The Mekong River is home to the largest inland fishery in the world, which is due in part to its exceptional sediment and nutrient loads. The number of dams in the basin is expected to increase from 16 in the year 2000 to between 77 and 136 by 2030. These dams retain and accumulate sediments and nutrients in their reservoirs; as such, planned dam development is expected to result in a 60 to 96% reduction in sediment flow to downstream Mekong waters. This loss of sediments and nutrients will have a serious negative impact on aquatic habitats and coastal zone ecology, as well as on water productivity, fish production, and ultimately on food security. In this first compilation of research on dam development, sediment, and fish in the tropics, we review the connections between sediment reduction, environmental changes, fish biology, and fishery production, with a focus on Mekong floodplains and the South China Sea.

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CGIAR RESEARCH PROGRAM ON Water, Land and Ecosystems

Greater MEKONG

WorldFish

FISH, SEDIMENT AND DAMS IN THE MEKONG

Eric BARAN, Eric GUERIN and Joshua NASIELSKI

How hydropower development affects water productivity and food supply

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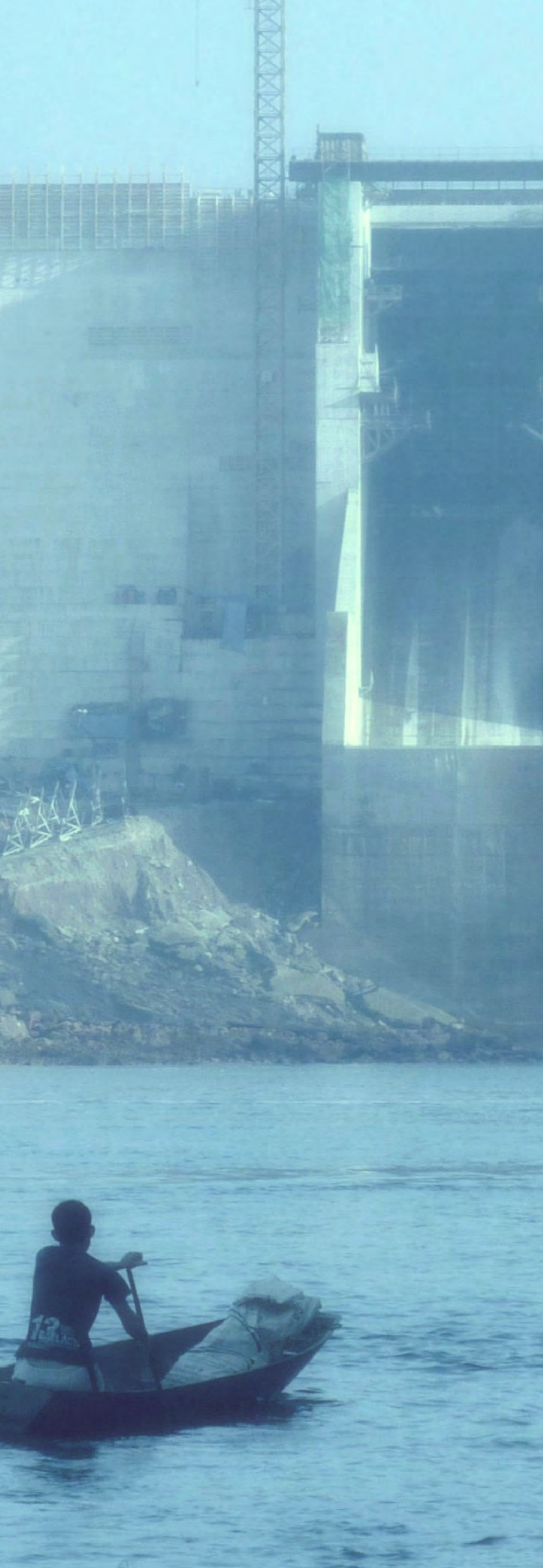

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FISH, SEDIMENT AND DAMS IN THE MEKONG

Eric BARAN, Eric GUERIN and Joshua NASIELSKI

The CGIAR Research Program on Water, Land and Ecosystems in the Greater Mekong (WLE Greater Mekong) is a research-for-development initiative that seeks to improve the governance and management of water resources in the Irrawaddy, Mekong, Red and Salween river basins. It aims to do this by generating and sharing the knowledge and practices needed to balance the costs and benefits of water, food, energy and the environment for sustainable growth through a wide range of partnerships. It is part of WLE global, which is led by the International Water Management Institute (IWMI), a member of the CGIAR Consortium, and is supported by CGIAR, a global research partnership for a food secure future.

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PREFACE

Sediments are crucial for the lives of riverine species, and in particular fish, playing a role in respiration, nutrition, reproduction and migration, as well as shaping habitats. Dams built on rivers create an obstacle to the flow of sediments and result in sediment deposition in dam reservoirs, and as a consequence, influence the volume, density and composition of sediments in rivers, as well as impact river ecology and fish production.

This publication represents the state of knowledge regarding the relationship between fish and sediment in tropical river systems, with a particular emphasis on the Mekong River Basin. Such research is of particular importance in the Mekong, a river basin where 2.1 million tonnes of fish are harvested each year from the river and contribute to the food security of several million people, and where on-going hydropower development plans will increase the number of dams from 16 in 2000, to between 77 and 88 by 2030.

This book is based on a series of research reports produced by WorldFish for the USAID funded project, “A climate resilient Mekong: Maintaining the flows that nourish life”, led by the Natural Heritage Institute. Our aim is to make the information contained in those reports available to a wider audience, and so inform research into sediments in the Mekong River.

With many dams being planned along the Mekong’s course, it is essential that governments in particular are made aware of the consequences such constructions could have for the fish and subsequently the people, markets and economies that depend on them.

There is every reason to hope that, with the right precautions in place, countries located along the Mekong’s course will be able to benefit from the building of these hydropower dams – in the form of more stable power supply, and without dramatic or unforeseen impacts on local food resources.

In this regard, this book will be a welcome contribution to the work required to create a more coordinated approach to the sustainable use of Mekong resources.

Program Director
CGIAR Research Program on Water, Land and Ecosystems

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EXECUTIVE SUMMARY

Context

The Mekong River is exceptional, by global standards, for its concentration of sediments, its biodiversity and its fisheries. It features 781 fish species, including 165 migratory species; more than 2.1 million tonnes of fish are harvested each year, which represents about 18% of the world's freshwater fish yield and makes it the largest inland fishery in the world. This is reflected in a record consumption of freshwater fish. As a consequence, the Mekong's fish resources are essential for food security in the basin.

The Mekong River is richer in sediment than the largest river in the world: the Amazon River. The river carries around 160 million tonnes of sediment per year (range: 140-180 Mt/yr); these sediments serve as a major carrier and storage agent for nutrients such as phosphorus, nitrogen and potassium.

The exceptional biological productivity of the Mekong floodplains is explained by a combination of flood pulse, high proportion of primary production (69%) entering the food web, and the high concentration of sediment and nutrients in water. The 67-145 million tonnes of sediment reaching the South China Sea each year also contribute to the biological productivity of the coastal zone.

The Mekong region is characterized by rapid hydropower development, with at least 77 projects expected by 2030, compared to 16 which were operating in 2000, and plans for up to 136 projects. All of these dams constitute obstacles to the free flow of water, and their reservoirs will retain and accumulate sediments and nutrients. Even though an abundant literature exists on eutrophication (excess of nutrients due to human pollution), very few studies worldwide have addressed the consequences of oligotrophication (sediment and nutrient rarefaction).

According to at least five independent studies, dam development is expected to result in a 60 to 96% reduction in sediment load in downstream Mekong waters. Following dam construction and climate change, models predict for Mekong floodplains a 53-59% reduction in sediment deposition, a 47-84% reduction in nutrient inputs and a 30-38% reduction in average net primary production. By 2030, Mekong dams are also expected to reduce by at least 50% the arrival of sediments and nutrients to the coastal zone.

Yet studies remain constrained by a large uncertainty about the comprehensiveness and quality of Mekong sediment data, in a context of large intra-and inter-annual variability.

Sediments and fish bio-ecology

In addition to their role in water productivity, sediments also play an important environmental role in fish bioecology, influencing fish's respiration, nutrition, reproduction and migrations.

For multiple reasons sediment rarefaction by dams simultaneously promotes and reduces oxygen production by aquatic plants, and it is not clear to what extent the outcome influences fish respiration.

The overall negative impact of sediment rarefaction on fish nutrition and growth is clear, but detailed processes are complex and sometimes in opposition. Permanently reduced sediment loads modify food webs and result in a change in fish communities and dominant species. However, there is not enough information in the Mekong to qualify the connection between sediment reduction and the nutrition or growth of local fish species.

The relationship between sediment and fish reproduction is also well established: a reduced sediment load impacts the reproductive success of species which lay their eggs on riverbeds and of species which spawn in the water column (egg buoyancy and survival issue). Freshwater fish at younger life stages are more vulnerable to and more severely impacted by sediment variations than adults. We detail the relationship between reproduction and sediments for 17 Mekong fish species.

Changes in turbidity or water color are a migration trigger for at least nine of the Mekong's migratory species. Given the amounts of nutrients sequestered in fish themselves, large-scale fish migrations between downstream floodplains and more oligotrophic upstream tributaries also influence nutrient distribution in the Mekong Basin. These migratory fishes represent at least 37% of the total fish biomass harvested, i.e. about 800,000 tonnes per year.

Sediment loads play a major role in determining the geomorphology of riverbanks and riverbeds. Sand in particular contributes to the creation of specific habitats for fish. Turbidity also influences the distribution and abundance of fish in the main habitats of tropical rivers. A modification of Mekong sediment concentrations may affect deep-pools, a critical habitat for many fish species, especially during the dry season. We detail known interactions between sediments and fish ecology for 21 Mekong species.

Sediments and fish production

Three main fish production zones can be distinguished in the Mekong: the near-shore zone, the downstream zone of the Lower Mekong Basin from the sea to Khone Falls and the upstream zone from Khone Falls to Tibet. From a fish generation perspective, the Srepok, Sesan, Sekong and Mun/Chi sub¬basins, the Lao tributaries and the Upper Mekong section are the most significant components of the Mekong system. From a fisheries perspective, the most consequential dams are the Lower Sesan 2 Dam on tributaries and the Stung Treng and Sambor Dams on the mainstream.

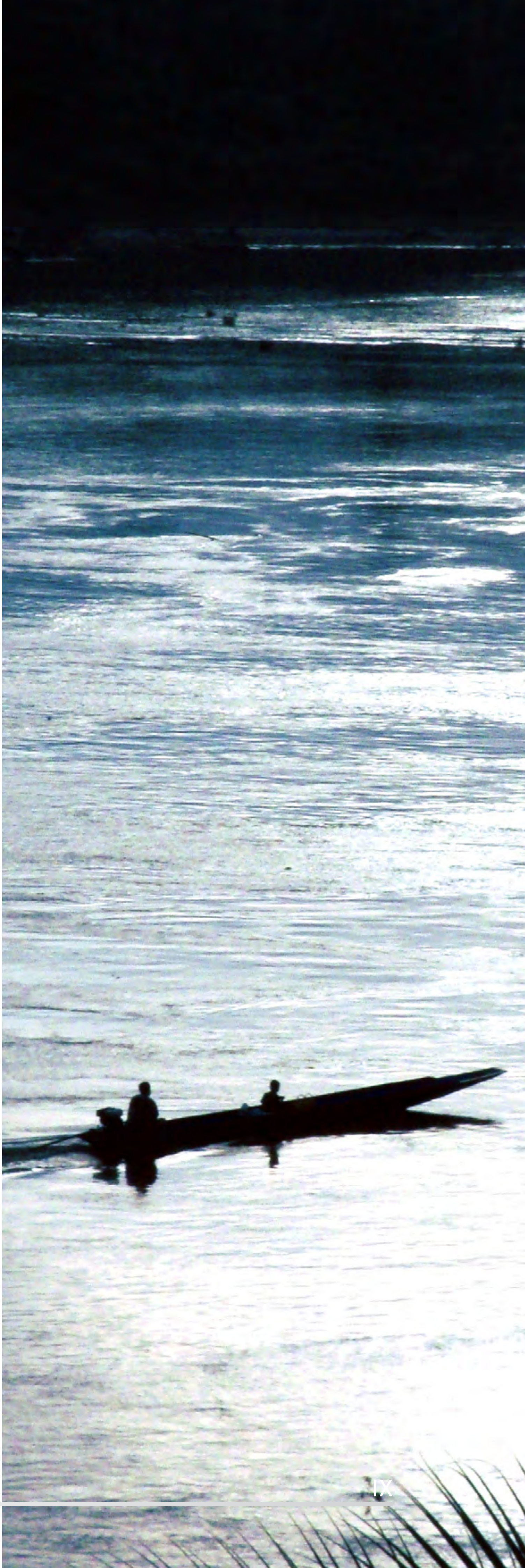
The high productivity of Mekong fisheries is largely linked to the presence and dynamics of sediments and nutrients. Thus, the Tonle Sap Lake and its floodplains retain 61 to 69% of the sediments they receive. The "*Dai*" (bagnet) fishery in the Tonle Sap River illustrates the correlation between fish catches and sediment inflows. According to a study, an 80% reduction in Mekong sediment input would result in a 36% decline of the total fish biomass in the Tonle Sap. However, the Tonle Sap's fisheries depend on a complex combination of multiple inter-related variables (as detailed in the BayFish model) and sediment cannot be considered in isolation. In all zones, an assessment of the fishing effort would be required in order to relate fish stocks to fish catches before the latter can be related to fish production drivers, including sediments.

Under natural conditions, the coastal zone receives 67-145 million tonnes of Mekong sediments each year, and the role of nutrients in sustaining both primary production and fish production in the coastal zone is well established. Thus, the Mekong sediment plume influences the productivity of coastal fisheries in twelve coastal provinces of Vietnam and Cambodia, from Binh Thuan to Sihanoukville. These provinces produce at least 0.5–0.7 million tonnes of fish per year.

However, the response of coastal ecosystems to river nutrient rarefaction is complex; it depends in particular on modified flow patterns, on local hydrodynamics, on the role of coastal systems (e.g. mangrove) and on urban and agricultural effluents. Furthermore, the study of the correlation between coastal fish catches and sediment outflows is hampered by fisheries data and fishing intensity issues. For these reasons, the amplitude of the change is currently not predictable.

Conclusions

Overall, fish production in the Mekong is a multi-factor phenomenon and is not related to sediments alone. In the coastal zone, fish stocks depend mainly on sediment loads, flood pulse and water quality. In the downstream part of the Mekong, they depend on sediment loads, flood pulse, migrations and water quality. In the upstream part of the Mekong, fish stocks depend mainly on sediments and migrations. Overall, dams are likely to impact fish resources in a number of ways that will not be related to sediments only, and dams themselves are just one among several human activities that have an impact on fish resources.



