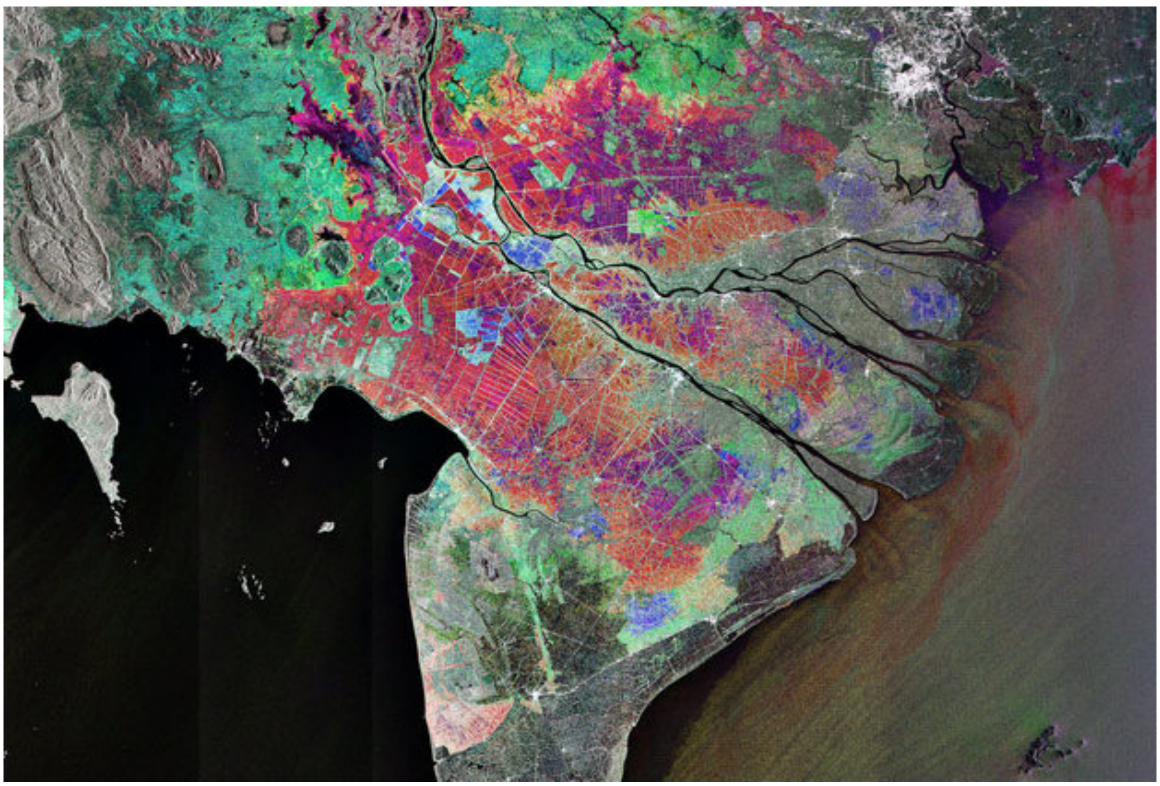
Climate Resilient Mekong (CRM): Maintaining the Flows that Nourish Life

Advancing Knowledge on Impacts to the Mekong Delta from Reductions in Sediment and Nutrient Inflows

Research Charter: Findings and Conclusions



MEKONG DELTA BY ENVISAT, EARTH-OBSERVING SATELLITE

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Summary of Key Points from Mekong Delta Workshop

Purpose of the Workshop

With seven dams built or under construction on the mainstem Lancang and another 133 built, under construction, or planned for the Lower Mekong River and tributaries, sediment trapping by upstream dams will affect downstream resources in significant ways. Trapping of sediment behind dams will reduce the delivery of sediment to the Delta, with the potential to severely affect the Mekong Delta's ecology, agricultural and fish production, and the very existence of the Delta as a physical feature.

What are likely to be the impacts of this reduced sediment supply on coastal erosion and subsidence throughout the delta, on the uniquely-productive Mekong River fishery, and on the riverine and offshore fishery and delta agriculture that depend on nutrients now transported by the river? In October 2013, Natural Heritage Institute convened a workshop of experts on the Mekong to present current research and share their perspectives on likely future impacts. The Vietnamese co-hosts were the Institute for Meteorology, Hydrology and the Environment (IMHEN) of the Ministry of Natural Resources and Environment (MONRE), and the Southern Institutes for Water Resources Planning and Research (SIWRP and SIWRR) of the Ministry of Agriculture and Rural Development (MARD). The workshop was sponsored by the USAID and the World Bank through a trust fund provided by UKAid.

Principal Findings and Recommendations

If all dams are constructed as planned, without modifications to allow sediments and fish to pass, the Delta will receive only about 4% of its pre-dam sediment load. If only the 41 dams defined by MRC as 'definite future' are built, nearly half of the pre-dam sediment load will reach the Delta (Kondolf et al, in revision). However, there will be some 'lag' time before the full effect of sediment trapping by dams is manifest because sediment stored in the channel and in adjacent floodplains will be subject to erosion, partially compensating for the loss of sediment to reservoir trapping. Quantification of changes in sediment transport downstream of dams on the Lancang has lagged behind sediment trapping, presumably reflecting such contributions from stored sediments (Liu et al. 2013). Most of the Mekong River is bedrock controlled, with limited sediment storage, so the 'buffering' effect of sediment stored in the channel will likely be exhausted relatively soon, but good estimates of this have not yet been made.

> *A research priority is quantification of sediment stored in the channel and adjacent floodplains that will potentially buffer the effects of sediment starvation from trapping in reservoirs.*

The total sediment load of the Mekong River has been estimated to be 160 Mt/y, a figure that has been widely adopted (Borland 1973, Milliman and Meade 1983, Milliman and Syvitski 1992). Recalculation of sediment loads by Liu et al (2013) suggest that the true load is lower, but detailed studies of the sand fraction suggest that sand has been systematically undersampled (Bravard and Goichot 2012, Bravard et al. 2013), implying that the true transport rate is larger.

The Delta system extends upstream to include Tonle Sap, a lake that grows seasonally with backwater from the Mekong, and whose seasonally-flooded shallow waters are an essential nursery area for the rivers' fish. The Tonle Sap system is an important component of the

Mekong River fishery that is globally without parallel, supporting 60 million people, mostly through subsistence fishing. The fishery, in turn, is supported by nutrients, which will be affected by dams. During flood stage on the Mekong, river backwater flows up the Tonle Sap River, expanding Tonle Sap Lake. The complex exchange of water, sediment and nutrients between the Mekong and Tonle Sap, and the relative contributions of nutrients from the mainstem Mekong and from tributaries to Tonle Sap is not well understood. Despite considerable work on Tonle Sap, significant uncertainties remain.

A key research priority is a coordinated program to monitor fluxes of water, sediment, and nutrients transported in/out via the Tonle Sap River, and to measure inputs from tributaries that drain directly into Tonle Sap Lake.

Nutrients occur both in dissolved form and adsorbed onto fine-grained sediments. The dissolved nutrients are more bioavailable and are used quickly. Nutrients associated with fine sediments can undergo changes and become more bioavailable during residence time on floodplains and in the lake.

Another research priority is to better understand the source of nutrients from various parts of the basin and their downstream movements, and how nutrients are processed and transformed during the complex interactions within the Tonle Sap system and on Mekong River floodplains.

One of the largest in the world (39,000 km^2), the Mekong Delta built out from Phnom Penh over the past 8,000 years by deposition of river sediments (Statteger et al. 2013). Current overbank sedimentation rates of 5-6 mm/y measured between low- and high-water dykes would not keep up with current subsidence rates of 10-25 mm/y in the Delta. Reduced sediment loads in the future will exacerbate this imbalance. Combined with anticipated acceleration of sea level rise (SLR) from the current 4 mm/y to 8 mm/y, the Delta will be increasingly vulnerable to coastal flooding and salt-water intrusion. The problem is exacerbated by dyking and channelization, which concentrates the river flow and directs the river's sediment load into deeper water offshore, without permitting it to deposit on deltaic floodplains, nor even contribute to the coastal sediment supply.

Coastal erosion rates vary: near distributary mouths in the eastern Delta, some parts of the coast are currently eroding, others accreting. However, the Ca Mau Peninsula, built of sediments redistributed southwestward from river mouths by coastal currents, is eroding rapidly, up to 70 m/y. Only in Ca Mau Peninsula we find a depocentre of Mekong derived sediments with high accretion rates on the shallow subaqueous delta platform (Uverricht et al. 2013.) Despite recent measurements of suspended sediment transport (Unverricht et al. 2014), it is not clear to what extent the Delta is already experiencing the effects of sediment starvation from upstream dams. Analyses of sediment loads suggests that the effects of the Lancang dams has been detectable only upstream, near the dams, and has not been manifest in downstream stations (Liu et al. 2013). Some lag time between upstream dam closure and downstream sediment starvation would be expected because the river would pick up sediment from erosion of deposits stored in the channel below the dams. However, in-channel mining of sand for construction has been so great immediately upstream of the delta (Bravard and Goichot 2012) that it has almost certainly already reduced sediment supply to the coast.

A research priority is continued and expanded monitoring of transport of suspended and bedload sediment and nutrients through distributary channels and in the near offshore environment, coupled with improved monitoring of coastal erosion and bathymetric changes.

The Mekong River is uniquely productive in fisheries, thanks to the favorable geography that aligns several key elements supporting productivity, such as mountain streams accessible to migrating fish, large tributaries, high sediment and nutrient load, and extensive floodplains and wetlands, notably those of Tonle Sap. Many of the important Mekong fish species are migratory, and while the principal area of harvest is in lower reaches of the mainstem, many of these harvested fish species swim upstream to tributaries in Laos, Cambodia, and the Vietnamese Highlands to spawn (Baran and Myschowoda 2009). Accordingly, proposed dams such as Lower Se San 2 have enormous potential to block access to spawning grounds for important fish species. Trapping sediment by dams can alter habitat conditions needed for fish reproduction (both on the bed and in the water column) and juvenile rearing, and disrupt the turbidity cues for seasonal fish migration (Baran and Guerin 2012). From ecological principles, we expect there should be a relationship between nutrient flux and fish productivity, and such relations are manifest for the Mekong, though noisy. If nutrient loads were to be reduced by 80%, a 36% reduction in fish productivity is expected (Sarkulla and Koponen 2010).

