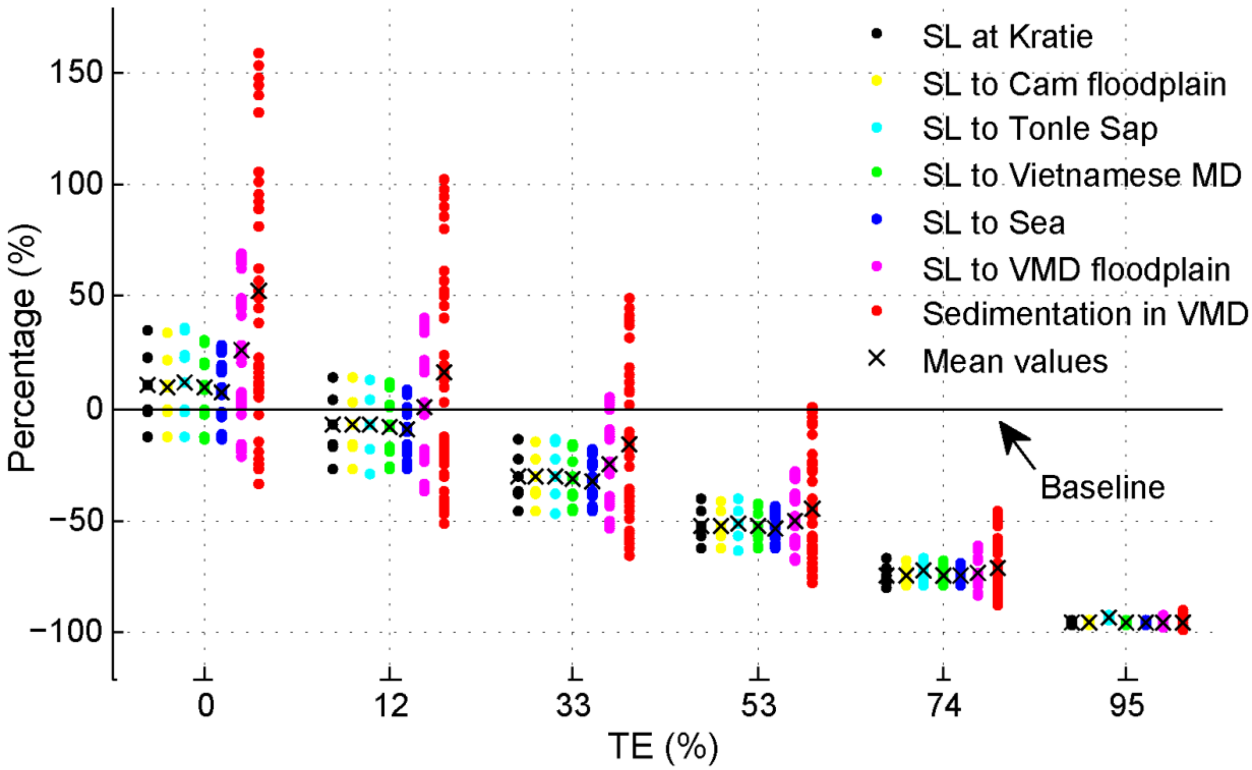

Figure 6: Change in sediment load (SL) and deposition relative to the baseline period in key areas of the Mekong Delta (MD). The 216 combinations are classified according to the six levels of trapping efficiency (TE) values. For each TE class 36 combinations (6 climate change levels x 6 sea level rise levels) are plotted. Frequently, groups of six levels can be distinguished for a given subsystem. These groups represent the different levels of climate change. The six levels within each group are the variability due to sea level rise. Note that sea level rise does not affect the upper areas of the MD, hence some of the cases lead to identical results for the upper areas. For the lower areas the 36 combinations form six clusters. These clusters are the effect of climate change, whereas the spread within each cluster shows the sea level rise effect.

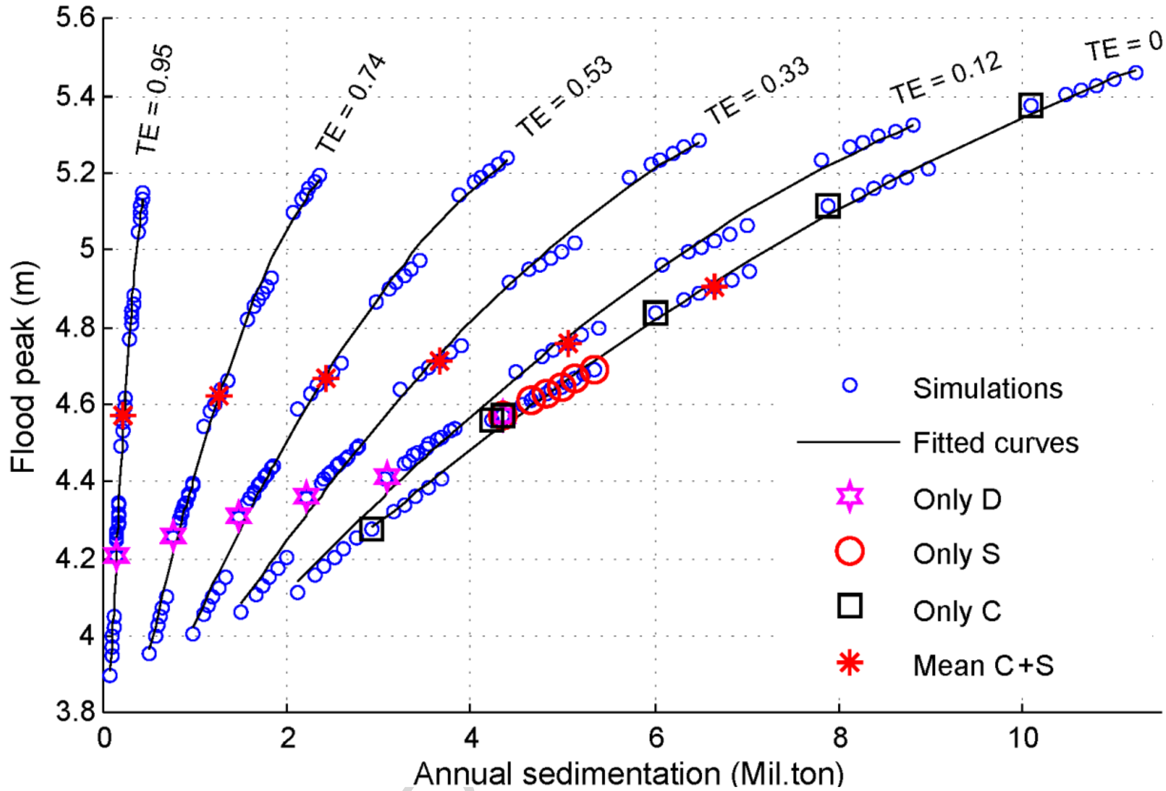

Figure 7: Annual sedimentation in the floodplain compartments of the Vietnam Mekong Delta (VMD) and annual flood peak at station Tan Chau (see location in Fig. 1) for all 216 combinations (blue circles) classified by trapping efficiency (TE) levels. Single effects and the mean value of the combined effect of climate change and sea level rise are marked. (Notation: S = effective sea level rise, D = dam development, C = climate change)

Highlights

We examine the future sediment dynamic in the floodplains of the Mekong Delta using a hydrodynamic model and sensitivity-based approach.

Plausible ranges of impacts are determined for the delta boundaries.

Hydropower dams are the dominant impact driver on floodplain sediment dynamics

Climate change and sea level rise acts as second-order impact effect.

The floodplains in the Vietnamese part of the delta respond most sensitive to the expected changes.