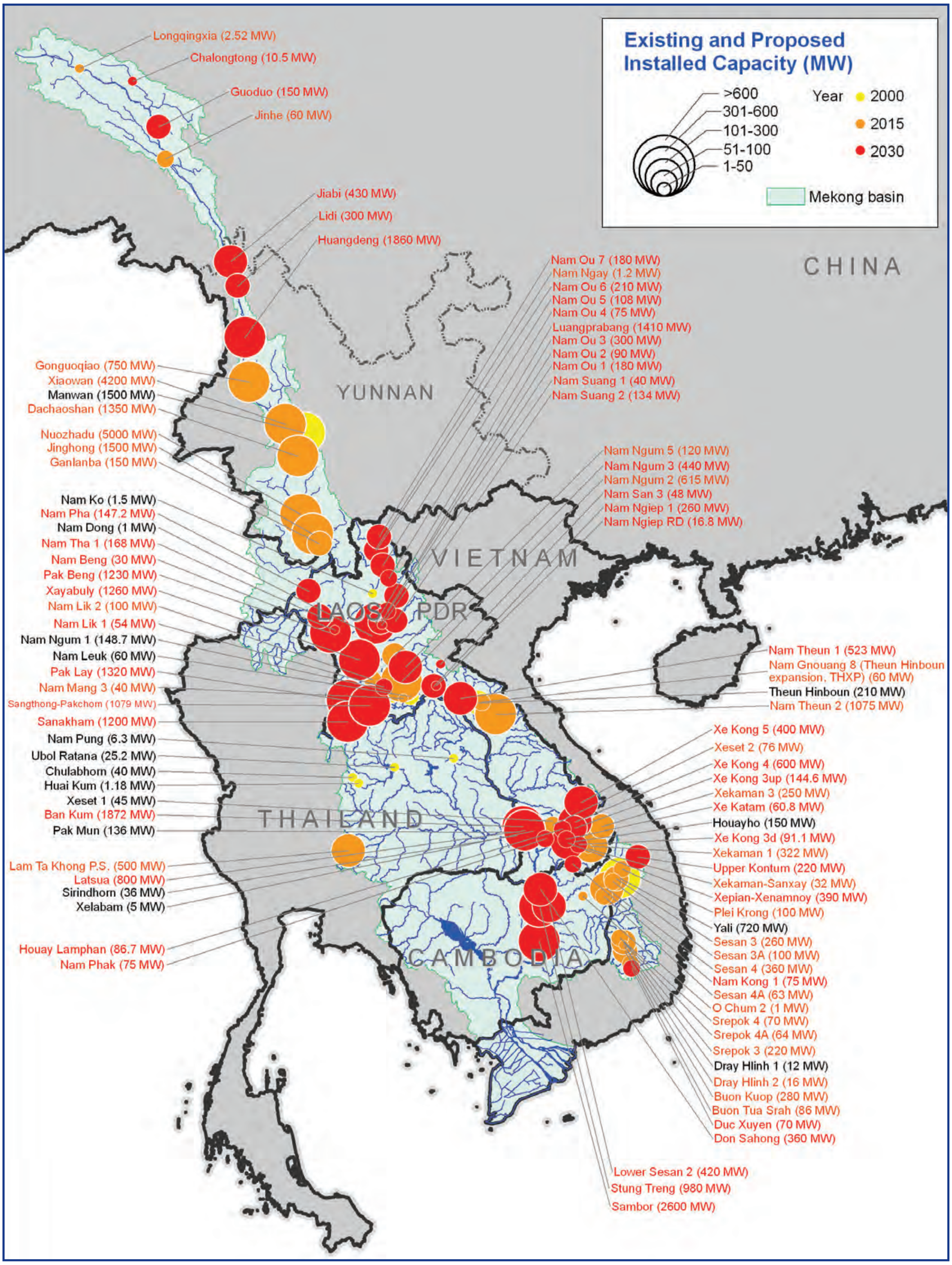


Figure 1: Dams expected to operate in the Mekong Basin by 2030

1

INTRODUCTION

The Mekong River is exceptional for its fish production, sediment load and hydropower development. The suspended solids load of the Mekong River is one of the largest in the world (Carling 2009), and about 50% of this sediment load originates from the Himalayas. It is also the third richest river in the world in terms of fish biodiversity. The Mekong is also formidably productive and generates about 18% of the world's freshwater fish yield; its fish resources are essential to food security in the basin (Baran 2010; Dugan *et al.* 2010). However, the region is also experiencing rapid development, with plans in place for the construction of 77 hydropower projects in the basin by 2030 (possibly up to 136 if all projects are realized, according to the MRC list of existing, likely and potential projects). This will have a very substantial impact on the river's sediment load, due to sediment trapping by dams. Figure 1 gives a visual representation of the dams proposed to be built up to 2030.

Sediments are an essential component of rivers and of their biological functioning, for in addition to their influence on river geomorphology (maintenance of river forms and habitats such as pools and sandbars), sediments include nutrients, detritus and organic debris of various sizes, all of which interact with the river's different life forms, including fish (USEPA 2003). The interaction between sediments and aquatic organisms, whether directly, or indirectly through the impacts of sediments on physical habitats, unquestionably influences the biodiversity and productivity of a river.

The Mekong's average sediment load is estimated at about 160 million tonnes per year. About half of that sediment load originates from the Upper Mekong in China, and the other half from the Lower Mekong Basin (see details in section 2.4). This load displays a wide range of intra-annual as well as inter-annual variability.

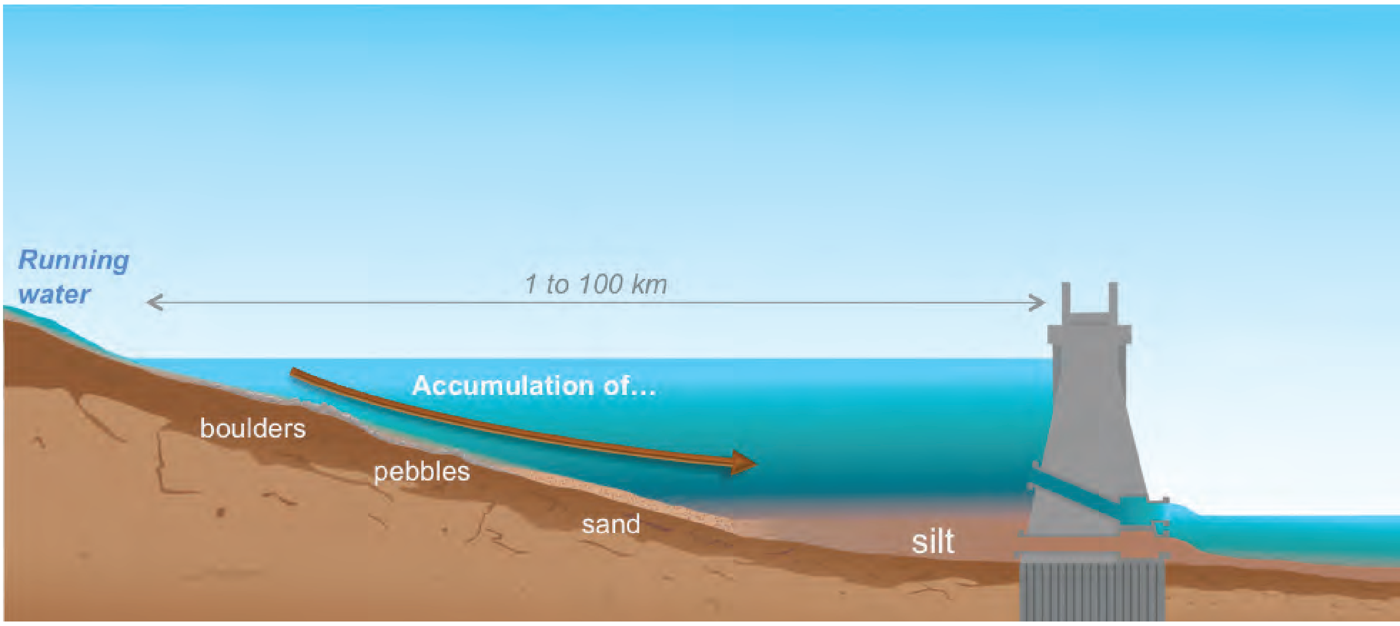


Figure 2: Accumulation of sediment behind dams

The sheer number of hydropower projects being built or considered in the Mekong Basin will result in a 60 to 96% reduction in sediment loads in downstream waters. Hydropower schemes extract energy from rivers (both electricity and river energy are expressed in the same unit i.e. Watts); following hydropower extraction, less energy is available in rivers for sediment transport processes, and solid particles begin to deposit, modifying the river's geomorphology. When river water enters a dam's reservoir, it also decreases in velocity, which results in a proportion of the transported sediment being deposited there, as shown in Figure 2 (Palmieri *et al.* 2003, Lu and Siew 2005, Ketelsen *et al.* 2013). In the Mekong, several authors have combined, in different models, hydrology, sediment inputs from sub-basins, and retention by dam reservoirs depending on their characteristics (136 dams at most, based on MRC list of existing, likely or hypothetical projects); their conclusions are detailed below:

- according to Kummu *et al.* (2010), the existing and planned sub-basin reservoirs have the potential to trap 95 to 100 million tonnes (Mt) of sediment each year, which represents around 70% of the total basin sediment flux;
- in the Upper Mekong, Liu *et al.* (2013) reviewed a series of early studies (in particular Lu and Siew 2006, Walling 2008, Walling 2009, Wang *et al.* 2009) in which sediment reduction is discussed. They show that three periods can be distinguished: stability (up to 1984), increasing sediment loads due to soil erosion following deforestation (1985–1992) and reduced sediments loads (after 1993) following dam development and improved soil conservation measures. Liu *et al.* predict a 17-38% reduction of the sediment load in the South China Sea in the future.
- sediment load at the mouth of the Mekong will be reduced by 75% if all the planned dams are built, according to the review of the Strategic Environmental Assessment of the impact of Mekong's mainstream dams (ICEM 2010);
- Thorne *et al.* (2011) conclude that the percentage of *sediment* trapped would reach 60-80%, 65-85% or 75-100% depending on the scenario, and the proportion of *nutrients* trapped would be 25-50%, 25-60% or 30-65% in the same conditions. In their "Definite future" (2015) scenario, they also predict a 50-60% reduction of sediment load compared to the 2000 baseline;

- the latter prediction is confirmed by Kondolf *et al.* (2014), who state that under a ‘‘definite future’’ scenario of 38 dams built or under construction, the cumulative sediment reduction to the Delta already reaches 51%.
- the two modeling results above can be related to Koehnken’s study, which analysed sediment monitoring data in the Lower Mekong Basin between 2009 and 2013 and suggests that the river is currently transporting only 72.5 Mt/yr on average, instead of the original 160 Mt/yr, i.e. a 55% loss in its sediment load already (Koehnken 2014 cited in Wild and Loucks 2015);
- in the 3S region alone (Sesan, Srepok and Sekong watersheds), Wild and Loucks find that 50-80% (depending on the assumptions made) of the sediment load may be trapped in reservoirs (Wild and Loucks 2014 a, b);
- according to Kondolf and his colleagues, under full build-out of all planned dams, cumulative sediment trapping will reach 96%, leaving only 4% of the pre-dam sediment load to reach the Delta (Kondolf *et al.* 2014, Rubin *et al.* 2015);
- finally, Nguyen *et al.* (2015) find that under their “median changes” scenario, sediment load to the South China Sea would be reduced by half, and that maximum changes in all drivers would result in a 95% reduction of the sediment reaching the sea by 2050-2060.

These results are in line with the conclusions of a major review by Vörösmarty *et al.* (2003), who found that at the global level more than 50% of basin-scale sediment flux in regulated basins is trapped in artificial impoundments. The same review also identifies eleven large river basins worldwide with sediment trapping higher than 70%, and seven in which observed sediment retention is superior to 90% (among them are the Nile, the Rio Grande, the Colorado and the Ebro Rivers). As for model accuracy in predicting sediment retention, there is an average difference of only 6% between modeled and observed results among 17 rivers detailed by Vörösmarty and his colleagues.

The consequences of reduced sediment loads are poorly studied. An abundant literature covers the effects on fish of increased sediment and nutrient concentrations caused by reservoir sediment flushing or organic pollution; however, very few studies detail the consequences of reduced sediment loads or reduced nutrient levels on fish communities and production. This is illustrated by classes of water quality used at the Mekong River Commission (MRC 2007); in these classes, good quality is defined as a maximum acceptable level of nitrogen or phosphorus – a classification which does not consider poor water quality resulting from nutrient rarefaction. This focus on excess might be explained by visibility and timing issues: while flushing operations are spectacular and their impact immediately measurable, the effects of reduced sediment loads on ecosystems involve long-term processes such as modifications to river morphology and changes in fish communities which may take decades to materialize. The consequences of such changes may also be buffered and so hidden for a period of time by a river's natural resilience and coping capacity – with for instance nutrients released by the floodplain and sediments released through erosion of riverbanks or riverbeds in order to overcome lower upstream inputs.

Sediments adsorb and facilitate the transportation of nutrients. Sediments in rivers are found in two main forms (suspended and bedded sediments) and they consist of a variety of particle sizes (roughly categorized as gravel, sand, clay and silt). One property of sediments is that they adsorb and, thus, facilitate the transportation of nutrients (in particular phosphorus and nitrogen) and organic particles. As the level of dissolved nutrients in water is generally low, the main nutrient load is associated with sediments. The dominant sediment categories in the Lower Mekong Basin are fine sands, silts and clays; the proportion of organic particles represents 2 to 8% of the total sediment load, which is considered high by global standards.

Sediments influence fish's respiration, nutrition, reproduction and migration. Sediments and their associated nutrient loads influence fish's biological functions, particularly their respiration (by influencing the amount of dissolved oxygen in the water), nutrition (by reducing photosynthesis and altering predator-prey relationships), reproduction (through the spawning grounds chosen by different species) and migration patterns (by acting as a trigger for migration movements). They also have an influence on habitats (changes in sediment loads may change habitat profiles), helping to explain the overall productivity of tropical river ecosystems (including floodplains, estuaries and coastal areas).

The process of nutrient rarefaction, though poorly studied, is likely to change food web structures and lead to a decrease in fishery resources. Oligotrophication is related to phosphorus or nitrogen deficiency, but the nitrogen/phosphorus ratio also has to be considered. Ongoing hydrodynamic and physical modeling will help clarify the retention rates of dams and the fate of sediments therein, but establishing a link between the presence of sediments and nutrients, and the role of nutrients that are independent of sediments, remains to be addressed.

Following this introduction, **Chapter 2** – "Core notions" introduces the concept of sediments in rivers, describing in detail the different types of sediments found, their properties and the relationship between sediment particle sizes and river flows. This chapter also gives an overview of the types of sediments to be found along different stretches of the Mekong River, the amounts of material carried by flows, the geographical and temporal variability of the load, the role of sandy sediments, and the knowledge gaps that remain.

Chapter 3 – "Sediments and fish bio-ecology", outlines the exceptional features of the Mekong River in terms of fish biodiversity, productivity, fish migration patterns and fisheries. This chapter reviews knowledge about the role of sediments vis-à-vis fish's respiration, nutrition, reproduction, and migration, and proposes three ecological zones of relevance for the study of the impact of sediment rarefaction on fish in the Mekong. Our literature review focussed on the Mekong River integrates lessons from other tropical rivers in South America, Asia, Africa, and Australia, but does not extend to temperate rivers and species such as salmonids in North America or Europe.

Chapter 4 – "Sediments and fish production", describes the influence of sediments on floodplain fish production, with a particular focus on the Tonle Sap's productivity and fishery yield. The role of sediments, nutrients and oligotrophication on coastal fish resources and fisheries is also detailed, drawing whenever possible information from literature on similar coastal systems in the rest of the tropical realm.