A key research need is to better understand effects of reduced sediment and nutrient loads on fish species of the Mekong, not only in terms of primary productivity of the system but also habitat requirements for reproduction and rearing.

With the pace of development in the basin, the Mekong River system is changing rapidly. Despite uncertainties regarding ultimate magnitude and timing of the effects, it is indisputable that the extensive dam construction as currently proposed would result in severe alterations to the Mekong Delta and the river ecosystem. Accordingly, the riparian nations and international agencies should urgently prioritize efforts to reassess dam development plans and modify dam siting and design to reduce their impact on sediment regime. We do not have a decade to conduct research before deciding what to do. Rather, we should move expeditiously forward with efforts to design dams 'smarter' so as to minimize their impacts and sustain, to the extent possible, the extraordinary natural and human environment of the Mekong Delta.

Background

The Intergovernmental Panel on Climate Change (IPCC) has identified the Mekong Delta as one of the most endangered in the world due to its extreme vulnerability to sea level rise, storm surges and salinity intrusion. This is of particular concern because the Mekong Delta is the most biologically productive in the world in terms of its annual fish capture and its aquatic biodiversity. It supports the livelihoods for some 18 million Vietnamese and Cambodians who call it home. Further, the Vietnamese Delta is one of the most productive agricultural regions in the world. It provides:

- 50% of Vietnam's total rice production and 95% of its rice exports
- 65% of aquaculture and 60% of fish exports
- 70% of fruit production

Yet the peril to this remarkable resource is even more stark and urgent than recognized by the IPCC. The delta's extraordinary productivity is directly dependent on the inflows of sediment and nutrients that are delivered by the Mekong River's annual monsoonal flood pulse. Some 48 dams are now either in place, under construction, or inevitable in the basin upstream of the delta, and another 100 are in prospect if the full hydropower potential is developed. Under the full build-out scenario, as much as 96% (Kondolf et al. in review) of the sediment and 65% (Thorne et al) (and possibly more) nutrients that sustain this delta will be trapped as reservoirs fill. The loss of the annual replenishment of the material that sustains this delta will cause it to erode and subside. When combined with the inevitable rise in sea level, the consequences could be an ecological and humanitarian catastrophe.

Yet, much of this damage can be prevented by well-informed decisions regarding upstream dam development by the national governments. These decisions that will shape the future of the Mekong delta will be made within the next 3-6 years. For that reason, it has become an urgent priority to advance the state of scientific knowledge regarding the choices and consequences of dam siting, design an operations for the continued productivity of the Mekong Delta.

The Climate Resilient Mekong project funded by US Agency for International Development (USAID) has taken on the challenge of identifying the more benign alternatives to these dams as currently planned. The Natural Heritage Institute (NHI) is the coordinator of that project. On October 7 and 8, 2013, NHI and its Vietnamese partner institutions convened a workshop of Vietnamese and foreign experts to advance the state of knowledge regarding the probable effects that reductions in sediment and nutrient inflows into the delta and the near shore marine environment, inflows due to their capture in existing and prospective upstream hydropower dams, will have on its morphology, habitat quality and diversity, ecosystem processes, and biological productivity. The Vietnamese co-hosts were the Institute for Meteorology, Hydrology and the Environment (IMHEN) of the Ministry of Natural Resources and Environment (MONRE), and the Southern Institutes for Water Resources Planning and Research (SIWRP and SIWRR) of the Ministry of Agriculture and Rural Development (MARD). The workshop was sponsored by the USAID and the World Bank through a trust fund provided by UKAid.

This paper reports the findings and conclusions from the workshop and the recommendations for further research to fill the critical knowledge gaps that are most relevant to the imminent policy decisions on upstream development and operations, and the institutions best positioned to undertake those studies.

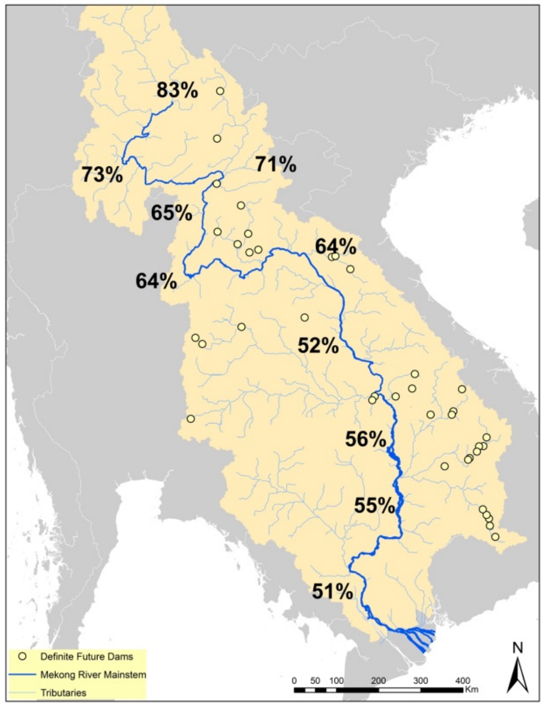
Mekong Delta in Vietnam. Photo by: Vietnam Airlines

SEDIMENT STARVATION EFFECTS ON DELTA MORPHOLOGY

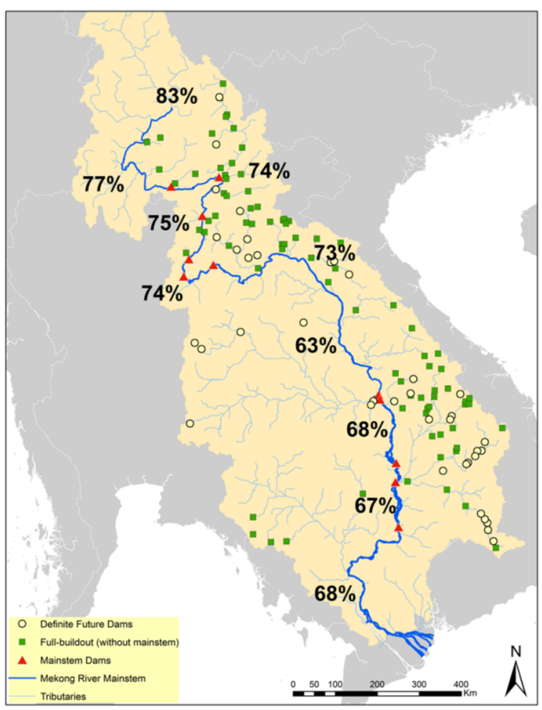
What we know:

Under any scenario for dam development in the Mekong basin, the depletion of sediment and nutrients reaching the delta will be profound. Four independent analyses (Kummu et al., 2010; Kondolf et al., in review, Thorne et al., 2013, and Hung et al., 2013) reached estimates in general agreement, though for a range of development scenarios:

- ➔ If only the 41 dams in the lower Mekong River basin that the Mekong River Commission finds to be inevitable are built (the "definite future" scenario), and seven Lancang dams in China are built, roughly half of the pre-dam supplies of sediment and nutrients will no longer reach the Delta (Kondolf et al., in review)

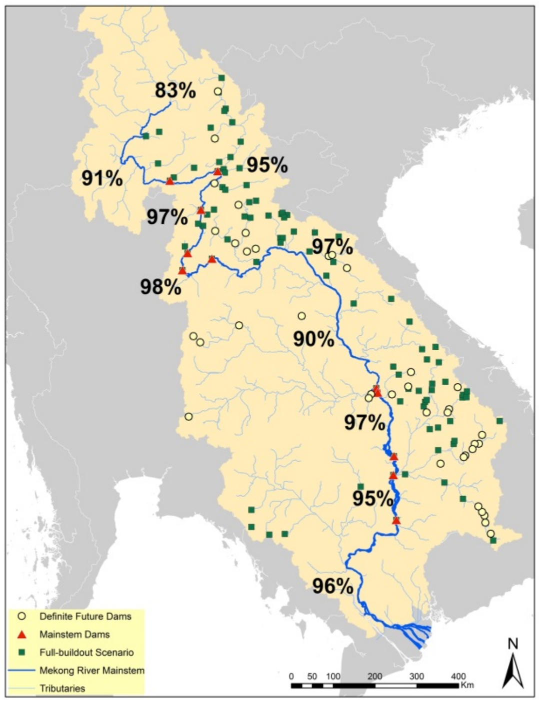


→ Under a scenario with full build-out of the tributary dams in the lower Mekong River basin, and the 7 Lancang dams are built, but without 11 mainstream dams, 68% of sediment is trapped, assuming no design or operation of these dams for sediment management.



➔ Under a scenario that includes the 7 dams in the Lancang headwaters in China + Xayaburi and Sambor on the mainstream, the prediction is that 80% of the sediment will be trapped (Le Manh Hung et al 2013))

➔ Under the 'Full-Buildout' Scenario, 60-96% of the sediment would be trapped by reservoirs. ((Kondolf et al., in review and Kummu et al 2010)). The higher number is probably a better prediction because it accounts for sediment trapping by each individual reservoir (whereas the lower estimate aggregates the reservoirs by sub basin), and it is based on total storage values for all reservoirs (not previously available), and estimates sediment yield within a geomorphic framework.

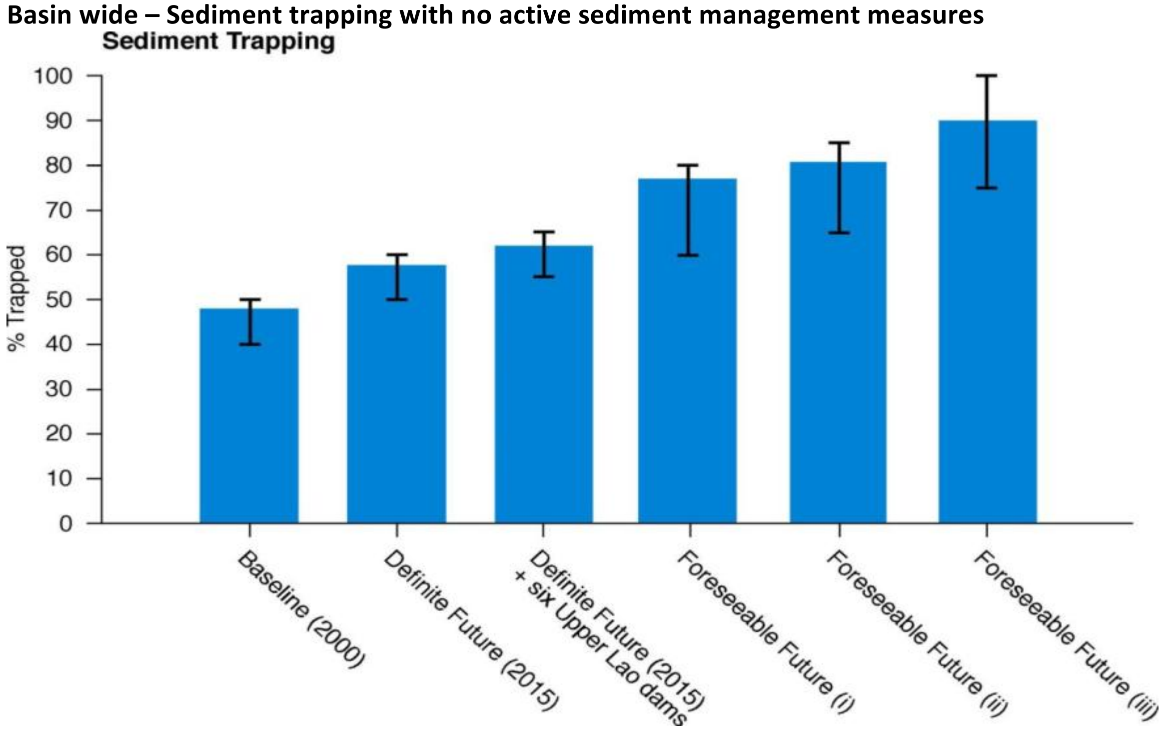


Another set of predictions by Thorne (Thorne et al 2013) looks at the following scenarios:

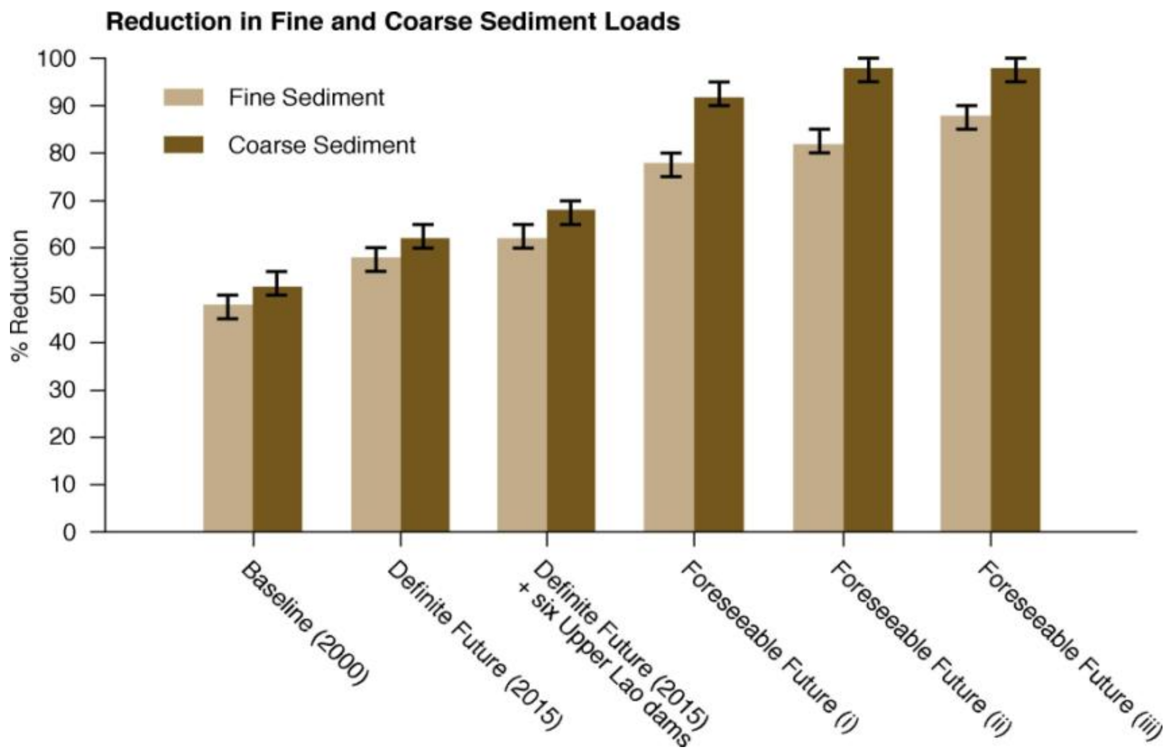
Scenario		**Dams Included**
1	Baseline – 2000	Existing Chinese mainstream dams +15 Tributary Dams
2	Definite Future – 2015	8 mainstream Chinese dams +26 Tributary Dams
3	Definite Future – 2015	8 mainstream Chinese dams, 26 Tributary Dams, + 6 mainstream dams in Lao PDR
4	Foreseeable Future (i)	8 mainstream Chinese dams, +71 Tributary Dams

5	Foreseeable Future (ii)	8 mainstream Chinese dams, 71Tributary Dams + 6 mainstream dams in Lao PDR
6	Foreseeable Future (iii)	8 mainstream Chinese dams, 6 mainstream dams in Lao PDR, 71 Tributary Dams + 3 mainstream dams further downstream in Lao PDR and 2 in Cambodia

Basin wide – Sediment trapping with no active sediment management measures



Reduced sediment supply into the Delta, combined with aggregate extraction, and construction of levees and embankments will cause channel incision and exacerbate saline intrusion. Sea level rise will compound the problem.



The workshop presented different estimates of the total sediment load reaching the delta under different dam development conditions. Lu's findings (Lu et al) indicated that from 2008-2010 the sediment load to the South China Sea has been much lower than the generally accepted pre-development estimate of 150-160 Mt/yr, showing the influence of dams and/or temporal variability in sediment transport. Additionally, Bravard and Goichot (2012) concluded that the historical average sediment load is probably considerably higher than 150-160 Mt/yr because the sand component (which moves both as suspended and bedload) has likely been undersampled. They point out that sand is transported mostly during the sharp spates of the annual flood, which will become less pronounced into and through the delta due to flow regulation in the upstream hydropower dams. However, the Mekong sediment sampling methods (e.g. monthly sampling in some locations) do not accurately sample the flood spates (Bravard 2012). It is notable that the dams will preferentially trap the coarser sediments, so the sand component of the sediment flux may be more severely impacted. Bravard and Goichot note that the sand is the most important material for maintenance of the delta landform.

Effects of Sediment Starvation in Mekong River channels and Delta

The implications of such extreme sediment starvation on the Mekong River channel and delta include:

- ➔ Erosion-led bank and channel instability involving rapid and unpredictable morphological changes in alluvial reaches (Thorne et all 2013);
- ➔ Stripping of sediment deposits in bedrock reaches (Kondolf et al, Rubin 2013)

- ➔ Unprecedented changes in the dynamics of the network of deltaic channels, due to increases and/or decreases in the distributions, rates and styles of channel avulsion, shifting and abandonment, including erosion-led bank and channel instability involving rapid and unpredictable morphological changes in channel dimensions, geometries, bedforms and planforms triggered by complex response in the fluvial-tidal system (Thorne et al 2013);

- ➔ Reduced rates of sedimentation on natural levees, flood and tidal plains, leading to reduced soil fertility and net lowering of the land because accretion no longer exceeds or balances subsidence (Thorne et al 2013);

- ➔ Accelerated erosion of the Ca Mau Peninsula, which is built of Mekong River sediment redistributed by coastal currents. Lack of sediment deposition over the delta surface will make the entire delta surface (most of which is less than 2m in elevation) vulnerable to sea level rise[1]

- ➔ Changes to flood and tidal plain ecosystems plus threats to agriculture, aquaculture, infrastructure, industry and people living/working in the Delta that are both chronic (e.g. loss of fertility) and acute (e.g. increased risk of coastal flooding, esp. during typhoons).

- ➔ Reduced nutrient supply and soil fertility in Tonle Sap and the delta. Hydrologic changes from the dams will also limit the area of seasonally-flooded land, an important contributor to fish productivity in Tonle Sap.

- ➔ Reduced nutrient and sediment delivery to the offshore fishery

- ➔ Changes in water quality, turbidity and aquatic/riparian habitats that are too rapid to allow key species and ecosystems to adjust to them.

- ➔ Loss of in-channel and floodplain ecosystems plus major disruption to agriculture, infrastructure, property, people living/working in or alongside the channels.

- ➔ Increased marine influence, more frequent and prolonged inundation, and salinization of soils all exacerbated by sea level rise and increases expected in magnitude and frequency of storm surges;

Overbank deposition of sediment will be less not only because of reduced suspended sediment concentrations, but also because of stopbanks that will prevent overbank flow. These stopbanks will concentrate flows in channels, where bed incision is likely to become worse. By

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[1] This is an order of magnitude greater than the other 33 deltas studied by Syvitski et al (2009) (**Kondolf et al, Zan Rubin)**

concentrating flow and sediment in channels, the monsoon pulse of sediment will likely be carried farther offshore and thus will be less available for deposition in the delta.

Overbank sedimentation rates are now being measured at 5-6 mm/year on sites between the low- and high-water dykes. However, subsidence rates range from 10-25 mm (with the highest rates of 26 mm recorded on the Ca Mau Cape). Projecting these subsidence rates into the future, in 50 years we will see subsidence of 500 mm to 1 m, enough to put large areas of the delta under water, even without taking climate-change induced sea level rise into account. When sea level rise is taken into account, the situation is much worse. According to SIWRP, the sea level has been rising 40 mm per decade in the East Sea and 60 mm per decade in the West Sea over the past 3 decades, but this rate is expected to accelerate to 80 mm per decade in the future.