Chapter 5 – "Sediments, fish production and the way forward" concludes by highlighting knowledge gaps about the relationship between sediments and fish production. It then reviews the most influential of the Mekong's sub-basins and dams, before identifying those factors and drivers most critical to fish production in the river and its tributaries. The chapter concludes by proposing a comprehensive framework to be used to further assess the impact of sediment retention caused by dams on fish stocks and fish production levels in the Mekong and the nearshore coastal zone, one that takes into account all the elements considered in this book.

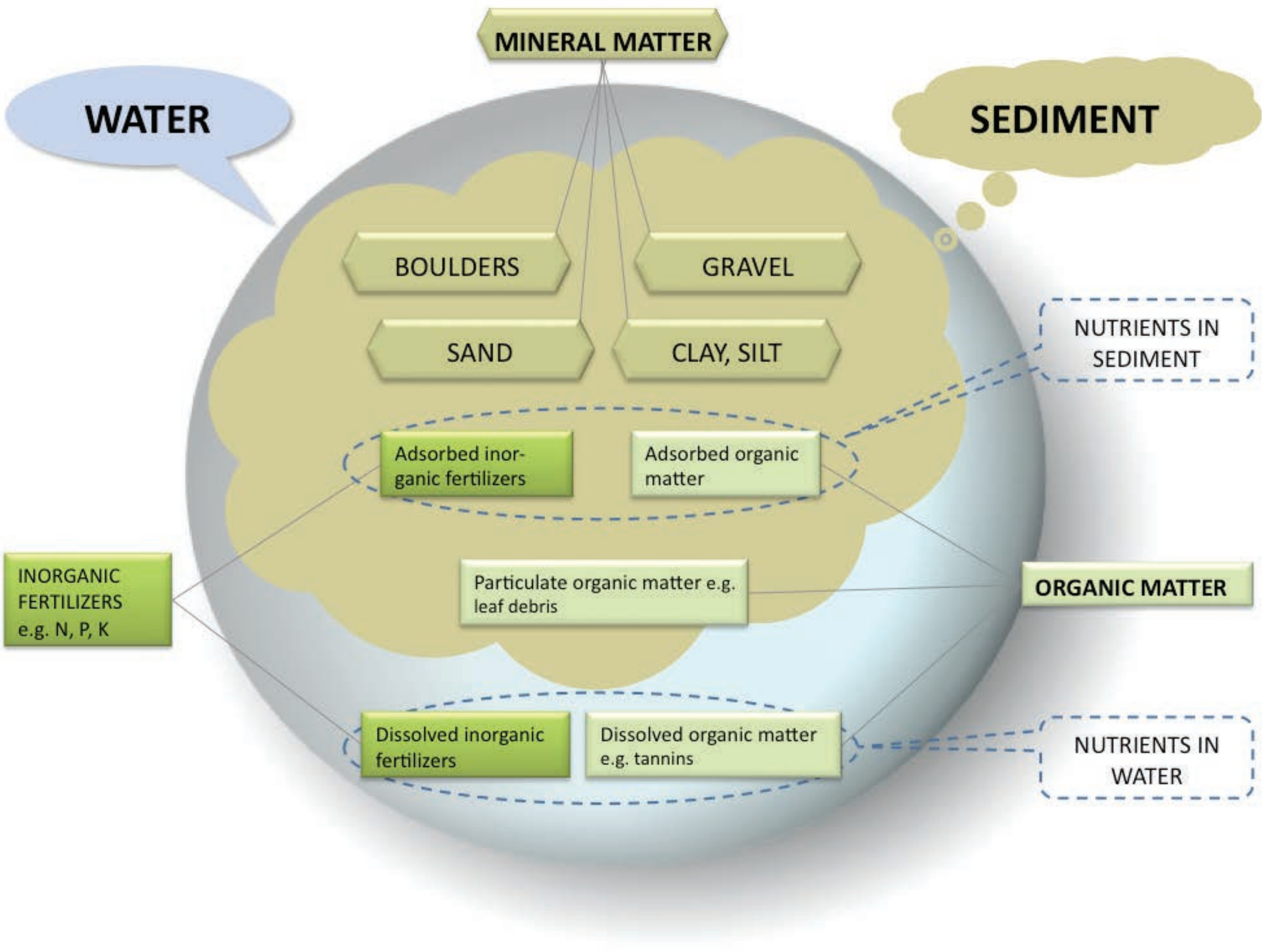


Figure 3: Main components of river sediment

2

SEDIMENTS: CORE NOTIONS

Sediments in rivers are found in two main forms: suspended and bedded. This distinction is based on their size, nature and mode of transportation through the water. *Suspended sediments* are made of "*particulate organic and inorganic matter that suspend in or are carried by the water*", while *bedded sediments* or *bedload* "*accumulate in a loose, unconsolidated form on the bottom of natural water bodies*" (USEPA 2003)[1]. Thus, coarse material, gravel and pebbles are transported by the bedload at the bottom of the riverbed, while fine materials, sand and silt, are transported in suspension (Fruchart 2009).

A major property of sediments is their ability to adsorb and transport small organic or inorganic compounds (i.e. compounds that stick to the sediment particles). This means that sediments are actually a combination of mineral, inorganic and organic compounds, all of which have different properties. It also means that sediments largely facilitate the transportation of organic or inorganic matter in the hydro-system. The key components of sediments are summarized in Figure 3.

[1] Castro and Reckendorf (1995) detail further the components of the bedload: "*Framework bedload refers to the larger particles that are moved only during large flow events. They create the structure of the bed. The matrix bedload refers to that part of the bed material that is small enough to be frequently entrained by low to moderate flows, but is large enough to settle out of the water column at lower velocities. This also includes sediment deposited by intragravel flows. This would incorporate the sand and silt sized material. The matrix bedload is often referred to as 'sediment' by fisheries biologists and is the size class that is of most interest and concern in fisheries studies.*"

2.1 Sediment particle size

A standard classification of mineral sediments based on particle size is detailed in Table 1.
Figure 4, as developed by Welcomme (1985), shows the relationship between the flow speed and the size of sediment particles moved by a river.

Table 1: Conventional grain size ranges for different sediment types. Source: Ketelsen and Ward 2010

Grain size	Name
> 256 mm	boulder
64-256 mm	cobble
32-64 mm	very coarse gravel
16-32 mm	coarse gravel
8-16 mm	medium gravel
4-8 mm	fine gravel
2-4 mm	very fine gravel
1-2 mm	very coarse sand
0.5-1 mm	coarse sand
0.25-0.5 mm	medium sand
125-250 µm	fine sand
62.5-125 µm	very fine sand
3.9-62.5 µm	silt
1-3.9 µm	clay
<1 µm	colloid

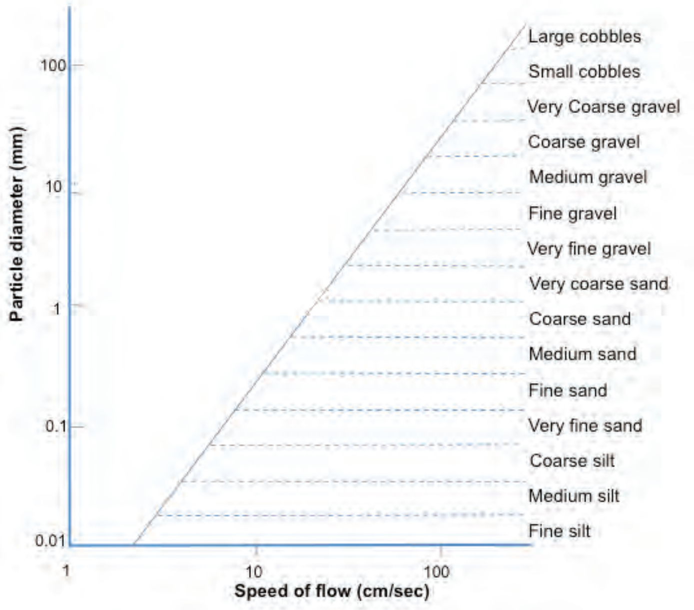


Figure 4: Relationship between flow speed and size of particles moved. Source: Welcomme 1985

A simplified sediment classification in relation to fish ecology. For the purpose of this book, we will use a simplified classification, reducing it to four categories, those significant in the case of fish bioecology (Rowe *et al.* 2003):

- *Coarse sediment* – defined as gravel and cobble, i.e. particles larger than 9.5 mm. Being the main component of the riverbed, these sediments affect the morphology of the river;
- *Medium sediment* – small gravel and sands between 0.85 mm and 9.5 mm;
- *Fine sediment* – consisting of fine sand particles between 0.85 mm and 0.063 mm, which can be either bedded or suspended, depending on a river's velocity. Medium and fine sediments shape fish habitats or spawning sites, and constitute the main biotope of several macro-invertebrate species that fish feed upon;
- *Silt and clay* – i.e. mud particles smaller than 0.063 mm which are suspended in the flowing water (thus leading to its turbidity), or are deposited on mudbeds.

The distribution of sediments along the Mekong River is illustrated in Figure 5.

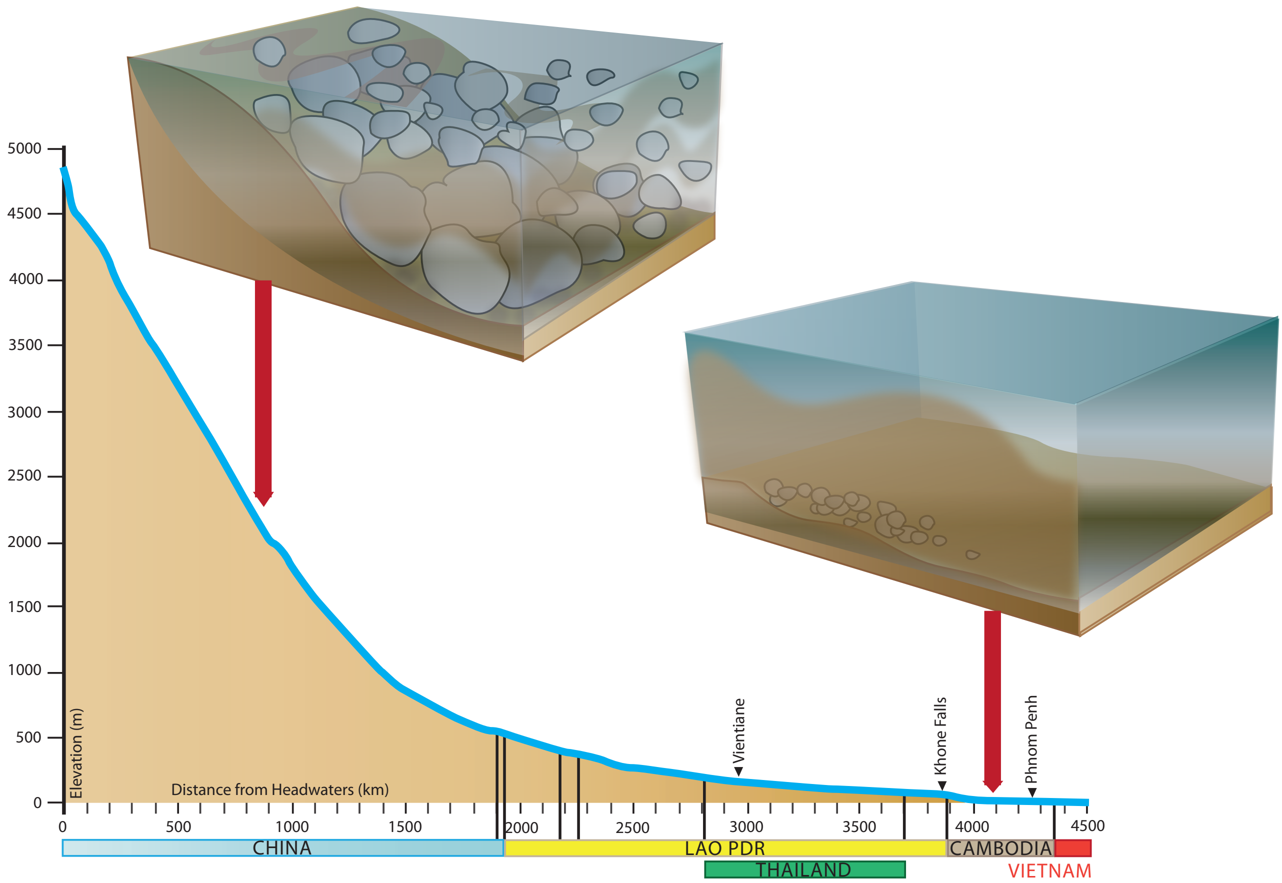


Figure 5: Nature of Mekong sediments - depending on their location, the gradient, and the water velocity

2.2 Sediments and organic matter

Two to eleven percent of Mekong sediment loads is comprised of organic elements of great importance for the biological productivity of the river. This organic component is made up of i) dissolved organic matter (e.g. degraded proteins from vegetal or animal origin, plus tannins), and ii) particulate organic material transported from the watershed slopes and subject to biological degradation and size reduction (Welcomme 1985). Dissolved Organic Matter (DOM) is part of the water flow, but is not sediment, whereas Particular Organic Matter (POM) is a part of the sediment load of rivers. Importantly, a proportion of this organic matter is adsorbed onto sediment particles, which facilitates the transport of such matter but also influences its chemical dynamics. This adsorbed organic matter may be stored within deposited sediments, or may be re-incorporated into the flow through erosion (Welcomme 1985). According to Pantulu (1986), this organic content ranges from 6 to 8% of the total Mekong sediment. More recently, Ellis *et al.* (2012) showed that the concentration of fine particular organic carbon ranges from 0.5 to 6.3 mg/l depending on the hydrological season (highest values during in the flood) and that the proportion of organic carbon in fine suspended sediment varies between 1.5 and 10.7% (lowest values during the flood). In all cases, these values are seen as large by global standards, with organic matter contributing significantly to the considerable productivity of the river. The transportation and fate of organic matter in streams depends to a certain extent on dams, but also on the characteristics of the catchment and on groundwater inputs, and is complicated by microbial degradation (Wilson and Xenopoulos 2009, Williams *et al.* 2010, Kunz *et al.* 2011, Nadon *et al.* 2015).

2.3 Sediments and inorganic matter

River sediments serve as a major carrier and storage agent for inorganic nutrients such as phosphorus, nitrogen or potassium, as well as for pesticides and metals (Yang 2003, Yi *et al.* 2008). As unpolluted water usually contains low concentrations of dissolved nutrients, a river's main nutrient load actually consists of nutrients associated with – or adsorbed onto – sediments. Thus, measurements in North America and Europe have shown that about 90% of the total phosphorus flux in rivers is associated with suspended sediment (Ongley 1996). The pattern seems to be similar in the Mekong (Meynell 2010).

The most important sediments for the transportation of nutrients are the very small size sediments such as clay and colloids. Those smaller than 63 µm (such as silt and clay) are chemically more active – in particular for phosphorus transportation, a nutrient highly attracted to ionic exchange sites that are associated with clay particles and with the coating found on small particles (Ongley 1996). In South America, rivers with high sediment loads and high levels of alkalinity have higher concentrations of nitrogen and phosphorus, and thus, are more productive than rivers with clear water (Forsberg *et al*. 1988). Suspended inorganic material from the mainstream channel is seen by some as more important to productivity than dissolved and particulate organic material (Vannote *et al.* 1980, Junk 1999).

In the Mekong, the nutrients associated with sediments are largely responsible for the fertility of the floodplains and the delta. In particular, several authors have shown that the high productivity of the Mekong floodplains is based on the nutrient loading associated with the sediments arriving from upstream areas, and that phosphorus is often the limiting nutrient. See sections 4.2.1 and 4.3.4 for more details.

2.4 Sediment loads in the Mekong: amount, nature and variability

A lot of uncertainty surrounds the Mekong's sediment data. A review of sediment-related information and data in the Mekong (Ketelsen and Ward 2010) has led to the conclusion that "*considerable skepticism surrounds Mekong sediment data, which has been collected with inconsistent methods, measuring different parameters and has often yielded widely divergent estimates*."

It is commonly agreed that the total annual sediment discharge of the Mekong amounts to about 160 million tonnes per year (range: 140 - 180 Mt/yr), which is high in comparison with other major rivers around the world (Milliman and Meade 1983, Meade 1996, Wolanski and Nguyen 2005, Sarkkula *et al*. 2010, Ketelsen and Ward 2010). Actually Nguyen *et al.* (2015) specify that estimates of the mean annual suspended sediment load at Kratie (Cambodia) vary from 50 to 160 million tonnes but 160 Mt is the figure most commonly found in the literature, and refers to the pre-2000 period. Thus, the Mekong's total load is less than that of the Ganges or Yangtze Rivers, about the same as the Mississippi's, and 12% larger than that of the Amazon (Carling 2009, Sarkkula *et al.* 2010)[2]. Under natural conditions, 50 to 65% of the sediment load originates from the Upper Mekong in China (review by Nguyen *et al.* 2015), and the rest comes from the Lower Mekong Basin (Wild and Loucks 2013, 2015; Wild *et al.* 2016). More specifically, the 3S catchments contribute between 5 and 15% of the total sediment load of the Mekong (i.e. 10 to 30% of the sediment production of

[2] These figures are somewhat disputed, since Welcomme (1985) indicates that 190 and 406 million tonnes of suspended load are carried by the Mekong and Amazon respectively, whereas the the Yangtze, Brahmaputra and Ganges carry 560, 812 and 1625 million tonnes respectively. The Yangtze, Brahmaputra and Amazon are not part of Carling's comparison.

the Lower Mekong Basin; Wild *et al.* 2016), and the remaining tributaries on the Lower Mekong Basin provide approximately 30% (Ketelsen and Ward 2010, Kondolf *et al.* 2013).

The dominant sediment categories in the Lower Mekong Basin are fine sands, silts and clays (Irvine *et al.* 2007, Carling 2009, Sarkkula *et al.* 2009 and 2010). A sediment distribution curve cited in Ketelsen and Ward (2010, Figure 6) shows that in Pakse, 99% of the sediment has a grain size smaller than fine gravel (>4.75 mm) and that 41% is finer than coarse sand (>0.45 mm). Yet, Bravard and Goichot (2012a) reckon that the amount of sand and coarse material, in particular in the bedload, has been much underestimated so far and deserves re-examination. According to Gupta and Liew (2007), most of the sediment in the Mekong upstream of Cambodia appears to be stored inside the channel, either on the bed or against the banks. In the Tonle Sap River, silts and clays are the dominant grain size (Sarkkula *et al.* 2010). The latter authors conclude that clay and cohesive sediments seem to remain in suspension until the Mekong enters the Cambodian floodplains and the Mekong Delta.

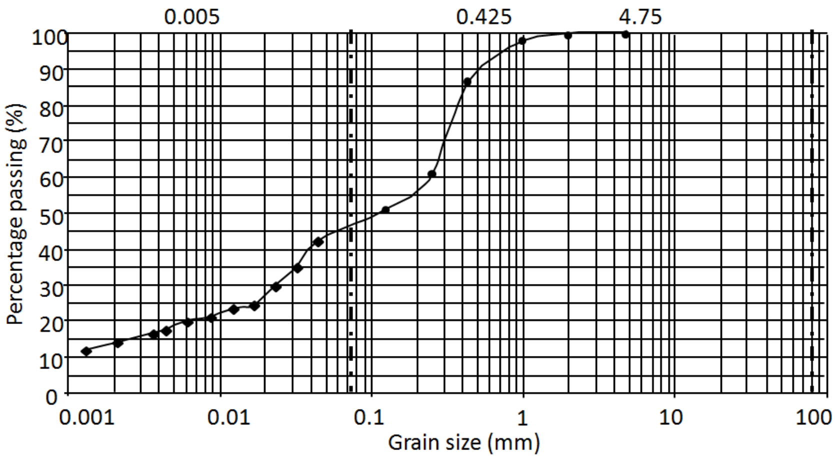


Figure 6: Sample grain size distribution curve in Pakse (cited in Ketelsen and Ward 2010)

Sand is an important component of the Mekong's habitats and ecology. Whether it is limited or more abundant than believed, sand is an important component of the Mekong's ecology. Sand and sandy islands are a typical feature of the wetland zone between Pakse and Kratie (zone nº 4

Figure 7: In some sections of the Mekong, sand is an important to major constituent of the riverbed (here in Vientiane).

according to MRC BDP 2, including the Siphandone wetlands) and are essential habitats for much of the Mekong's biodiversity, as detailed in Baird (2001), Bezuijen *et al.* (2008), Allen *et al.* (2008) and Meynell (2010). Sand transportation and dynamics (re-suspension, the movement of sand bars or in-channel consolidation) are directly dependent upon hydrodynamic conditions (Sarkkula *et al.* 2010), which implies that changes in these conditions may have a disproportionately large impact on sandy habitats in the Mekong. More generally, coarse materials are very important for the stability of the riverbed, as they constitute a carpet protecting the river bottom from incision by water-driven erosion (Figure 7). Unfortunately, coarse materials settle completely when entering dam reservoirs and cannot be flushed downstream (Fruchart 2009). Several authors note that sand, although heavily affected by dams, is not part of any current analyses (Kummu and Varis 2007, Ketelsen and Ward 2010, Bravard and Goichot 2012a).

The Mekong's sediment load is characterized by large intra- and inter-annual variability (Walling 2009, Ketelsen and Ward 2010 and Figure 8). On a seasonal level, the water is heavily charged with silt during the rising floods, deposits its suspended sediments over the floodplains during the flooding season and then becomes clear during the dry season (Welcomme 1985). From an inter-annual perspective, the Lower Mekong Basin tributaries contribute a greater proportion of the annual load during wet years, while in dry years the amount of input from China is higher than normal (Ketelsen and Ward 2010).

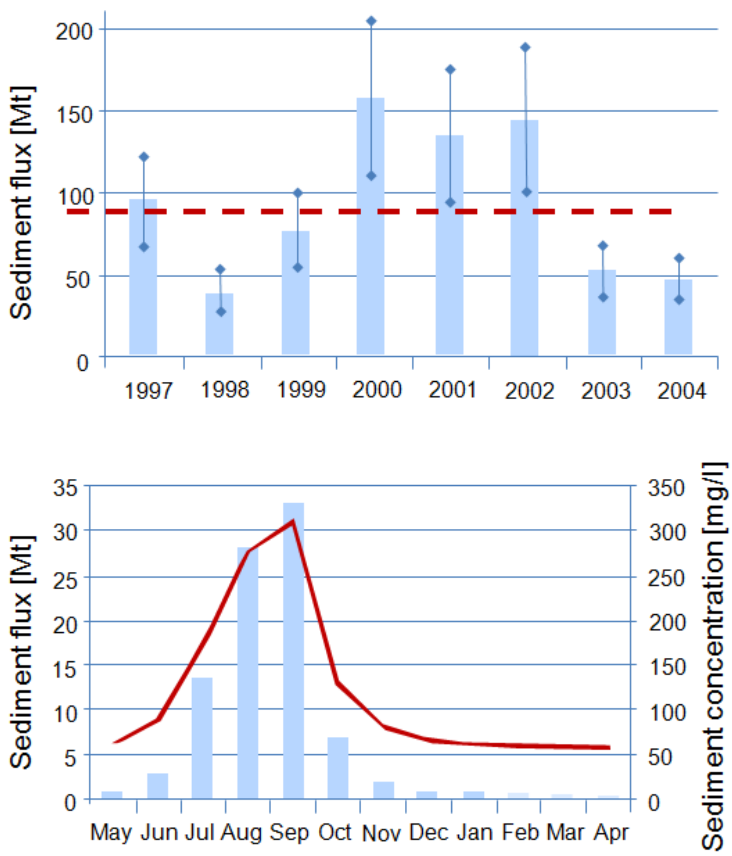


Figure 8: Average sediment load at Kratie (Cambodia): annual average (1997–2004 period, top histogram) and monthly average (load and concentration, bottom histogram). Source: Kummu et al. *2008a*

The Mekong's sediment load is also characterized by strong geographical variability – the total suspended load increasing farther downstream. Thus, the annual total suspended load has been estimated to be 67, 109 and 132 million tonnes per year at Chiang Saen, Vientiane and Khone Falls respectively (Carling 2009). Overall, the Cambodian floodplains and Mekong Delta receive 95% of the total suspended sediment flux from upstream (Kummu and Varis 2007), and 80% of the suspended sediments that enter Tonle Sap Lake are deposited on its floodplain (Lamberts 2006), which makes these intensive fishing grounds heavily dependent on the flow conditions of the Upper Mekong (Baran *et al.* 2007a).

2.5 Conclusion

We have looked at the core notions related to sediments, the key properties of the latter – including their different forms and sizes, and their relations with organic and inorganic materials, as well as where they are found within the river system and their varying loads. The next chapter will introduce the Mekong River system itself in more detail, including the bio-ecology of its fish species, its major ecological zones and how sediments impact Mekong fish in terms of their respiration, nutrition, reproduction, migration and habitats.

3

SEDIMENTS AND FISH BIO-ECOLOGY

3.1 Mekong fish ecology

The exceptional features of the Mekong's fish resources have been detailed in several publications (e.g. Lagler 1976; Pantulu 1986; Van Zalinge *et al.* 2003; Baran *et al.* 2007b, 2013; Hortle 2009; Baran 2010) and we will briefly review them here before focusing on the features of sediments in relation to fish.

The Mekong Basin, the Tonle Sap Lake and the 3S system are places of exceptional fish biodiversity by global standards. With 781 species, the Mekong is the world's third richest river after the Amazon and the Congo Rivers (2014 figure based on *www.fishbase.org*). An analysis of species and endangered species among 302 countries or territories worldwide shows that Lao PDR, Thailand and Vietnam are among the top 5% in terms of the number of freshwater fish species and threatened fish species present. The Mekong mainstream is characterized by a gradient of increasing species richness as it flows from the headwaters down to the sea, with just 24 species in Tibet, but 484 species by the time the river reaches its delta. With 296 species, the Tonle Sap Lake has the highest fish biodiversity of any lake in the world after the East African Great Lakes. The 3S system (Sekong, Sesan and Srepok Rivers) is home to 42% of total Mekong fish biodiversity (i.e. 329 fish species out of 781), though the surface area of that system represents only 10% of the Mekong's watershed area; the 3S system is also home to 17 endemic species found nowhere else in the world.

The Mekong produces about 18% of the world's freshwater fish yield; the fish catch, estimated to be between 755,000 and 2.6 million tonnes (the most reliable assessment being 2.1 million tonnes per annum out of 11.6 million tonnes globally), comprises about 18% of the global freshwater fish catch (ranging from 7 to 22%), making the Mekong the largest inland fishery in the world.

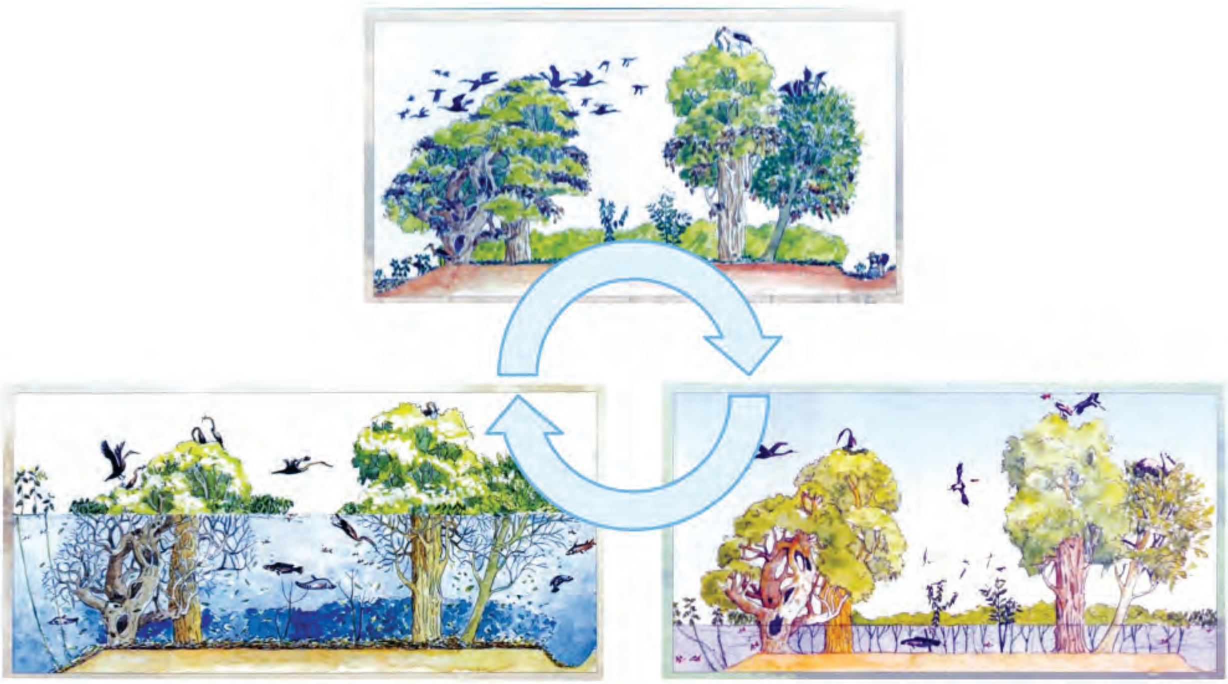


Figure 9: Flood pulse in Tonle Sap Lake. Source: poster from Osmose NGO, Cambodia. Illustrator: Poy Chhunly

As a result, the Mekong's fish resources are essential for food security in the basin, with Cambodia, Lao PDR, Thailand and Vietnam being the top four countries in the world in terms of their freshwater fish consumption, which ranges between 24.5 and 34.5 kg/person/year, while fish contribute 81% and 48% towards protein intake in Cambodia and Lao PDR respectively. Estimates of the economic value of the Mekong fish catch range between USD 2.2 and USD 3.9 billion per year.

The Lower Mekong Basin experiences a strong annual flood pulse that boosts its productivity. Each year a surge of water flows during the wet season from the swollen Mekong River into downstream floodplains (increasing the volume of water contained within Tonle Sap Lake ten-fold), and then drains back into the riverbed during the dry season (Figure 9). The flood pulse is one of the main factors explaining the very high productivity of tropical rivers, in Southeast Asia but also in South America and Africa.

Fish migrations are an essential feature of the Mekong Basin's ecological regime. Of the 781 Mekong fish species known, 165 are migratory (Baran 2006); these species represent more than 37% of the total yield, that is, more than 780,000 tonnes per year. At the end of the dry season, more than 100 migratory species (Ziv *et al.* 2012) migrate up the Khone Falls towards the Mekong's tributaries where a majority of them lay their eggs in riverine environments characterized by clear water and the associated seasonal flora and benthofauna (Figure 10).