However, the reduction in high flows caused by dams may partially counteract some consequence of climate change. Climate change is likely to intensify flood peaks and make flow patterns more variable, which would likely increase bank erosion rates. However, the upstream dams will reduce these flood peaks and flow variability, and thereby reduce bank erosion rates. Moreover, sediment trapping by dams may reduce sedimentation in navigation channels, reducing dredging requirements, and less turbid water will allow more penetration of sunlight into the water column, which may stimulate photosynthesis and provide some benefits to ecosystem productivity. These can best be regarded as short-term benefits, which would be manifest only so long as the integrity of the delta landform itself is maintained.

The effects of sediment capture in the hydropower reservoirs are cumulative with the other causes of sediment depletion, particularly sand mining from the river. The removal of the bed material for use in construction and/or land reclamation is concentrated in Cambodia now, as the Vietnamese sources have been largely exhausted. Estimates of the magnitude of this anthropogenic modulation of the Mekong's sediment budget are limited by the paucity of data on both the volume of sediment removed by dredging and on the volume of the bed load flux. Bravard and Goichot (2012) roughly estimated extractions exceed 43 million tonnes per year (more than a quarter of the river's total transport). Notwithstanding the limited data, it is clear that sand mining is unsustainable.

With closure of dams and cut off of upstream sediment supply, sediment starved water will tend to mobilize sediment stored in-channel and the effects of sediment starvation be delayed by this 'buffering'. However, this buffering will be relatively short-lived, especially in light of the massive sand mining that has occurred.

What we need to learn:

- **Historical and Current Suspended Solids and Bed Load Fluxes:** The available suspended solids records on the Mekong River are well known to be unreliable, discontinuous in space and time, and limited in duration. In many places the available record exists only for a few years. However, in recent years the national hydrological monitoring agencies have increasingly been adopting acoustic Doppler current profiles (ADCP) as the primary means of measuring flow discharge. This change in practice presents an important opportunity: the ADCP instruments also return an acoustic backscatter signal with intensity proportional to suspended solids concentration. If the ADCP instruments being used by the national agencies were all calibrated then it would be possible to undertake a post-hoc calculation of observed suspended sediment fluxes using the ADCP data already routinely stored in the MRC database. This calibration is technically straightforward and involves the collection of a limited number (~30) of suspended solids samples at a point that are co-eval with the ADCP backscatter returns. This simple approach (in progress for stations in Cambodia as part of the STELAR-S2S project outlined above) has the potential to increase by a factor of ~2 the availability of historical, high quality, suspended solids estimates for only a modest investment of resource (Darby et al 2010), (Darby et al 2013), and (Darby S).

- **Improving the estimates of bed load fluxes:** There are even fewer data available to estimate the bed load flux of the Mekong River. The STELAR-S2S team are currently employing dune tracking methods (as surveyed using repeat multi-beam echo sounder (MBES) surveys) to estimate bed load on the Mekong in Cambodia (see above). This approach could be extended to other locations by 'piggy-backing' onto STELAR fieldwork planned in the 2015 flood season. It is important to understand that a clearer understanding of the partitioning of total sediment flux between suspended and bed load components is an important consideration in evaluating the likely impacts of damming on morphological response and the flows of sediments to the delta region. In particular the changing relationship between different grain-size fractions in transport under damming scenarios could be better evaluated (Darby et al 2010), (Darby et al 2013), and (Darby S) .

- **More reliable flow data.** Although there is now a good network of gauging stations on the Mekong River and its tributaries, the reliability of estimates (both historical and current) of flow discharge remains open to question at some stations. Yet, reliable flow discharge data are fundamental to a wide range of environmental assessments on the Mekong. A concerted effort is needed to review historical flow gauging records in order to verify (and if necessary, update) the rating curves used at key monitoring stations. There are opportunities to re-develop rating curves using the ADCP instruments that are now routinely employed by the national monitoring agencies. This could be done by a specialist hydrological technician at relatively little cost. Within the delta, more complex currents may result from tidal interactions, stratified flow, and multiple distributary channels, such that standard gauging techniques may have to be supplanted by more sophisticated modeling approaches (Darby et al 2010), (Darby et al 2013), and (Darby S)

- How much will the effects of sediment starvation be delayed by mobilization of sediment stored in-channel?

- What is the relationship between bank erosion and supply of sediment to the delta? And how long can that bank erosion continue before the available floodplain supply is exhausted?

- What are the sediment dynamics in the Lower Mekong floodplains for both coarse and fine sediments? There is a rather good understanding down to Mukdahan, but not reliable data from there to the delta. To what extent and at what rate will overbank deposition of sediment be reduced due to both reduced suspended sediment concentrations and the channel incision that will prevent overbank flow? Kummu estimated that, on average, there is a 55% reduction in sediment load between Mukdahan & Cambodia-Vietnam border, but substantial uncertainty still exists. However, there is the fundamental problem that no increases in sediment storage have been documented between Mukdahan and the Vietnam border to account for the missing 55% sediment load, so an unknown fraction of this discrepancy may be attributable to measurement error, a common problem when calculated sediment budget components as residuals (Kondolf and Matthews 1991).

- What are the sediment size distributions in the Mekong River system (e.g. how much of the load is clay, silt, fine sand, etc.), what is the relative proportion of fine (suspended) versus coarse (bedload) sediment transport, and what are the sources of different types of sediments. What proportion of different size fractions will be trapped in proposed reservoirs? Uncertainty stems are not only from limitations of data availability and model accuracy but also from natural variability which is an attribute of the river that cannot be reduced.

- What are the sediment contributions coming into the Lower Mekong River from the various tributaries?

- What is the nutrient composition of the sediments trapped in the reservoirs?

- What will be the impact of increased climate variability and future land use on sediment yield and transport?

House in Ca Ma, Mekong Delta

Monitoring recommendations:

Sediment and nutrient monitoring are recommended continually through the period of dam operations with the aim of supplying data relevant to the following issues:

- Sediment accumulation in the reservoir with an emphasis on sediment features at the upstream and lateral margins and siltation in deep locations, including the deep pools. Frequency: at least biannually, prior to and following the monsoon. This frequency may be adjusted as experience is gained on the actual rate of sedimentation.

- Changes in sediment (quantity and composition) and in the morphology of the river reach between the upstream dams and the delta. Emphasis to be placed on river banks and flood-level lines, mid-channel islands, and sediment deposits at tributary junctions. Frequency: at least annually, following the monsoon, later adapted as experience dictates.

- To what extent and at what rate will reduced sediment supply into the Delta cause channel incision and consequent saline intrusion, compounded by sea level rise? A program of monitoring cross sections of channels is needed to detect bed incision.

- Water quality flowing into and out of the upstream reservoirs, including: all fractions and total amounts of inorganic nutrients, suspended sediment, organic content (COD or BOD), chlorophyll, main taxonomic groups of algae, oxygen, PH and temperature, and light adsorption/penetration capacity of the water. Such a sampling program should be conducted monthly (or adjusted to proportionally sample different flows and seasons) and should include stations intermediate between the dams and the delta to account for other influences of these variables.

Vietnam Mekong Delta. Photo by: Vietnam Airlines.

MORPHOLOGICAL EFFECTS IN THE COASTAL ZONE

What we know:

To estimate the effects of various degrees of reduction of sediment inflows to the coastal zone, improved understanding of coastal processes and sediment dispersion by waves, tides and coastal currents is needed. Coastal erosion is certainly occurring in major parts of the deltaic coast and is most pronounced in Ca Mau Peninsula where the rates in some areas is up to 70 meters per year and up to 6 km for the last century, but rates are highly variable and some accreting sections of coastline are also evident, as illustrated in recent mapping of coastal changes available on the website of the Soc Trang Province (http://czm-soctrang.org.vn/en/About%20the%20project.aspx?ID=22). These effects will be greatly exacerbated by sea level rise, which will also amplify saltwater intrusion.

The eastern delta now has areas of accretion and areas of erosion. As the sediment load (especially sand) declines, the coast is likely to become increasingly erosional.

Sea level rise will bring changes in wave action, larger storm surges, increases in monsoon intensity, more precipitation, and (therefore) more sediment erosion and transport into the ocean. Best estimates at this time are that the coastal area is subsiding at the rate of 10-30 mm/year and sea level is rising at the rate of 3-4 mm/year.

Impacts of reduced sediment inflows on coastal resources

➔ Reductions in sediment/nutrient concentrations in plumes of Mekong River water that extend offshore to form a primary connection between the land and the ocean (Thorne et al 2013).

➔ Net coastal erosion and incremental destruction of the delta through time, plus increased erosion risks along the coast in the downdrift direction (Thorn et al 2013);

➔ Destruction of land, natural resources, infrastructure and property along the deltaic coast where it is undefended and coastal squeeze that destroys inter-tidal habitats and ecosystems in areas protected by coastal embankments, plus the need for massive, long-term capital investment to raise/protect/maintain coastal defenses, embankments and polders (Thorne et al 2013).

➔ Increased marine influence, inundation, and salinization – all exacerbated by sea level rise and storm surges (Thorne et al 2013);

What we need to learn:

- To better understand the relationship between local coastal circulation and biogeochemical processes, a systematic monitoring effort is needed to collect data of the water and associated dissolved and particulate materials on the delta plain, along major tributary channels and coastline of the Mekong Delta. Hydrodynamics (winds, waves, currents, temperature, salinity, etc.), sediments (grain size, suspended sediment concentration, settling velocity, critical shear stress, etc.), and water quality (nutrient concentration, toxic level, etc.) data should be collected periodically

- At present, we do not know how much sediment is now arriving at the coast and how this compares to the historical pattern. We can gain a better understanding through two approaches:

  (1) We can start monitoring
      - sediment transport at selected areas, e.g. Bassac river mouth and easternmost distributary;

- changes in bathymetry at selected cross sections on the subaqueous delta platform and delta slope at Cape Ca Mai (Unverricht et al. 2013).

(2) We can analyze satellite images and aerial photographs to follow the history of erosion for the last 50 years

- To estimate the effects of reduced sediment inflows to the coastal zone, improved understanding is needed of coastal processes and sediment dispersion by waves, tides and coastal currents, and knowledge of the ultimate fate, dilution and cumulative effects (both over long times and from multiple sources) of terrestrial sediments, nutrients and pollutants introduced into the South China Sea by the Mekong. That knowledge will enable better predictions of the consequences of sediment trapping by dams. This is very important in view of the recent finding that approximately 53% of the surface water in the western South China Sea originates from the Mekong River (Thorne et al 2013).

- A high resolution, integrated ocean-sediment-ecosystem model, covering the entire Mekong River Delta and adjacent coastal waters, could provide insights into the relative importance of river discharge, hydrologic conditions, land use change, and climatic events in driving regional sediment and ecosystem dynamics. Such a high-resolution model could improve our understanding of the coupling between circulation and sediment/ecosystem dynamics and assess the potential impacts of extreme events and future climate scenarios on the stability of the coastline and the health of the coastal ecosystem (Xue). Such a model would be an ambitious undertaking and require detailed data inputs.

- Research is needed to better predict how sea level rise will interact with the reduction in sediment inflows to affect the coastal zone.

- Finally, more experimentation on the efficacy of mangrove regeneration and other "soft" techniques to mitigate the combined effects of sediment reduction and sea level rise are needed. Mangrove destruction occurred in large areas during the Vietnam War and some replantation has been done since. However, original mangrove stands at Ca Mau Peninsula are eroding at the present time.

Mekong River from Phou Si. Photo by Wikimedia.

EFFECT OF REDUCTION IN NUTRIENT INFLOWS TO THE DELTA and MARINE ENVIRONMENT

What we know:

Nutrient inputs to the Mekong River system come from many sources, including hillslopes, human and animal wastes, and runoff of fertilizers from agricultural lands. Some of these sources are beneficial to the food web, some are harmful.

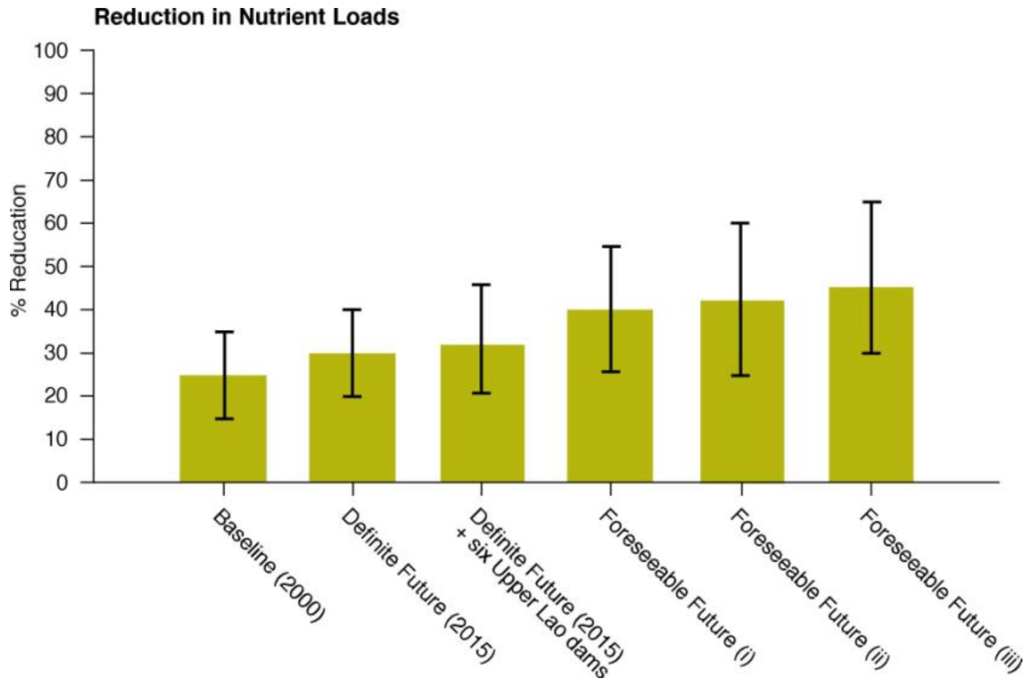
In tropical systems, nutrients dissolved in the water are typically used rapidly, but nutrients attached to sediments are transported long distances before becoming available for use biologically.

Dams in the Mekong affect nutrient availability in several ways. To the extent that dams capture sediment, they also trap nutrients associated with fine-grained particles.

However, the nutrient content of the sediment fractions that are captured under various dam designs and operating regimes is not well understood.

Dams that regulate floods—storage dams rather than run-of-river dams—will reduce the frequency, duration, timing and extent of flooding could have serious impacts on the dispersal of nutrients in the floodplains. The residence time of water in the reservoir strongly affects nutrient capture. Sediment-deleted flood waters may leach nutrients out of the soil rather than bringing nutrients to the soil. Flooding processes in the Mekong delta are complex. So the effect of nutrient capture in dams is complex.

Thorne has estimated the reduction in nutrient flows into the delta under the same set of dam development scenarios listed previously for reductions in sediment inflows. These range from about 25% to about 40% (Thorne et al 2013).



Tonle Sap:

Tonle Sap is properly viewed as being within the delta as the tidal influence in the Mekong River extends as far as Kratie. However, the delta in Cambodia is at a higher elevation– a terrace surface-- compared to the delta in Vietnam.

The productivity of Tonle Sap depends on the annual flood pulse and recession, and the sediments and nutrients that it carries and deposits.[2] Kummu et al (2008) found that large part of sediment entering the lake is trapped by the floodplain ~5 Mt/yr. Lu et al (under review), however, found that in Tonle Sap River sediment inflow and outflow are in balance, with mean sediment inflow into the lake from the Mekong mainstream calculated in this study (6.3 Mt) close to the value of 5.1 Mt reported by Kummu et al. (2008), but the outflow (8.5 Mt) was higher than the value of 1.4 Mt reported by Kummu et al. (2008). L.X. Thuyen (unpublished data) found an increase in deposition rates in the delta formed by Mekong River waters flowing *into* Tonle Sap Lake, based on radionuclide dates from two sediment cores. Some researchers

[2] Junk et al. have found that "the overwhelming bulk of the riverine animal biomass derives directly or indirectly from production within the floodplains". And "the basic fertility of the floodplain depends on the nutrient status of the water and on the sediments deriving from the river".

have found that there are now eutrophication problems in Tonle Sap due to nutrient overloading and that sedimentation rates are high on the floodplains around the Tonle Sap – the lake itself seems to be in balance. [3] Thus, the sediment balance and long-terms trends in Tonle Sap are still uncertain.

There are strong positive relationships between sediment load and primary production in the Tonle Sap. The SYKE report to the Mekong River Commission's Information and Knowledge Management Programme: "Primary and Fish Production Report" (December 2010)[4] estimated an 80% reduction in sediment load from the Mekong into Tonle Sap. It finds that "large areas in the lake proper and in the floodplains will lose 50% or more of the productivity" (p.57). This conclusion is premised on the actual or intended siting, design and operation of the existing and future dams, which are generally devoid of consideration of measures for sediment passage.[5]

What we need to learn:

- **Estimation of Future Sediment and Nutrient Fluxes to the Mekong Delta:** Estimates of the magnitude of the fluvial sediment/nutrient flux delivered to the Mekong Delta under scenarios of climate, land-use, development and hydropower development are of first order significance for evaluating associated impacts within the delta region. The critical location within the Mekong network at which such estimates are required is in the Phnom Penh area, as (i) this can be considered to be the practical upstream limit of the delta and (ii) it is also the location of the major exchange of flow and sediments and nutrients between the Tonle Sap and Mekong Rivers. It is important to understand that water and sediment/nutrient fluxes to the Mekong Delta are likely to be strongly modulated by the exchange fluxes within the Tonle Sap River and its lake. Thus – and although such fluxes into/out of Tonle Sap Lake are also of considerable interest in their own right due to their ecological significance – estimation of fluxes to the delta cannot be separated from the issue of exchange flows with the Tonle Sap(Darby et al 2010), (Darby et al 2013), and (Darby S) .

- To what extent will the quantities of the key nutrient components in Tonle Sap be affected by upstream dam development? Choices regarding the pace and magnitude of upstream dam development, and decisions regarding the siting, design and operations, will substantially affect the composition and quantities of nutrient inflows to Tonle Sap

[3] Beung Tonle Chma, May 2013

[4] In that work, SYKE collected test samples of sediments and their nutrient content from flood waters of the Mekong mainstream at Phnom Penh and from the Tonle Sap River at Prek Kdam and analyzed the amounts of bioavailable phosphorus, under the assumption that phosphorus is the nutrient that generally controls primary production in freshwater ecosystems. The study modeled the reduction in primary productivity and fish production in Tonle Sap as a consequence of flow alteration and sediment trapping due to the "most probable future hydropower dams" considered in the MRC's Basin Development Plan scenario impact assessment. This includes the Chinese dams and the 10 proposed mainstream dams, as well as the tributary development.

[5] There are also numerous assumptions about the general ecology of the ecosystem largely based on northern temperate ecosystems or the Amazon River.

from the River. The current dam development plans were formulated without sediment passage considerations. These provide the base case against which alternative dam sites, designs and operations, formulated to facilitate sediment/nutrient passage, can be compared. Most critical are sediment alternatives for the most impactful Cambodian dams, Sambor and Lower Se San 2, as well as the Lao dams on the Se Kong tributary. Under these plans, some sediment will be retained, and some will be passed through the reservoirs. Considerations such as the residence time of the water in the reservoir, its geometry, the size of the reservoir relative to inflows, and various techniques for sediment passage or removal will all affect the amounts and grain sizes of the sediments that are ultimately discharged and their timing. For instance, the fine washloads will have a different nutrient profile than the coarser sediments; the clays will have a different nutrient profile than the silts, etc.[6] Estimating nutrient constituents in the sediments that are discharged under the various alternatives will provide a basis for comparing these alternatives to the base case with respect to the availability of nutrients to the Tonle Sap ecosystem.