Thus, the larger tributaries in Lao PDR, Thailand and Cambodia are, for many migratory species, breeding or feeding areas, as well as migration corridors (Figure 11). More than 40% of the adult or mature fish harvested in the floodplains of the Lower Mekong Basin actually originate from upstream tributaries, in particular those in Lao PDR and in the 3S area.

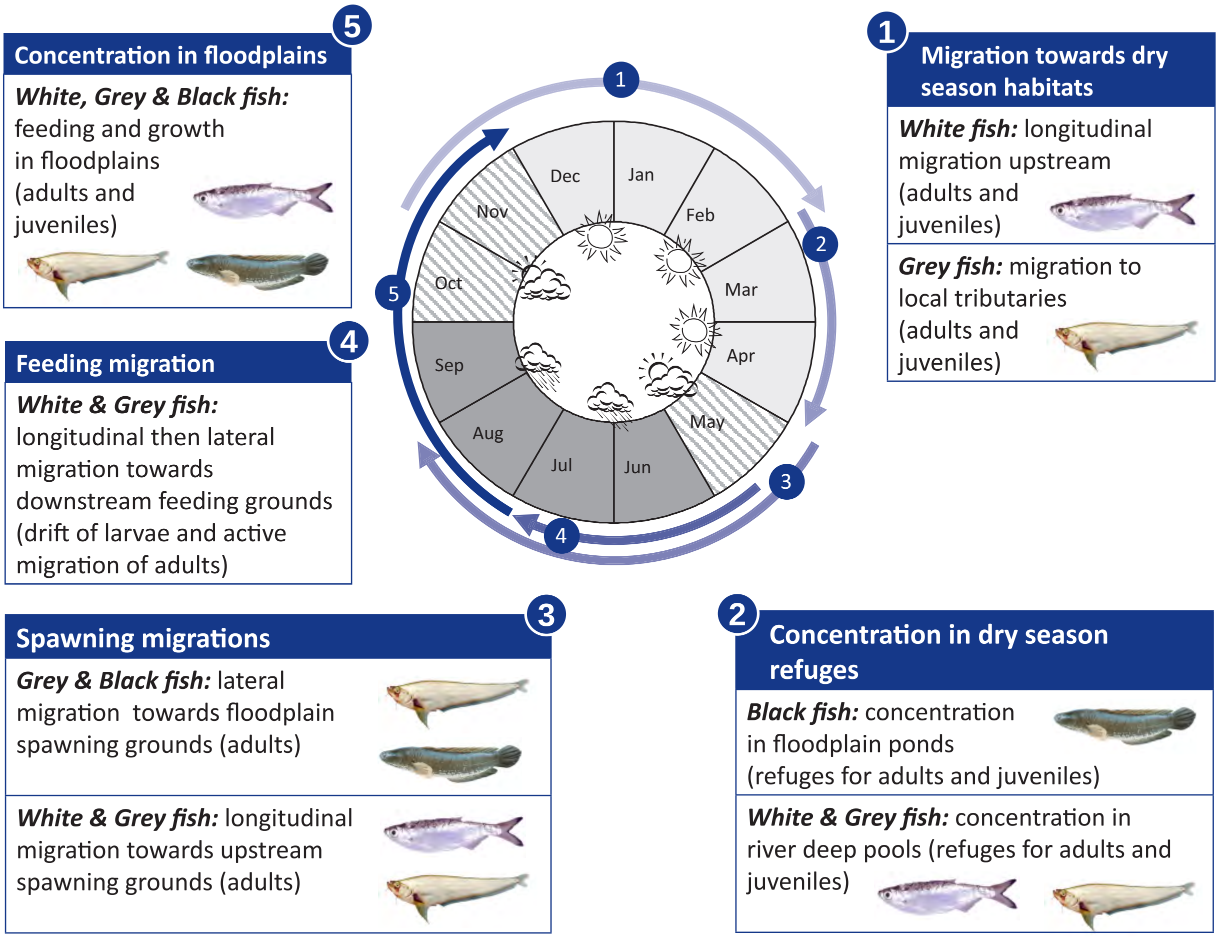


Figure 10: Fish migration patterns in the Mekong. "Black fish" is an ecological group of usually dark floodplain residents. "White fish" is a group of long distance migrants, whose dominant color is silver. "Grey fish" is an intermediate group of short distance migrants; their body color varies. Source: adapted from Baran and Un (2012)

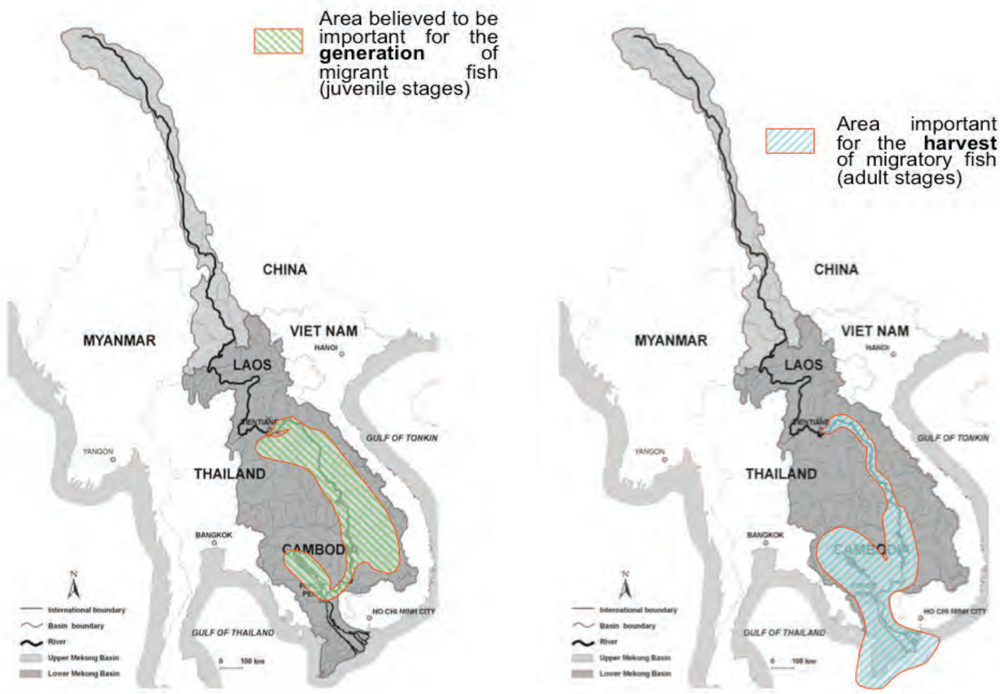


Figure 11: Generation vs. harvesting areas for migratory fish. The left map reflects dominant hypotheses about the functioning of the system but is not backed by numerical data, and the limits of hatched areas, although based on those of major watersheds, are arbitrary. Source: Baran 2010

The exceptional abundance of the Mekong's fish resources can be explained by the combination of high levels of fish biodiversity, high productivity linked to high sediment load and flooding, and a high exploitation rate, as illustrated in Figure 12.

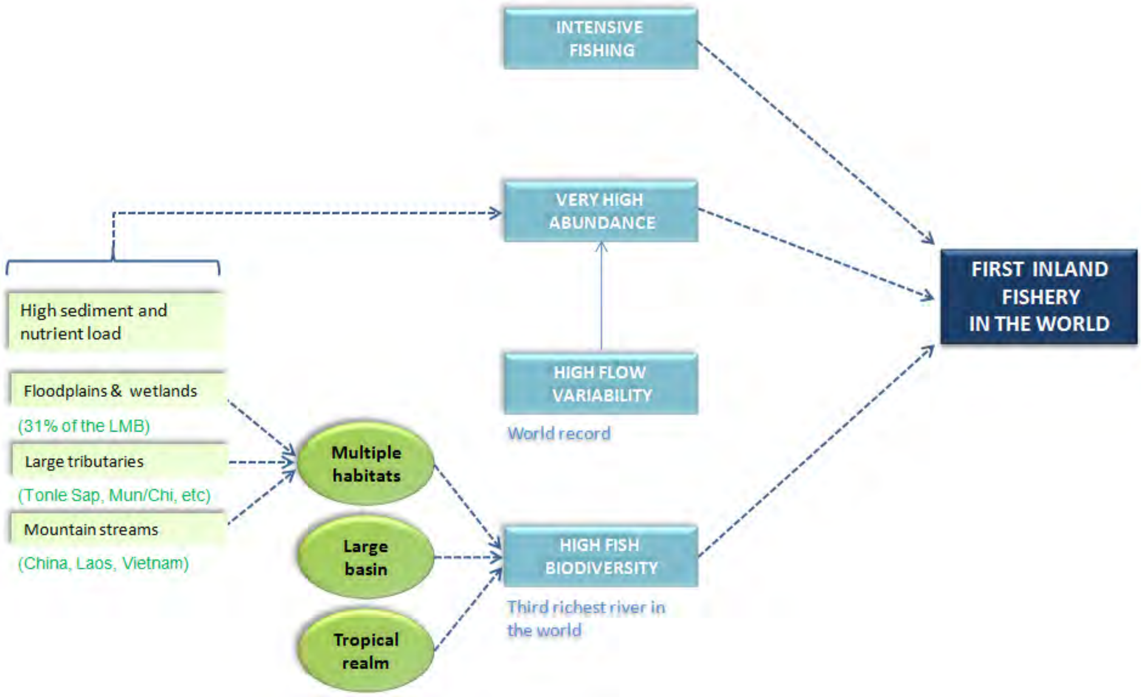


Figure 12: Factors explaining the size and importance of Mekong fisheries.
Source: adapted from Baran and Un (2012)

3.2 Sediments and fish biology

Sediments play an important environmental role in fish bio-ecology. Fish species inhabiting a river body are either adapted to specific sediment characteristics, which are not constant (e.g. seasonal and inter-annual variations), or tend to leave an area subject to excessive sediment load, before returning after the event (flash or seasonal flooding). Thus, from a fish ecology viewpoint, the presence of sediments is normal; it is any variation outside of the normal range that is detrimental to species, and this "normal" range varies with each species (Sanderson 2009).

In all of the world's rivers, there is a relationship between energy availability and sediment availability (Welcomme *et al.* 1989, Figure 13), and in the Mekong, the hydropower potential is estimated to be 53,000 MW (ICEM 2010), with 30,000 MW in the Lower Mekong Basin alone (MRC 2001). If power extraction is to take place to its fullest extent along the course of the river, the impact this is likely to have on nutrient availability deserves to be studied in more detail.

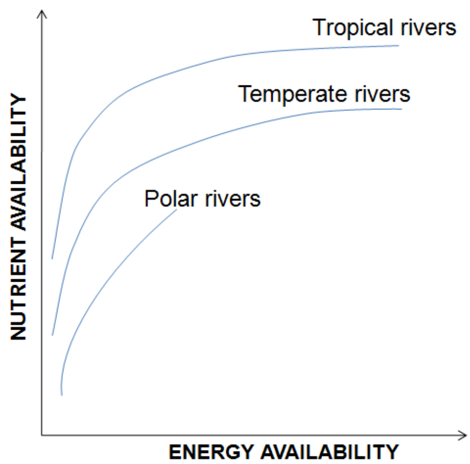


Figure 13: Relationship between energy availability and sediment availability. Source: Welcomme 1989. A higher altitudinal gradient corresponding to energy availability in rivers (i.e. a potential for hydropower production) is correlated with a higher concentration of sediments and nutrients in these rivers, in particular in tropical rivers.

3.2.1 Sediments and fish respiration

There are two main sources of oxygen in the aquatic environment: the atmosphere and photosynthesis by plants. Oxygen from the atmosphere is diffused in the water through the air/water interface, and this process is accelerated by wind and wave action. However, photosynthesis by aquatic plants, algae and phytoplankton is the most important source of dissolved oxygen in the aquatic environment (Francis-Floyd 2011).

The organic component of sediments has a direct and negative impact on dissolved oxygen, through its oxygen demand. These organic compounds consume oxygen for oxidation processes, which reduces the amount of dissolved oxygen available in the water column (Welcomme 2001). WUP-FIN studies mention this phenomenon in the case of the Tonle Sap floodplain; sediment carried by the wet season freshwater pulse can dramatically reduce dissolved oxygen levels, sometimes down to anoxia (Sarkkula and Koponen 2003, Koponen *et al.* 2005), and subsequently impact on fish presence.

Dams simultaneously promote and reduce oxygen production by aquatic plants, and two different pathways can be noted here (UTAH State Water Plan 2010, Holtgrieve *et al.* 2013). First, turbidity reduces the amount of sunlight reaching the aquatic vegetation and; thereby, reduces its oxygen production (a negative effect), and second, nutrients associated with suspended sediments favor plant growth and so increase their oxygen production levels (a positive effect). As a result, dam developments, while reducing sediment concentrations, simultaneously promote and reduce plant-driven oxygen production (Figure 14; the release of hypoxic or anoxic reservoir water is ignored here). The combination of these different forces, therefore, makes it difficult to predict the overall impact of sediment load reduction caused by dams on oxygen concentrations in water.

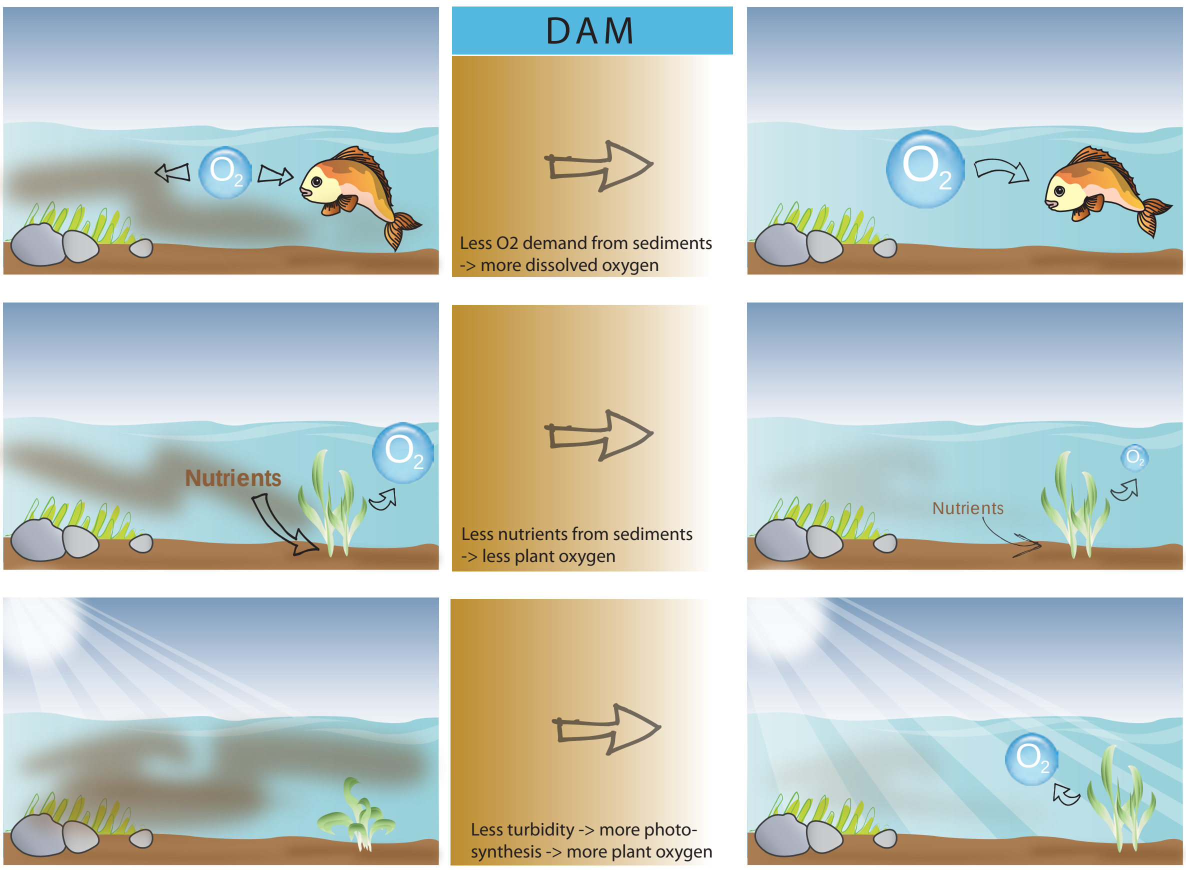


Figure 14: Influence of suspended sediments on the oxygen content of water

In the Mekong mainstream, the average dissolved oxygen concentration in the running waters ranges between 5.5 and 8.5 $mg.l^{-1}$ (1985-2005 data; IKMP 2009). Dissolved oxygen concentrations below 5 $mg.l^{-1}$ may be harmful to fish, and fish piping (gulping air at the surface) has been observed when dissolved oxygen levels fall below 2 $mg.l^{-1}$ (Francis-Floyd 2011).