- **Role of Floodplain channels:** Many of the ecosystem services that support the livelihoods of riparian communities are 'hosted' on the Mekong's floodplains in Cambodia (just upstream of the delta). However, details of the processes of water and sediment exchanges (and hence the nutrient and geochemical exchanges that support the key ecosystem services) between the Mekong and its network of floodplain channels are almost entirely lacking. It may be speculated that the flood pulse is transmitted into this network of floodplain channels and that sediment/nutrient/geochemical transfer pathways over the floodplain are conditioned strongly by the morphology of the floodplain channel network(Darby et al 2010) , (Darby et al 2013), and (Darby S) .

- The nutrient content (both phosphorous and nitrogen) of the sediment fractions—coarse sediments, washload, clay, sand, and organic debris—captured in reservoirs, in terms of both quantity and spatial distribution, must be determined for various reservoir design and operating regimes.

- The nutrient binding (especially phosphorus) to sediments coming into Tonle Sap and the delta must be evaluated to determine nutrient mobility and bioavailability

[6] Algae don't directly utilize particulate nutrients. They assimilate dissolved nutrients, which means there needs to be a mechanism to mineralize the particulates. The ecology is complex but sediments can actually be a sink for nutrients rather than a source depending on their carbon content. We do not yet know what the specific processes are for this ecosystem.

- Other factors bearing on nutrient availability that need to be studied include the turnover of nutrients within sediment accumulations and the risk of local landslides adversely affecting nutrient loadings and water quality

- In Tonle Sap, the nutrient inflow is not only from the Mekong, but also from local rivers. There are disagreements among the experts regarding the relative importance of these nutrient sources. The data are not now sufficient to resolve this important issue.

- To understand how changes in nutrient inflows to Tonle Sap will affect its productivity, it is necessary to establish the limiting resource for aquatic primary productivity. Phosphorus is generally assumed to be the limiting nutrient, as it was in the SYKE Report. However, the presence of nitrogen fixing cyanobacteria during low water periods suggests that nitrogen dynamics may also be important. Light (affected by turbidity) and other factors may also play an important role. The 3D model developed as part of the SYKE report is a tool that can address the factors that determine the production potential of Tonle Sap as a flood-pulsed ecosystem. However, there are a number of model parameters that have not been quantified for the Tonle Sap which could be addressed with a year or more of field work.[7]

- The baseline water, sediment, and nutrient dynamics must be determined for at least the mainstream and the 3-S tributaries, and perhaps other tributaries as well. To do this, it will be necessary to:

  (a) measure and sample the flux of water, sediment, and total and dissolved nutrients now flowing into and out of Tonle Sap during the annual flood and recessional regime, including sampling of tributary inputs; and

  (b) assess to the extent possible the source of the nutrients to Tonle Sap, including sources to the Mekong River mainstream flows that ultimately flow into Tonle Sap.

[7] Importantly, opportunities exist to collaborate with extant research projects run by the University of Southampton (UK) in the region during 2013-2014, and ongoing work by the University of Washington. These offer a chance to leverage key data for relatively little additional investment.


Floating Market in Mekong Delta. Photo by ABSTRAVEL

BIOLOGICAL EFFECTS OF REDUCTIONS IN SEDIMENT AND NUTRIENT AVAILABILITY:

What we know:

- Fishery productivity is impaired by four factors associated with dams: (1) sediment capture, (2) barriers to fish migration (3) reduced water quality; and (4) reduced flood pulse. Dams not designed and operated to pass fish and sediment will reduce the downstream sediment concentrations and block fish migration. If these dams are also storage dams (in contrast to run-of-the-river dams, such as the Mekong mainstream dams), they will also minimize the flood pulse and alter water quality. Thus, depending on the design and operations of the dams, fishery productivity will be affected in multiple ways.

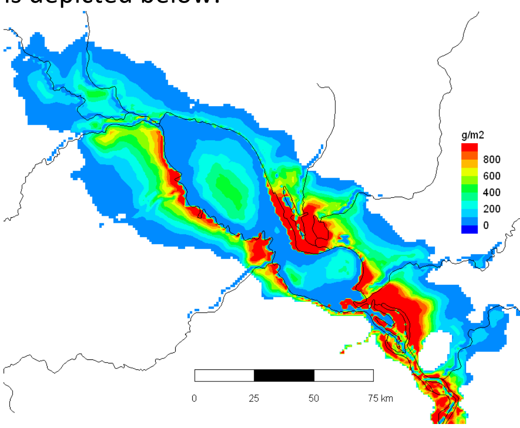
- What matters most for fish productivity is not sediment but **nutrients**. Dissolved nutrient concentrations are generally low and nutrients are mostly adsorbed on sediments, primarily silt, clay and sand. These finer sediments are the fractions that are least likely to be trapped in reservoirs and most likely to be flushed.

- Without dams (or with dams that pass sediment and fish), there are large nutrient outputs, high floodplain productivity and transfer of organic matter to tributaries through fish migration. With dams that do not pass sediment and fish, there are reduced nutrient outputs, lower floodplain productivity, reduced fish migration, and reduced transfer of organic matter into the tributaries.

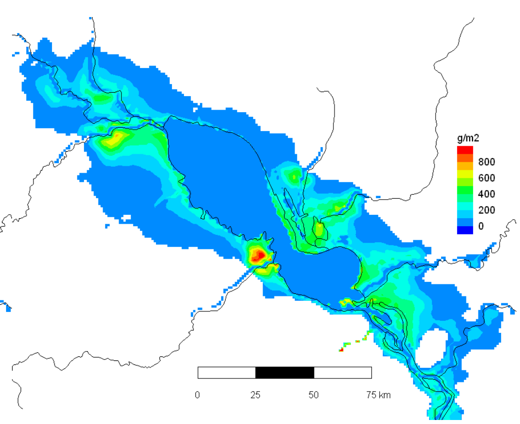
- ➔ The areas of the Mekong River system that are the predominant zones for generation of the extraordinary migratory fish yield in the delta are the Tonle Sap and the 3-S tributaries. Therefore, to maintain the productivity of the delta fishery, we must be concerned with the effects of sediment and nutrient depletion in these generation zones.

- ➔ Application of the primary productivity based fisheries model showsa 36% decline in [Tonle Sap] total fish biomass production if Mekong sediment input is reduced by 80%. *Sarkkula and Koponen 2010 DMS final report.*

- ➔ The future productivity of Tonle Sap as a consequence of sediment and nutrient change is depicted below:

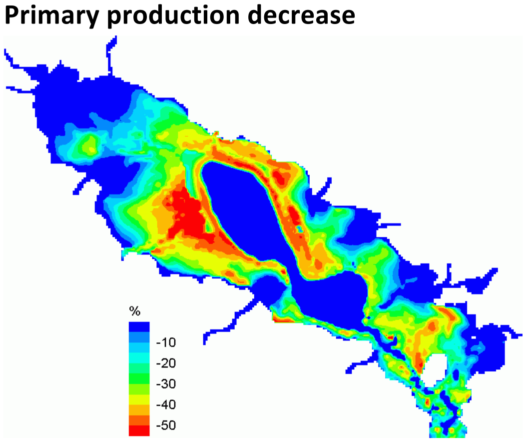


Baseline

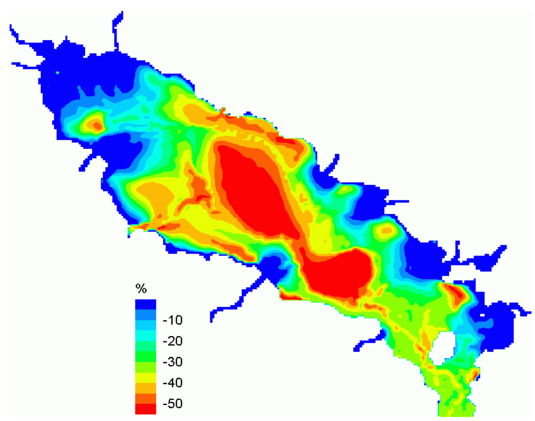


20 year dams

Primary production decrease

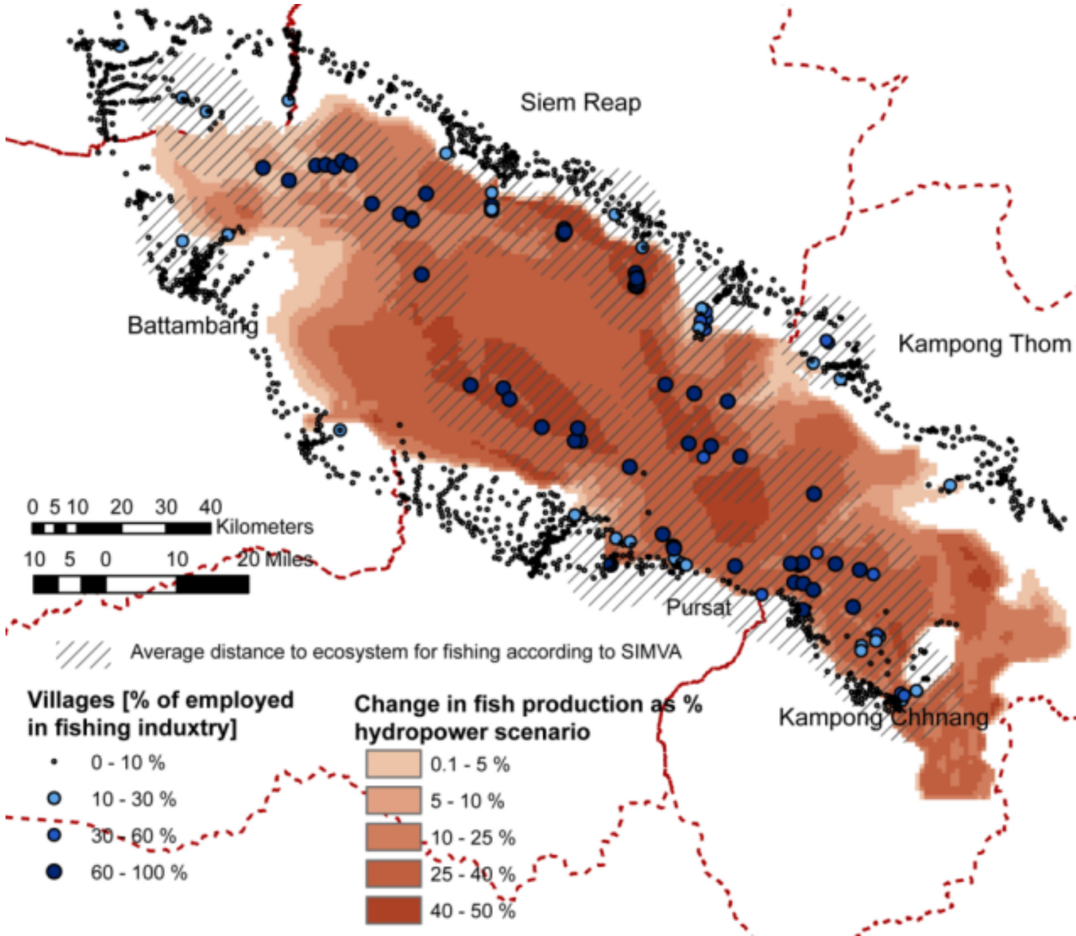


Periphyton decrease



Phytoplankton decrease

Decrease of fish production in Tonle Sap



- ➔ Sediment and nutrient retention by dams is expected to impact coastal fish production, and subsequently the Vietnamese fishing sector and fish trade. This would also impact the delta aquaculture sector which is dependent on protein from marine 'trash-fish' to feed the aquaculture fish for feedstock. ICEM 2010. SEA of hydropower on the Mekong mainstream