3.2.2 Sediments and fish nutrition

In the Mekong, there is not enough information to establish a detailed connection between sediment classes and the feeding of fish species. For this book we reviewed (Figure 15) the feeding habits of fish species in relation to sediments, as compiled in a literature review of 296 Tonle Sap species (period covered: 1938-2003; Baran *et al.* 2007c) and originating from FishBase (*www.fishbase.org*) and the Mekong Fish Database (MFD 2003). The information on diet contained in these two databases refers to the following food items and all their combinations: detritus, algae, plants, plankton, zooplankton, zoobenthos, nekton, animals and insects. Although some of these categories (e.g. detritus and zoobenthos) reflect to some extent a sediment-related feeding mode, the databases are not explicit about the type of sediment involved. Alternatively, Valbo-Jørgensen *et al.* (2009) reviewed, from unspecified data, the food items of Mekong fish species, and found that mud-feeders constitute 1% of the Mekong fish species and that 69 species are detritivores.

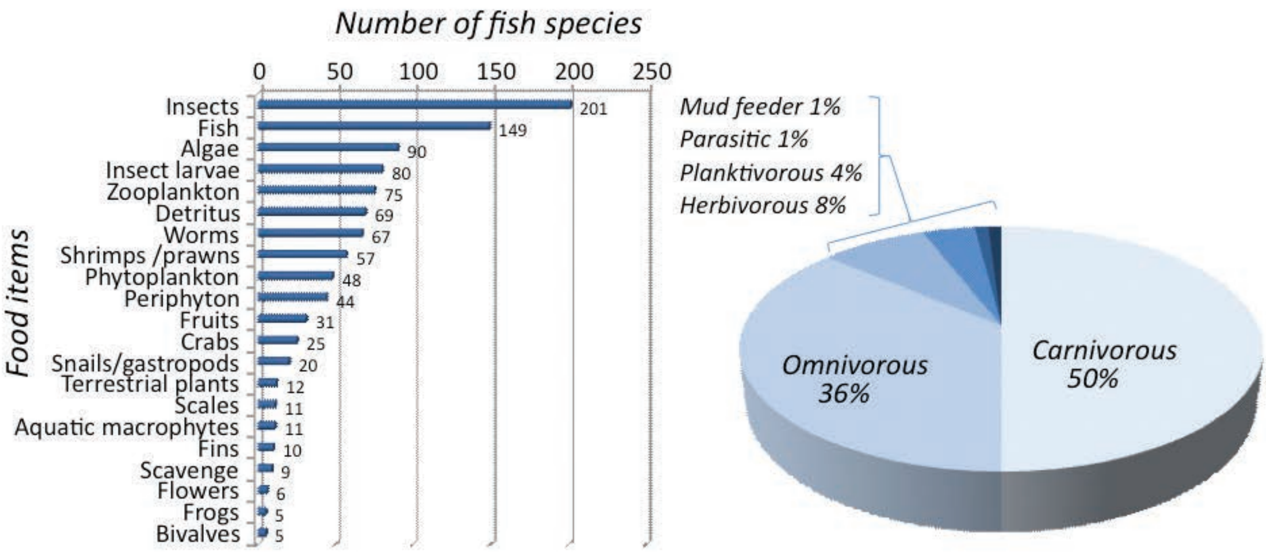


Figure 15: Number and percentage of Mekong fish species feeding on various food sources.
Source: Valbo-Jørgensen et al. *2009.*

Evidence from other tropical rivers shows that sediment concentrations influence the trophic food webs that fish are part of or depend on, predator-prey relationships and also the dominance of given species in fish assemblages. We detail these aspects in the following paragraphs.

Fish nutrition and growth depend on the concentration and composition of sediments in the river. Fish sometimes feed directly on sediment (e.g. mullets), but more importantly sediments condition the presence and abundance of fish prey. Nutrients dissolved or adsorbed onto sediments (together with nutrients released from floodplain soils) are the main input for vegetation growth (i.e. phytoplankton, algae and macrophytes), while organic matter carried by the river (as well as originating from the flooded vegetation) feeds zooplankton and detritivores. Both constitute the base of a trophic pyramid topped by high value fish species and are thus essential to fish productivity. In the Paraná Basin in Brazil, Hoeinghaus *et al.* (2007) concluded that fishes below impoundments are more dependent on algal production than those above impoundments, and hypothesized that this is due to sediment trapping by dams increasing water transparency in tailwaters, resulting in greater light penetration and algae growth. In the 3S system (Sesan, Srepok and Sekong Rivers in Cambodia), Ou and Winemiller (in press) showed that fish biomass derives mostly from algae during the dry season and from macrophytes in the wet season, but both algae and macrophytes need nutrients from water. Although the details of these very complex food webs are not well known and debates remain about the dominant sources of carbon in rivers, there is ample evidence that fish nutrition and productivity ultimately depend on the concentration and composition of sediments (in particular nutrients and organic particles) available in a river (Gray and Ward 1982, Ward 1992, Power *et al.* 1996, USEPA 2003).

Although the overall positive impact of sediments on fish nutrition and growth is clear, detailed processes are complex and sometimes in opposition. A decrease in sediment loads – and the attached nutrients – might result in a reduction of primary production (UTAH State Water Plan 2010), but can also be favorable to primary production through increased irradiance (Lloyd 1987). The latter phenomenon has been observed in the Nile River, where there is a significant reduction in water turbidity (from 3,000 to 15-40 $mg.l^{-1}$) following sediment trapping by the Aswan Dam resulted in increased phytoplankton density (Dubowski 1997), and yet the Nile fishery gradually collapsed (Bebars *et al.* 1996). In coastal zones, maximal phytoplankton production is often found at some distance from the mouth of a river, in a zone of lower nutrient concentration, and this is related to increased light availability (Parsons *et al.* 1977, Randall and Day 1987). Yet in the Mekong, Wyatt and Baird (2007) note a paradoxical effect – sediment retention by the Yali Falls dam on the Sesan River resulted in increased sediment load and turbidity downstream due to increased riverbank erosion in the early years of the dam, and this phenomenon in turn *"reduced the light available for algal growth, or smothered bottom-growing algae, which are an important food source for some species"*.

Permanently reduced sediment loads also change fish community structures and the dominant species by altering fish predation patterns. Turbidity decreases underwater visibility, and it is now well established (review in Kerr 1995) that this in turn influences the predation efficiency of visually oriented fish species. Unlike species located at the bottom of the trophic pyramid, which usually filter water (planktivores) or forage at random (detritivores, bottom feeders), piscivorous predators mostly depend on their vision to catch prey. Turbidity therefore influences the predator-prey relationship and ultimately the progressive dominance of specific predators and prey. Thus, de Melo *et al.* (2009) show that in the Bananal floodplain (Mato Grosso in Brazil), changes in water transparency have influenced the composition of fish assemblages and also the dominant species to be found among Cynodontidae. Following the closure of the Tucurui Dam in Brazil and a subsequent downstream reduction in sediment load, the biomass of piscivorous fish increased, while that of planktivores diminished, and some species changed their diet (e.g. de Merona *et al.* 2001). In estuaries, Blaber *et al.* (1985) also report that predation, usually low due to high turbidity, can increase under clear and deep-water conditions. However, the relationship here is not clear; reduced turbidity following retention of sediments by dams might favor top-level predators, but prey might also be able to perceive them better.

Overall, permanently reduced sediment loads modify food webs and result in a change in fish communities and dominant species. Welcomme (2001), summarizing the impact of human interventions on fish, indicates that decreased suspended silt loads result in changes to fish communities, with in particular a reduction in the number of non-visual predators and carnivores occurring, and that a lack of sediment downstream of dams changes the nutrient cycle and causes a loss of illiophages (mud feeders).

3.2.3 Sediments and fish reproduction

The main relationship between fish reproduction and sediment occurs in relation to spawning grounds. The reproductive guilds[3] of fish formalized by Balon (1975, 1981), and encompassing all the 30,000 fish taxa, are based on three main criteria: forms and functions in early development stages, features of reproductive behavior and preferred spawning grounds. The latter makes extensive reference to the nature of the substratum where eggs are laid. Table 2 illustrates the importance of sediments to river fish reproduction activities, and the very specific role different sediment classes play in terms of fish spawning.

Table 2: Main fish guilds whose reproduction is related to sediments. Source: Balon 1981

<table>
<tr><th>Ethological Section</th><th>Ecological Group</th><th>Guild</th><th>Meaning</th><th>Notes</th></tr>
<tr><td rowspan="4">NON-GUARDERS</td><td rowspan="4">Open substratum spawners</td><td>Lithopelagophils</td><td>Rock and gravel spawners with pelagic larvae</td><td>Embryos pelagic by positive buoyancy or active movement</td></tr>
<tr><td>Lithophils</td><td>Rock and gravel spawners with benthic larvae</td><td>Early hatched embryos hide under stones</td></tr>
<tr><td>Phytolithophils</td><td>Non-obligatory plant spawners</td><td>Eggs adhere on to submerged items</td></tr>
<tr><td>Psammophils</td><td>Sand spawners</td><td>Eggs adhere to sand or roots over sand in running water</td></tr>
<tr><td rowspan="4">GUARDERS</td><td>Brood hiders</td><td>Lithophils</td><td>Rock and gravel spawners</td><td>Eggs buried in gravel depressions called redds or in rock interstices</td></tr>
<tr><td>Substrate choosers</td><td>Lithophils</td><td>Rock spawners</td><td>Strongly adhesive eggs; attached at one pole by fibers</td></tr>
<tr><td rowspan="2">Nest spawners</td><td>Lithophils</td><td>Rock and gravel nesters</td><td>Eggs always adhesive; free embryos</td></tr>
<tr><td>Psammophils</td><td>Sand nesters</td><td>Thick adhesive chorion with sand grains gradually washed off, or bouncing and buoyant eggs</td></tr>
</table>

For their reproduction some river fish species are dependent upon bedload, while others are dependent upon washload. A number of fish species, in particular those which inhabit upstream environments and floodplains, spawn on the riverbed and deposit their eggs in the empty spaces between gravel (e.g. croakers), or on fine sediment and vegetation debris (e.g. some snakeheads). These fish may use their fins to create a microenvironment within the riverbed (e.g. tilapias). Egg development requires a fine balance between discharge, velocity and bed material for spawning to be a success. In contrast to this strategy, other species release their eggs within the water column (e.g. freshwater clupeids), and in this case egg development requires a fine balance between egg buoyancy and water/sediment density.

[3] A guild is defined as "*a group of species that exploit the same class of environmental resources in a similar way*" (Root 1967).

There is little information in the literature about the relationship between tropical fish reproductive activities and the impact of a *reduced* sediment load; however, there is much about sediments and fish in temperate rivers (in particular about salmonids subject to sediment flushing), and also about the spawning behaviors and preferences of East African lake fish species (in particular tilapias). The relationship between fish and sediments in tropical rivers is not well covered, and reproduction as a physiological and behavioral process remains largely unstudied in environments that have a high number of fish species with a diversity of life strategies. Furthermore, a considerable body of information details the impact of an increased sediment load (mainly due to erosion following deforestation and mining activities) on spawning, spawning sites, egg development and overall reproduction success in clear temperate streams (Kerr 1995, Castro and Reckendorf 1995[4]), but very little information is available about the impact of a reduced sediment load on fish reproduction, which is the main focus of this book.

A reduced sediment load may impact the reproductive success of species which lay their eggs on riverbeds. In particular, when bedload transport is reduced, the riverbed's sediments are not replaced by upstream sediments, which results in "armoring" of the bed. The resulting rockiness is less suitable for fish species that require specific substrate compositions to be in place for reproduction purposes (Bizer 2000). Fish eggs directly exposed to water friction are also generally more vulnerable than eggs buried in the substrate (Newcombe 1994, Kerr 1995).

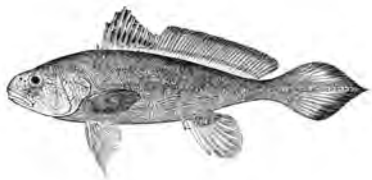
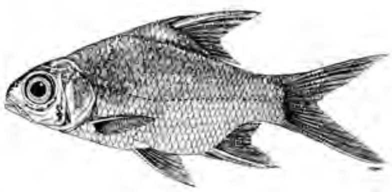
Reduced sediment loads may also impact the reproductive success of some species which spawn in the water column (*pelagophils*). The eggs of such species must stay near the oxygenated water surface, meaning their buoyancy has to match the water density in the river at the time of spawning, a factor driven by the water's silt content. When oocytes are released and fertilized, they get hydrated, which increases egg volume several times and reduces their specific weight, prompting flotation and drifting (Carolsfeld *et al.* 2003). However, in the case of reduced silt content, eggs lose their buoyancy, sink and die. This phenomenon, relatively undocumented for river fish, is now well known for marine fish (e.g. Griffin *et al.* 2009, Ospina-Álvarez *et al.* 2012) but was flagged by Baran *et al.* (2007d) as possibly having large-scale implications for Tonle Sap fish resources. This buoyancy issue may also be significant in the case of juvenile fish (Pavlov *et al.* 1995, 2008).

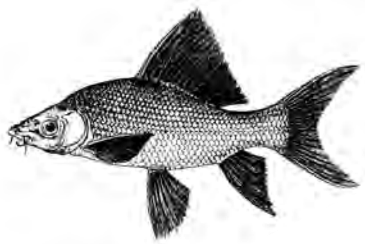
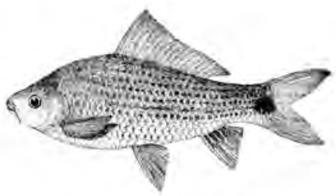
Freshwater fish at earlier life stages are more vulnerable to and more severely impacted by sediment variations than adults (Alexander and Hansen 1986, Appleby and Scarratt 1989, Newcombe 1994); however, the most sensitive stage is the larval stage – more sensitive than the egg or juvenile stages (Appleby and Scarratt 1989, Isono *et al.* 1998). In estuaries, high turbidity levels are favored by the larvae of many fish species which spawn in the coastal zone; the larvae then actively migrate towards river estuaries where the turbidity caused by a high concentration of suspended organic matter decreases predator efficiency and increases their survival rates (Blaber and Blaber 1980; Cyrus and Blaber 1987a, b; Baran 1995; Lévêque and Paugy 1999).