- ➔ Mekong marine fisheries are dependent on the nutrient and sediment dynamics of the river. The Mekong marine fishery is a significant component of the Vietnamese delta economy, with a production in the order of 500,000 – 726,000 tons per year. Coastal fisheries will decrease significantly due to reduced sediment and nutrient input to the sea. Increased fertilizer use in the basin will not necessarily compensate for the loss of trapped nutrients; increased chemical fertilizer use is not sustainable in the long run and fertilizer prices have recently experienced sharp increases (Sarkkula and Koponen 2010, ICEM 2010).

What we need to learn:

- In the delta below the Tonle Sap tributary also, natural vegetation, fauna, fish and fisheries will all be affected by the trapping of nutrients. These are some of the data gaps that should be addressed.

    - **Ecosystems:** Sediments with nutrients support algae and diatoms that are the base of the food chain – hence nutrient trapping may undermine plants, fish, and birds all the way to apex predators. The extent of these impacts is an important research need.

    - **Primary production:** This occurs in the river channels, on floodplains and in seasonal lakes, but in different ways depending on the size of sediment deposited – which is mostly a function of distance from the channel. Silt is deposited closer to the channel, clay further away and areas far from the river channel get little or no sediment.

    - **Fish:** Most of the studies on inland fisheries resources in the Mekong Delta and their dependence on hydrological regime of Mekong River have been related to water level fluctuations, flooded area, flooding time, water depth and water discharge, but not to changes in water quality and nutrients to the flood chain and consequently to fish production, in which sediment may play an important role. The relationship between fish production/yield and natural food densities and sediment concentration in the flooded areas should be analyzed and assessed. Nutrient availability affects fish biomass and diversity for some species more than others, and for some life stages more than others. Flushing sediment from reservoirs may overload the downstream ecosystems with nutrients, or generate unnaturally high concentrations at unnatural seasons, with adverse effects. This will affect the capture fishery also and hence people (subsistence fisher folk, social impacts) and livelihoods (commercial fisher folks). Therefore, studying techniques for flushing reservoirs that can avoid these impacts is an urgent research need.

    - **Agriculture and aquaculture:** The effect of changes in nutrient availability for the productivity of aquaculture (fish farms) and floodplain farms has not been studied. The relationship between rice production and the availability of nutrients from the river also needs to be studied.

    - **Habitats:** The effect of changes in nutrient balance on turbidity, and hence on plant growth and habitats has not been studied. Also mangrove forest in the coastal zone of the Mekong Delta largely absorbs sediment from the MR and becomes important habitat in the life cycle of many marine fishes and other aquatic animals. Therefore, the change of sediment accumulation it the mangrove foresee and its impacts on fisheries resources in the mangrove should be studied.

- **Coastal zone:** The significance of river borne nutrients to the near coast zone is unknown. It may be important, in which case nutrient trapping may have impacts on the marine fishery. There is some evidence that phosphorous may be a limiting factor for marine ecosystems, especially in the coastal zone. If the river borne nutrients (dissolved and sediment related) are important, the effects may extend down drift to Cambodia! Because the near shore marine fishery in the South China Sea is as important economically as the freshwater fishery, this issue is a critical research need.

- It is critical to assess how changes in the availability of specific nutrients are likely to affect the primary productivity of Tonle Sap. The dam development and operational alternatives will result in differing levels of key nutrients reaching Tonle Sap. This is a complex analysis. Nutrients associated with sediments may not be biologically available until they pass through complex floodplain processes. Floods change the physical state of the ecosystem which in turn alters the chemical state and ultimately the biological state. Thus, the availability of the nutrients for cycling through the floodplain ecosystem is a function of the flood pulse extent, duration and timing. These too will be affected by the operating policies for the reservoirs (as well as their design and locations). In this respect it is not just the sediments trapped in the dams but also alternation in the flows of both water and sediments that will affect primary production in the Tonle Sap.[8]
  This Task will entail specific data collection on the determinants of primary productivity for all of the other relevant floodplain components (terrestrial and aquatic) of the Tonle Sap ecosystem for which data exists. These include the hydrodynamic characteristics of the flood pulse (timing, modality, speed, height, and duration), sedimentation, flooded vegetation cover and composition. This final step will also require research on the relative role of nutrients in relation to the other drivers of primary productivity such as sunlight.

- In addition to the data and modeling on the Tonle Sap from the SYKE report, it may also be useful to utilize information developed in other flood pulsed ecosystems that are better known. The Amazon is the best-documented large tropical floodplain. But there is also valuable information from other sites like the Okavango Delta and the Northern Territory in Australia with a similar hydrology, scale and vegetation. Using information from the SYKE report on modeling of Tonle Sap (together with information from such reference river systems) may allow an integrated ecosystem productivity indicator to be developed that could be continued and updated. However, each floodplain is unique and there is no replacement for *in situ* observations.

- It is essential to relate changes in nutrients and primary productivity to changes in fishery production. Such studies are currently ongoing at the University of Washington.

[8] Sediment core data being collected by the University of Southampton provides a means to validate this modeling using historical reconstructions of trajectories of ecosystem functioning, especially in terms of primary productivity.

Landscape Mekong Delta. Photo by Joep Janssen

MITIGATION & ADAPTATION STRATEGIES

Given the complexity of relationships between sediment and nutrient inflows and biological productivity of the delta, the large uncertainties and data gaps, and the pace at which development decisions are being made, it is not realistic to directly quantify the reduction fish production due to sediments/nutrient trapping, or to identify the critical thresholds of impact. A more realistic approach is to accept that the magnitude of the impact will be proportional to the reduction and place the research priority on options for improving the siting, design and operation of hydropower dams to minimize the capture of sediments or the alteration of dispersal pattern into the downstream river system.

Factors that bear on the degree of sediment/nutrient passage through dams include:

- The annual water and sediment inflow volumes comparing to reservoir storage volumes.
- The size and geometry of reservoirs
- The turnover rate of water (CAP/MAR = total capacity/mean annual runoff) and sediment (CAP/MAS = total capacity/mean annual inflow sediment)

POLICY AND ACTION RECOMMENDATIONS:

- Much more data has been collected than has been revealed, shared and processed. The latest results of the MRC sediment sampling program are one example. This information is now in the hands of the National Mekong Committees. All relevant agencies of the national governments should be encouraged to contribute this information to a central organ, such as the MRC, to be freely accessed by interested parties.

- There is no static baseline under the current conditions of rapid development of the basin, so continuous monitoring is needed. This requires a program of remote sensing by the international institutions plus ground-truthing carried out by the local institutions.

- The effects of sediment starvation and reduction in nutrients will be more pronounced in some areas than others, suggesting that an analysis of relative losses and the gains at different locations, as a basis for identifying appropriate interventions.

- Dam designs must be modified to enhance and optimize the capacity for sediment routing and flushing. Dams must have the capability to allow future generations of dam operators to manage sediments adaptively, by making changes to the way that sediment routing and flushing operations are implemented as appropriate to future conditions and changing priorities for river and resource management in the LMB. Recommended designs would involve modifications to the spillway and include low-level outlets with dimensions sufficient to allow operators to re-create the river-like flow conditions required for flushing.

- For dam operations, it is highly recommended that an environmental flow strategy be established for the river downstream of the dam that considers sediment and nutrient dynamics and incorporates sediment flushing to avoid potential serious, adverse impacts on downstream environments and ecosystems. Recognizing that uncertainty will never be eliminated by even the most advanced modeling, the sensible way forward is to keep dam operations dynamic and adaptable as knowledge is gained from long-term monitoring programs

- The new research recommended by the workshop should be undertaken to by the national research institutions in close cooperation with international institutions and foreign experts. Otherwise the decision-makers in each country will not accept the outcomes or see their relevance. Ideally, the studies must be undertaken cooperatively by the Mekong riparian countries.

- We do not have a decade to collect needed data, as specified by the Strategic Environmental Assessment of the MRC. We need a short-cut: a prioritized matrix of the most critical research.

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Annex A: Roster of Experts Attended Mekong Delta Impacts Workshop

Ho Chi Minh City, October 7 -8, 2013

Invited Sediment Experts

1. **Dr. Chu Thai Hoanh**: Chu Thai Hoanh has 30 years of experience in research and management with wide and varied subjects in GIS and modeling for agriculture and water management, including hydraulic modeling, crop modeling, optimization and supply-demand analysis. In the early 70's he was the chief hydrologist in charge of hydrological measurement and analysis for the Mekong River Delta, Vietnam. During 1976 - 1996, he was in charge of hydrological measurement, water modeling, remote sensing applications for water resources planning and management in the South Vietnam. He was also a lecturer on remote sensing at the University of Ho Chi Minh City during 1987-1989. He joined the International Rice Research Institute (IRRI) in 1997 for research in GIS and water modeling for rice and shrimp production in the coastal area, crop modelling and socio-economic analysis for regional and national balancing of rice supply and demand, and developing optimization model for land use planning with many case studies in India, Malaysia, Philippines, Thailand and Vietnam. In 2001, he was awarded a medal by the Ministry of Agriculture and Rural Development of Vietnam in recognition of his contributions to Agriculture and Rural Development. From May 2002 he was joint-appointed by IRRI and IWMI as International Research Fellow to continue the GIS water modelling studies and from May 2003 he is Senior Water Resources Specialist at IWMI.