In the Mekong, the relationship between fish reproduction and sediment is known for 21 species only. Spawning ground requirements have not been described for the large majority of fish species (Chea *et al.* 2005); however, for this book we reviewed the reproduction activities of Mekong species in relation to sediments, based on a literature review of 296 Tonle Sap species (period covered: 1938-2003; Baran *et al.* 2007c), as detailed in FishBase (*www.fishbase.org*) and the Mekong Fish Database (MFD 2003). Our findings are detailed in Table 3.

[4] In their review, Castro and Reckendorf note that "*Researchers have consistently found that the introduction of excess matrix bedload can have disastrous results for the spawning habits of fish that require gravel substrate for spawning*".

Table 3: Tonle Sap species dependent on sediments for reproduction. Source: FishBase and MFD 2003

Fish species whose reproduction is dependent on sediment	
Species: *Probarbus jullieni* 	**Habitat/Reproduction:** Decreasing turbidity is one of the factors controlling the arrival time of Probarbus at its spawning grounds. River rapids are important habitats for the spawning of this species. Generally intolerant of habitat alterations, this fish has disappeared from areas affected by impoundments. **References:** Ukkatawewat 1979; Roberts 1992; Amatyakul *et al.* 1995; Rainboth 1996; Baird and Flaherty 2000
Species: *Pangasius macronema* 	**Habitat/Reproduction:** Spawns in rapids at the beginning of the wet season. **References**: Schouten *et al.* 2000
Species: *Boesemania microlepis* 	**Habitat/Reproduction:** The identified spawning areas for this fish are located at over 20 meters deep, with hard rock or pebbles, and a silt or sand substrate. These areas have slow to moderate counter-current eddies in the dry-season and steep, rocky sides which descend into pools. **References:** Baird *et al.* 2001
Species: *Probarbus labeamajor* 	**Habitat/Reproduction:** Large dams on the mainstream in Stung Treng and Kratie provinces will eliminate most of the rapids, important for the spawning of this fish species. **References:** Roberts 1992
Species: *Puntioplites proctozystron* 	**Habitat/Reproduction:** Spawning occurs in slow moving waters with a muddy bottom. The eggs are of the semi-buoyant type. **References:** Watanadiroku and Murada 1985; Duangsawasdi *et al.* 1988; Banyen 1988; Banyen *et al.* 1989a, 1989b
Species: *Channa gachua* 	**Habitat/Reproduction:** Spawns in shallow water with a silt or gravel substrate. **References:** Talwar and Jhingran 1992

Fish species whose dependence on sediments for reproduction is unclear	
Species: *Datnioides pulcher* 	**Habitat/Reproduction:** Spawns in March; the eggs are buoyant and approximately 0.8 mm in diameter. **References:** Rithcharung and Mahawong 1993
Species: *Labeo chrysophekadion* 	**Habitat/Reproduction:** It has been reported that this fish species spawns in swamps, flooded areas or just upstream from shallow sandbars that lie alongside river bends. The eggs are semi-buoyant. **References:** Smith 1945; Rainboth 1996; Baird and Phylavanh 1999; Poulsen and Valbo-Jørgensen 2000
Species: *Osteochilus melanopleurus* 	**Habitat/Reproduction:** A pelagic spawner, which produces semi-buoyant eggs. **References:** Watanadirokul *et al*. 1983; Warren 2000
Species: *Osteochilus hasseltii* 	**Habitat/Reproduction:** Spawning occurs on floodplains in areas covered with submerged vegetation that have a gravel bottom. The eggs are buoyant or semi-buoyant. **References:** Pholprasith and Janesirisak 1972; Pennapaporn *et al.* 1991; Warren 2000

Species whose reproduction is known not to be dependent on sediment:

Clupeichthys aesarnensis
Tenualosa thibaudeaui
Barbonymus altus
Cirrhinus molitorella
Labeo dyocheilus
Monopterus albus
Corica laciniata
Amblyrhynchichthys truncates
Cirrhinus microlepis
Cyprinus carpio
Puntioplites falcifer

3.2.4 Sediments and migration

Changes in turbidity or water color are a migration trigger for at least nine of the Mekong's migratory species. Eighty seven percent of the species whose migration status is known (i.e. 135 species) are migratory species characterized by longitudinal or lateral migrations. Of these, more than 100 species are long-distance migrants (Ziv *et al.* 2012). Changes in turbidity or water color at the beginning of the wet season are a migration trigger for at least nine of these species, which makes them potentially sensitive to changes in sediment concentration. These species are: *Pangasius polyuranodon, Pangasianodon gigas* and *Pangasius bocourti* (three catfish species, including a critically endangered one), *Cyclocheilichthys enoplos* and *Paralaubuca typus* (two cyprinids very prevalent in catches), *Bangana behri, Labeo chrysophekadion, Mekongina erythrospila* and *Tenualosa thibaudeaui* (Baran 2006).

Conversely, fish migrations can influence the nutrient distribution in a river basin. In South America, some "blackwater" hydro-systems are poor in nutrients (i.e. oligotrophic) with limited in-situ primary production, and yet they are characterized by a high fish biomass (Goulding *et al.* 1988, Polis *et al.* 1997). In fact, migratory fish are the main vector of nutrient transfer from nutrient-rich turbid whitewater hydro-systems to nutrient-poor clear blackwater systems in South America (Kern and Darwich 1997, Winemiller and Jepsen 1998, 2004) and this system of "foodweb spatial subsidy" also characterizes mainstream-floodplain exchanges (Junk 1999), temperate streams (Schuldt and Hershey 1995, Bilby *et al.* 1996, Childress *et al.* 2014) and estuaries (Deegan 1993).

In the Mekong, a similar process of nutrient transfer from nutrient-rich downstream floodplains towards more oligotrophic upstream tributaries via fish migrations is expected. This hypothesis is supported by the fact that at least 37% of the fish biomass is made-up of migratory species (Baran 2010). The 3S system in particular contains at least 89 migratory fish species representing 60% of the total fish catch (Baran *et al.* 2014), and in the Tonle Sap River, more than 2,000 tonnes of migratory fish are harvested per day during the migration peak[5] (see section 4.2.2.1 for more details). Thus, a reduced sediment and nutrient load due to upstream dam construction activities would result in lower productivity in downstream floodplains, but also in reduced fish migrations, reduced nutrient transfer and lower productivity in the upstream tributaries not directly blocked by dams (Figure 16).

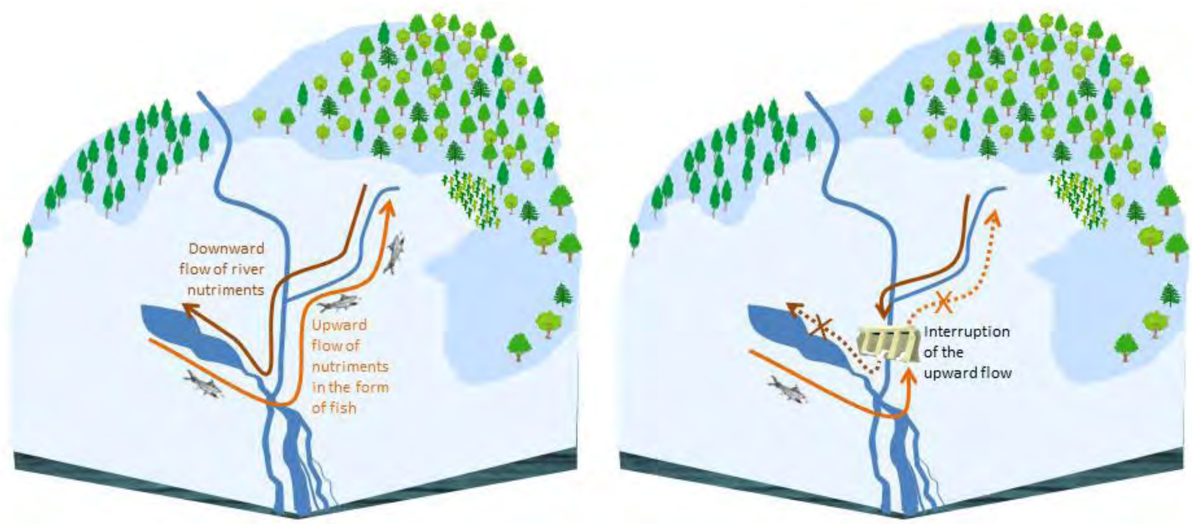


Figure 16: Reduction in nutrient transfers between river systems due to reduced fish migrations

[5] Common catch rates during the days preceding the January full moon amount to 350 kg per haul every 15 minutes for each "Dai" net, and there are 63 nets operating 24 hours a day at that time of the year.

3.2.5 Sediments and fish habitats

Sediments definitely influence fish by affecting their habitats. Tropical rivers should not be seen as a continuum of habitats but as groups of physically separated biotopes (feeding, spawning and nursery areas; dry season refuges; Poulsen and Valbo-Jørgensen 2001, Nguyen *et al.* 2008, Hortle 2009). Sediment plays a role in affecting the characteristics of these habitats, since i) the geomorphology and bed substratum are determined by sediment loads; ii) water turbidity is directly correlated with suspended sediment, and iii) the pH of the water can be influenced by sediments (Figure 17). In the case of Mekong floodplains, Arias *et al*. (2011, 2012, 2013) underline that hydrological changes triggered by dam development are likely to modify the extent of flooded vegetation (-13 to -22% in the case of the Tonle Sap Lake) and vegetal communities composition, subsequently altering sediment deposition and fish habitat structure in these floodplains.

Sediment load plays a major role in determining the geomorphology of riverbanks and riverbeds – two key drivers in the development of aquatic organisms' communities, and in particular fish communities. The composition of aquatic organism assemblages basically reflects: i) nutrient inputs, and ii) the physical form of the river system (Welcomme 1985). A reduction in upstream sediment load results in large-scale changes in the downstream riverbed, the latter being a dynamic system in which sediments removed from the channel are replaced by the inflow of sediments from upstream. Such changes in sediment makes river microhabitats less suitable for aquatic organisms – those requiring specific substrate compositions for reproduction and/or foraging (Bizer 2000, Osmundson *et al.* 2002). Thus, the long-term ecological consequences of dams and other stream disturbances are related to such geomorphological changes (Trush *et al.* 1995, Pitlick and Van Steeter 1998).

A modification of Mekong sediment concentrations may affect deep-pool fish habitats, and these habitats are critical for many fish species, especially during the dry season (Poulsen *et al.* 2002a, Baran *et al.* 2005, Viravong *et al.* 2006, Baird 2006). Hydropower development on the Mekong would most likely result in reduced flows during the wet season and therefore, less flushing of the sediments

Figure 17: The Mekong's sediments largely determine river habitats

that have accumulated in the deep pools, leading to increased sedimentation (Conlan *et al.* 2008, Ou and Winemiller *in press*). However, dam construction would also reduce sediment concentrations and downstream bedload waves, resulting in a slower or reduced sedimentation process within such pools. The balance between these two phenomena and the overall impact on deep pools as fish habitats is not well known.

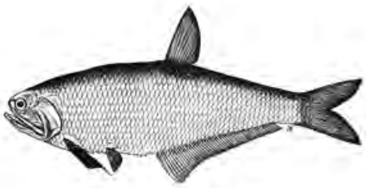
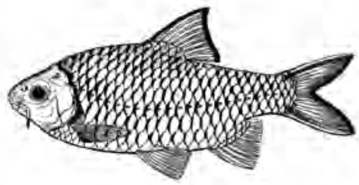
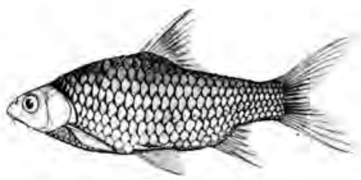
Water turbidity resulting from the sediment load is also part of the fish habitat. Turbidity influences the composition, structure, and abundance of fish communities in tropical rivers, floodplains, estuaries, and coastal plumes. Several studies conducted in tropical floodplains have indicated that water transparency is a good predictor of fish assemblage composition and distribution (e.g. Tejerina-Garro *et al.* 1998, Pouilly and Rodriguez 2004). In South American floodplains, seasonal changes in the relative abundance of visually and non-visually oriented fish groups follow water turbidity fluctuations (Tejerina-Garro *et al.* 1998). In the Missouri River, fish populations have been shown to decline following the degradation of their habitats by river flow stabilization and sediment load reduction (Cross and Moss 1987, Pfleiger and Grace 1987, Hesse *et al.* 1993). Turbidity is also a parameter that strongly influences the distribution and abundance of communities in estuarine waters (Kennish 1990, Lévêque and Paugy 1999). For example, Diouf (1996) - based on a review of 50 studies in estuarine areas - shows that in 75% of cases, turbidity is one of the structuring factors of fish communities.

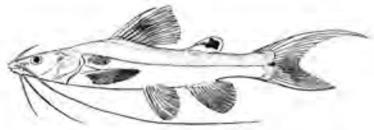
Water acidity (*pH*) is also influenced by sediment concentration. In most tropical rivers, the ionic composition of the water is derived primarily from the rain, and the rock or sediments over which a river flows (Welcomme 1985). Fine sediment particles adsorb and neutralize dissolved humic acids (Carolsfeld *et al.* 2003) and help maintain pH at values compatible with fish survival. Modifications in water pH can affect the reproduction and other biological processes of fish. Extreme pH values, i.e. those below 4.5 or above 9.5, alter aquatic organisms' ionic regulation and are usually lethal (Gonzalez 1996, Val *et al.* 1999)

Among Mekong fish species, dependence on sediment through habitat is clearly known for 21 species. We reviewed for this book the ecology of Mekong species in relation to sediments, as compiled in a literature review of 296 Tonle Sap species (period covered: 1938 to 2003; Baran *et al.* 2007c), and detailed in both FishBase (*www.fishbase.org*) and the Mekong Fish Database (MFD 2003). The detailed findings are given in Table 4.