2. **Dr. Colin Thorne:** Dr. Colin Thorne is a fluvial geomorphologist with an educational background in environmental sciences, civil engineering and physical geography. He has published 9 books and over 120 journal papers and book chapters. During a career spanning four decades, has held academic posts at UEA, Colorado State University, the USDA National Sedimentation Laboratory, USACE Waterways Experiment Station, NOAA Fisheries, and the University of Nottingham. He is also a Concurrent Professor at Nanjing University and an Affiliate Professor at Colorado State University.

3. **Dr. Eric Baran**: Eric Baran is a tropical fisheries specialist and a Senior Scientist at the WorldFish Center. Eric holds a Ph.D. in Biological Oceanography and has worked in twelve countries in Africa, South America and Asia. For the past 12 years he has been working in the Mekong, with a focus on fish ecology, impact of

dams and environmental management. He recently completed a research study on fish and sediments for NHI. His 45 publications on fish and Mekong fisheries are accessible at: www.worldfishcenter.org

4. **Dr. Erland Jensen:** Chief Technical Adviser at Mekong River Commission Secretariat
Monitoring and Evaluation: has developed and managed numerous M&E systems including Qualitative and Quantitative indicator systems and links to other M&E.
He has deep knowledge about energy and material monitoring and reporting, including recycling, reuse and reclaim related to waste, discharge and effluents, all basic constituents for sustainable development strategies; has detailed knowledge of supply chain operation between links exchanging products and services; has years as consultant to implement Food safety standards in the supply chain, using standards like ISO22000, ISO14000, ISO9000, HACCP, SOP, EurepGapetc; has developed The Traceability system based on EDI and SMS data exchange of traceability information between all links; has worked as consultant in procurement for major ADB programmes in Vietnam.

5. **Dr. George Mathias Kondolf**: Dr. G. Mathias Kondolf is a fluvial geomorphologist specializing in environmental river management, impacts of human development on runoff and sediment yield, and restoration of rivers and streams. He is Professor of Environmental Planning at UC Berkeley. He was a principal investigator in the National River Restoration Science Synthesis project, a national-level study of river restoration; a member of the Federal Interagency Levee Policy Committee; a member of the National Research Council Committee on Hydrology, Ecology, and Fishes of the Klamath River Basin; and the Environmental Advisory Board to the Chief of the US Army Corps of Engineers. Dr. Kondolf was a co-author of the CALFED Ecosystem

6. **Dr. Gregory Thomas**: Gregory is the Natural Heritage Institute’s founder and president. Greg has practiced natural resources law since 1974, primarily for non-profit conservation organizations. In the 1970's, he played a central role in the enactment of many of the foundational federal laws in the energy and environmental field. He was a senior staff attorney with the Natural Resources Defense Council's international program, and became the managing attorney of its San Francisco office. He was a Fulbright Professor and advisor to the national environmental ministry of China, and he taught law at UCLA and UC Berkeley. Greg’s practice has encompassed many areas of natural resource management, including water resources, energy, air quality, biodiversity, environmental planning, and international conservation. He has 35 years of experience in litigation, administrative trials, legislative advocacy, policy analysis, institutional

design, and consensus building processes. At NHI, he develops and manages large-scale projects in California, throughout the United States and internationally.

7. **Dr. Jeff Opperman**: Jeff Opperman, senior freshwater scientist, has been working to protect rivers and lakes for nearly 15 years. He has provided strategic and scientific guidance to freshwater conservation projects across the United States as well as in China, Africa and Latin America. In his role at The Nature Conservancy much of Jeff's focus is on improving the environmental sustainability of hydropower both by advancing sound policies and by supporting on-the-ground projects.He is a member of the governing board of the Low Impact Hydropower Institute (LIHI), which certifies "environmentally preferable" hydropower and recently served on an Independent Review Panel that provided recommendations for floodplain management to California's Department of Water Resources. Jeff earned his B.S. in Biology from Duke University and a Ph.D. in Ecosystem Science from the University of California, Berkeley. He then studied floodplain ecology during a post-doctoral fellowship at the University of California, Davis. His scientific and policy research has been published in journals such as Science, BioScience and Ecological Applications. Jeff strives to communicate the challenges and opportunities of protecting fresh water through his "Cool Green Science" blog on nature.org.

8. **Dr. Jorma Koponen**: Dr. Koponen is a senior modeler at the Environmental Impact Assessment Centre of Finland, EIA Ltd. He has worked as deputy team leader and main modeler for the WUP-FIN project. He has long-term experience in development, validation, use, and practical application of hydrological, hydrodynamic, water-quality, and ecosystem simulation models. He has been developing the EIA 3D model over the last 20 years.

9. **Pro Hiroshi Takebayashi**: Kyoto University, Japan. His research focuses on stream and bed deformation analysis method, sediment (material) runoff method and prediction method of habitat for fauna and flora have been developed by clarifying mechanism of sediment transport and bed deformation. Furthermore, the method to produce sediment transport system which has a well-balanced sediment environment for both safe for our life and eco-system has been developed by use of these methods.

10. **Professor Karl Stattegger**: Karl Stattegger completed his studies of geology and paleontology in 1977 with the " Promotio sub auspiciisPraesidentispublicaerei "(Latin for promotion under the auspices of the President from). To 1986 he was

assistant professor at the Institute of Geology and Paleontology of the University of Graz and qualified in the same year in Mathematical Geology. Until 1988 he worked as a lecturer at the Institute of Geology and Paleontology of the University of Graz. In 1990 he became Professor at the Institute of Geosciences, Christian-Albrechts-University of Kiel . Since 2006 he is a senior scientist in the Cluster of Excellence "The Future Ocean"in Kiel University “Sea level rise and coasts in danger ".

11. **Professor Kazuya Yasuhara:** Professor at Ibaraki University, Japan. He has on-going projects on the Mekong and its sustainability.

12. **Professor Lu Xixi:** Professor Lu Xixi is an associate editor of International Journal of Sediment Research, and a member of the editorial boards of Hydrological Processes, Earth Surface Processes and Landforms, Singapore Journal of Tropical Geography, Online Journal of Earth Science and The Open Geology Journal.
    He is a Treasure of AOGS, a Singapore representative of the International Association of Geomorphologists (IAG), and a member of the International Association of Hydrological Sciences (IAHS). Within the Department, Associate Professor Lu is the Deputy Chairs of the Tropical Environmental Change Group (semester two) and NUS Students Sub-Committee (NSSC) (semester two).

13. **Dr. Matti Kummu**: Water Resources, Helsinki University of Technology, Mekong River Commission. Ongoing projects include: Human Interaction on Global Water Resources; Tonle Sap futures (part of Mekong Region Futures led by CSIRO); Mekong Challenge: Mekong Basin Project MK3, part of the Challenge Programme on Water and Food (CPWF); and Asian Large River Basins.

14. **Rubin, Zan:** University of California, Berkeley Berkeley, CA. PhD, Environmental Planning

15. **Professor Stephen Darby**: Professor of Physical Geography in Geography and Environment, where he leads the Earth Surface Dynamics Research Group. He has worked at Southampton since 1997. He currently serves as the Vice Chair (Research) of the British Society for Geomorphology.
    B.Sc. (Geography) Queen Mary-Westfield College, University of London
    Ph.D. (Geography) University of Nottingham

16. **Dr. Tetsuya Sumi**: Professor at Disaster Prevention Research Institute, Kyoto University. His research themes include study on reservoir sedimentation and

sediment flushing reservoir sedimentation, sediment flushing research field; study on high turbidity discharge during sediment flushing and its environmental assessment, sediment flushing, wash load, suspended sediment concentration, side bank erosion; and study on flow regime changes in rivers.

17. **Professor Zuo Xue**: Professor at Department of Marine, Earth and Atmospheric Sciences North Carolina State University, USA.
    Ph.D., North Carolina State University, 2010
    M.S., First Institute of Oceanography, China, 2005
    B.E., Ocean University of China, 2002

Sediment Experts from Vietnam

18. **Dr. Dang Kieu Nhan**: Lecturer at Can Tho University, Vietnam and researcher at Irrigation and Water Management, Mekong Delta Development Research Institute.
19. **Professor Le Quang Tri**: Head of the Dragon, Can Tho University
20. **Associate Professor Nguyen Hieu Trung**: Dean of the College of Environmental and Natural Resources, Can Tho University
21. **Dr. Nguyen Van Lap**: Vietnam Academy of Science and Technology (VAST)
22. **Dr. Ta Thi Kim Oanh**: Vietnam Academy of Science and Technology (VAST)
23. **Dr. Van Pham Dang Tri** : Department of Environment and Natural Resources Management, College of Environment and Natural Resources, Can Tho University, Vietnam
24. **Dr. Hoang Van Huan**: Director of Institute for Coastal and Offshore Engineering (ICOE)
25. **Dr. Nguyen Van Trong**: Deputy Director, Research Institute for Aquaculture No.2
26. **Dr. Le Xuan Bao**: Deputy Director, Institute for Water and Environmental Research
27. **Dr. Le Song Giang**: Ho Chi Minh University of Technology
28. **Dr. Le Xuan Thuyen**: University of Science, Ho Chi Minh City, Vietnam

29. **Dr. Pham Van Song**: Department of Hydraulic Structure, Falculty of Hydraulic Engineering, Institute of Water and Environment Rerearch (IWER). Water Resources University (WRU)

30. **Mr**. **Nguyen Huy Phuong**: Vietnam National Mekong Committee

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Observers

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2) John Ward (CSIRO Ecosystem Sciences)
3) Bach Tan Sinh (NISTPASS)
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12) Martijn van de Groep (Water Netherlands)
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