Table 4: Fish species whose ecology is dependent on sediments

Fish species found in rocky or sandy habitats	
Species: *Hypsibarbus lagleri* 	May migrate into flooded forests immediately adjacent to rivers, but does not live over fine-grained sediments – preferring rocks. **Reference:** Rainboth 1996
Species: *Homaloptera smithi* 	Adults are found in high gradient streams over fast bedrock, cobble runs and rapids, and juveniles can be found in slower stretches composed of gravel with exposed tree roots. **References:** Krachangdara 1994; Rainboth 1996
Species: *Crossocheilus atrilimes* 	Usually associated with clear, relatively fast flowing waters with gravel or boulders. **Reference:** Kottelat 2001
Species: *Opsarius koratensis* 	Found over gravel substrate in clear, fast-flowing small streams, and along fast-flowing stretches of large rivers, especially in areas with many rocks. ***References:*** Rainboth 1996; Baird *et al.* 1999
Species: *Tor sinensis* 	Found in pools and runs over gravel and cobble; in clear rivers within forested areas. **Reference:** Rainboth 1996
Species: *Schistura pellegrini* 	Inhabits shallow, clear, fast-flowing water with a rocky bed in upland streams. **Reference:** Rainboth 1996
Species: *Garra fasciacauda* 	Inhabits the rocky beds of fast-flowing rivers and streams of all sizes. **Reference:** MFD 2003

Fish species found in muddy habitats	
Species: *Garra cambodgiensis* 	Inhabits rocky beds in the fast-flowing water of small- and medium-sized streams. **Reference:** MFD 2003
Species: *Setipinna melanochir* 	Abundant in the middle Mekong when water levels rise and turbidity increases. Inhabits shallow, clear, fast-flowing water over a rocky bed in upland streams. **Reference:** Rainboth 1996
Species: *Macrognathus maculatus* 	Found in lowland streams and peat bogs. Often found in clear water over a rocky bed in fast-flowing streams. **Reference:** Vidthayanon 2002
Species: *Mystacoleucus marginatus* 	Found in the lower depths of rivers and streams, both large and small. Inhabits areas covered with sand or gravel. **Reference:** Rainboth 1996
Species: *Hypsibarbus malcolmi* 	Found in large rivers during the dry season, then moves to medium-sized rivers in the wet season. Usually found over coarse substrate. **Reference:** MFD 2003
Species: *Glossogobius aureus* 	**Habitat/Reproduction:** Found in rivers with clear to turbid water; usually over sand or gravel beds, and mud. **References:** Allen 1989, Allen *et al.* 2002
Species: *Mastacembelus favus* 	Inhabits fast-flowing waters. Most often found over gravel substrates where it buries itself during the day. **Reference:** MFD 2003
Species: *Tuberoschistura cambodgiensis* 	Inhabits streams with sandy beds. Has been found in fast-flowing streams with a sandy bed between Siem Reap and Kompong Thom, near the Tonle Sap Lake. Has also been found in sandy-bottomed streams south of Phnom Penh. **Reference:** Rainboth 1996

Fish species found in muddy habitats	
Species: *Hemibagrus nemurus* 	This species occurs in most habitat types, but most frequently in large, muddy rivers with slow currents and a soft bed. **Reference:** Kottelat 1998
Species: *Channa striata* 	Survives the dry season by burrowing into mud found on the bottom of lakes and canals, and in swamps – as long as its skin and breathing apparatus remain moist. **Reference:** Davidson 1975
Species: *Pangio anguillaris* 	Found near the riverbed over sand or silt substrate among debris and decaying vegetation. Spends much of its time buried in the sand or foraging slowly across the surface. **References:** Rainboth 1996, Kottelat 1998
Species: *Macrognathus siamensis* 	Spends much of its time buried in silt, sand or fine gravel – with only a part of its head protruding. Emerges at dusk to forage for food. **Reference:** Rainboth 1996
Species: *Macrognathus taeniagaster* 	During the day spends much of its time buried in silt, sand or fine gravel with only its snout and eyes protruding. Emerges at night to forage. **Reference:** Rainboth 1996

Species whose dependence on sediment is unclear:

Syncrossus helodes
Lepidocephalichthys hasselelti
Nemacheilus pallidus

Species whose ecology is not dependent on sediment:

Parachela oxygastroides

3.3 Conclusion

In this chapter we have looked at the ecology of fish species in the Mekong River system, and in particular at the interactions between these species and sediments, and how the different types of sediments influence fish distribution and biology throughout the river system.

In the next chapter, we will explore how the nutrients trapped by sediments influence fish production, both in the Mekong floodplains (incorporating the Tonle Sap) and nearshore in the Mekong plume, where sediment discharges and the nutrients carried by such sediments have a significant influence on fish resources and coastal fisheries.

4

SEDIMENTS AND FISH PRODUCTION

4.1 Mekong fish production

According to the most reliable estimate, Mekong fish production amounts to 2.1 million tonnes of fish each year. There are four sources of fish production estimates in the Mekong: national statistics compiled by the FAO, assessments based on areal productivity and surface area of wetlands, assessments based on fish consumption by local populations, and estimates based on catch assessment. These statistics, their sources and their level of reliability are detailed in Baran (2010). In short, national statistics are produced annually but are not based on field studies (Coates 2002, Barlow *et al.* 2008); estimates based on wetlands productivity include a large error range and estimates based on catch assessments correspond to very few and limited studies conducted almost two decades ago; the most reliable estimates are those based on 20 household fish consumption assessments in four countries (Hortle 2009). According to this approach, fish production in the Mekong amounts to 2.1 million tonnes annually. None of the three latter estimates are subject to annual updates, and no fish production statistics based on actual fish catch monitoring have ever been produced. Out of these 2.1 million tonnes of freshwater fish, floodplains contribute 1.2 to 1.5 million tonnes per year (Barlow *et al.* 2008) and are therefore home to the most productive fisheries in the world (Dugan *et al.* 2010).

When coastal fisheries are included, the Mekong fisheries yield between 2.6 and 3.3 million tonnes of fish per year. Fish yield in the upstream zone of the Lower Mekong, i.e. between the Khone Falls and the Chinese border, ranges between 0.9 and 1.1 million tonnes per year (Barlow *et al.* 2008). In the downstream zone of the Lower Mekong Basin, i.e. from the Khone Falls to the river mouth, production amounts to 1.2 to 1.5 million tonnes per year. Provincial statistics reviewed in 2010 indicate that the Mekong coastal fisheries produce 0.5 to 0.7 million tonnes of fish each year (Baran 2010). The extent of the Mekong plume shows that this should be complemented with catch statistics from Ba Ria - Vung Tau, Binh Thuan, Kampot and Sihanoukville provinces (see details in section 4.3.4.2), although figures for the latter are not known at this point. Overall, the Mekong fisheries (i.e. freshwater plus coastal fisheries) yield between 2.6 and 3.3 million tonnes per year[6].

Table 5: Mekong fish production estimates based on different approaches. Source: Baran (2010). The national statistics correspond to an average over the 2000 – 2007 period

	Cambodia	Lao PDR	Thailand	Vietnam	Total
National statistics	388,000	27,000	207,000	133,000	755,000
Estimates based on wetlands productivity	[198,000-395,000-790,000]	[20,000-41,000-82,000]	[173,000-347,000-694,000]	[190,000-381,000-761,000]	[582,000-1,163,000-2,327,000]
Estimates based on fish consumption	482,000	168,000	721,000	692,000	2,062,000
Estimates based on fish catch	682,000	183,000	932,000	845,000	2,642,000

4.2 Sediments and floodplain fish production

River nutrients drive the river's productivity. Nutrients transported by sediments in tropical rivers are a primary driver of aquatic food webs; they are essential to vegetation growth (phytoplankton, algae and plants), determine the productivity levels of higher trophic levels and ultimately influence fish productivity. The majority of these nutrients are transported by the suspended sediment load, and in this section we identify the linkages between sediments, flood pulses and fish production, and the consequences of a reduced sediment load (oligotrophication) on river productivity.

The exceptionally high productivity of the river and its associated floodplains is explained by the river flood pulse. The flood pulse concept developed by Junk (Junk *et al.* 1989, Junk and Wantzen 2004) and based on the Amazon hydro-system, focuses on the lateral exchange of water, nutrients and organisms between a river or lake, and the connected floodplains (Figure 18). This concept suggests that an annual flood pulse is the most important aspect and the most biologically productive feature of a relevant river ecosystem. A flood pulse is typically characterized by three main components: amplitude, duration and timing. Dam development results in reduced sediment concentrations downstream, but also in reduced amplitude of the flood and in a delayed flood (change in timing due to the filling of the dam reservoirs at the beginning of the wet season). This combination of sediment retention and reduced hydrodynamic pulse is expected to have a synergetic and negative effect on the overall productivity of the river downstream.

Figure 18: The Mekong's waters bring sediments and nutrients to floodplains. Upstream sediment-loaded waters (right) spread into downstream floodplains, whose more transparent water originating from the surfacing water table looks dark (left).

[6] Fish production estimates: lower range = 0.9 +1.2 + 0.5 = 2.6 million tonnes per year; upper range = 1.1 + 1.5 + 0.7 = 3.3 million tonnes per year for the whole Mekong Basin and the coastal zone under Mekong influence

Although an abundant literature exists on eutrophication or naturally oligotrophic hydro-systems, only a handful of studies have addressed dam-driven oligotrophication at a large scale (Milliman and Meade 1983; Meade 1996; Vörösmarty *et al.* 2003 and the special issue of *Global and planetary change* 2003; Kunz *et al.* 2011). Oligotrophication is the process by which a hydro-system becomes nutrient-deficient and less productive, i.e. the opposite of the more common "eutrophication" (Figure 19). While eutrophication was considered in previous decades as one of the major environmental issues for hydro-systems under human influence, oligotrophication was perceived as an aesthetic improvement, resulting in "clean" water, though from a fisheries perspective, it also implies low productivity (Stockner *et al.* 2000).

Oligotrophication is related to phosphorus or nitrogen deficiency, but the nitrogen/phosphorus ratio is also important. In aquatic systems, phosphorus is often a more limiting nutrient than nitrogen for plankton and vegetation growth. Consequently, oligotrophication often reflects a decrease in phosphorus levels, in particular in temperate zones. The ratio of nitrogen to phosphorus is also important and determines some ecosystem characteristics such as the presence and quantities of certain algae (Liljestrom 2007). In some tropical aquatic systems, nitrogen may be the limiting factor (Moss, 1969, Lehman and Branstrator 1993, Guildford *et al.* 2003). Knowing which nutrient is the limiting nutrient is valuable for planning and management purposes.

Oligotrophication results in changes to the food web structure and downstream river productivity (Stockner 1987, Tonn 1990, Mann 1993 in Stockner *et al.* 2000). Nutrient-rich and productive hydro-systems (e.g. coastal upwellings and eutrophic lakes) are usually characterized by short food chains and productive fish resources (Cushing 1989, Ware and Thomson 1991). In hydro-systems that are becoming nutrient-poor, primary production declines and food chains become less energy-efficient and longer (Pomeroy 1974, Stockner and Porter 1988, Weisse and Stockner 1993). Oligotrophication also results in a decline in fisheries resources, and declines in yields from inland fisheries over the last 20 to 30 years in Europe and North America have largely been attributed to this process (Hess *et al.* 1982, Hartmann and Quoss 1993, de Bernardi *et al.* 1995, Ashley *et al.* 1997). Oligotrophication following

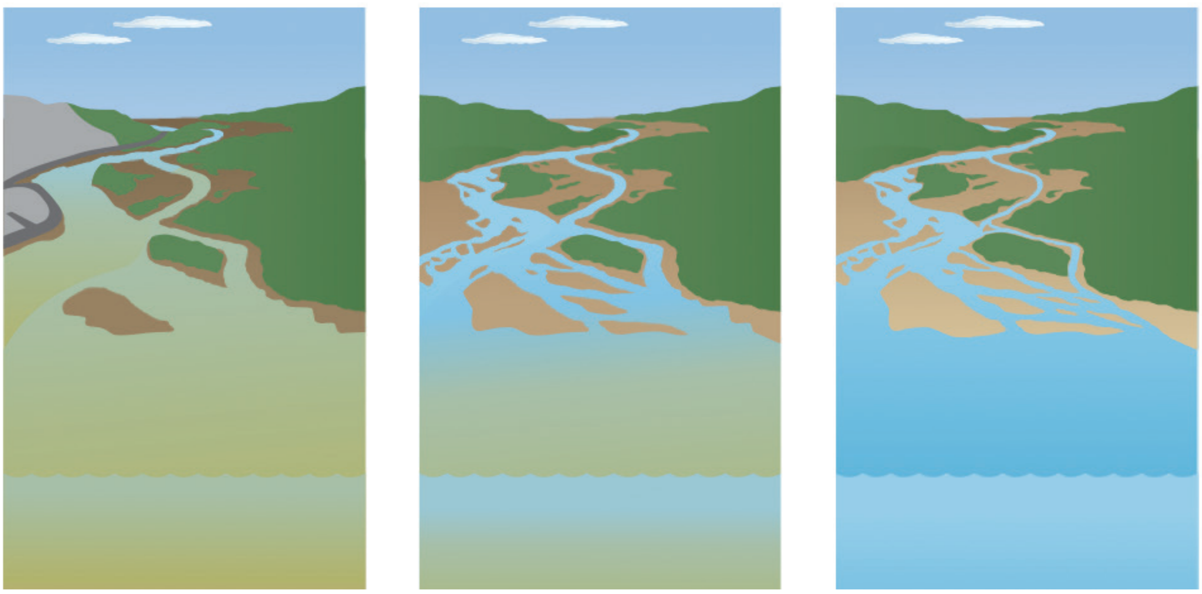


Figure 19: The process of oligotrophication or reduction of the sediment and nutrient load in a river. Illustrator: Tracey Saxby, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/)

dam construction may also impact fish production in coastal zones (Marmulla 2001). Thus, in Cuba, a reduction in sediment flows following a combination of river damming and reduced fertilizer use has caused a dramatic decrease in the catches of estuarine species (Baisre and Arboleya 2006). In Brazil, a cascade of dams on the Sao Francisco River trapped 95% of the suspended sediment, reducing nutrient concentrations in the river plume by 90% and causing the estuary to become transparent, oligotrophic and unproductive (Knoppers *et al.* 2012). In Egypt, oligotrophication due to sediment trapping by the Aswan Dam has had a catastrophic effect on coastal fisheries at the mouth of the Nile River (El-Sayed and Van Dijken 1995, Bebars *et al.* 1996).

4.2.1 Sediments and floodplain fish production in the Mekong

The Mekong system is characterized by its extensive floodplains subject to an annual flood pulse. Each average year the Mekong inundates approximately 1.2 to 1.8 million hectares. The floods last between a few weeks (at the fringe of the floodplain) and six months, and the water depth ranges from between a few centimeters, again at the fringes of the inundation zone (Carling 2009), and up to five meters. The outer limit of the floodplain area is Kratie in Cambodia (TKK and SEA START 2009), and its maximal extent is 38,900 km^2 – as assessed during the year 2000 record floods (Figure 20).

Figure 20: Extent of the 2000 floods, showing the limits of the Mekong floodplains. Source: Carling 2009

The flood pulse is widely accepted as an explanation for the exceptional productivity of the Mekong floodplains (Lamberts 2001 and 2006, Poulsen *et al.* 2002b, Sverdrup-Jensen 2002, Sarkkula *et al.* 2004, Davidson 2006, Baran *et al.* 2007a, Kummu *et al.* 2008b, TKK and SEA-START 2009, Hortle 2009, Holtgrieve *et al.* 2013, Arias *et al.* 2014). Campbell *et al.* (2009) are the only authors who reject this explanation, without providing details. However, the more specific dependency of Mekong floodplain fisheries on sediment loads is not well documented, with only two studies having quantitatively addressed the role of sediments vis-à-vis fisheries productivity (Koponen *et al.* 2010a, Holtgrieve *et al.* 2013).

Following dam development and climate change, studies predict a 53-59% reduction in sediment deposition and a 47-84% reduction in nutrient inputs in Mekong floodplains. Multiple studies unanimously predict reduced sedimentation in Mekong floodplains due to sediment retention by upstream dams (e.g. Kummu *et al.* 2005a, Kummu and Sarkkula 2008, Baran and Myschowoda 2009, Kameyama *et al.* 2009, Ketelsen and Ward 2010, Holtgrieve *et al.* 2013, Kondolf *et al.* 2014, Rubin *et al.* 2014, Nguyen *et al.* 2015). In the case of the Tonle Sap, the most detailed study to date (Arias *et al.* 2014) estimates that the annual average net sedimentation in the floodplains and open waters reaches 3.28 ± 0.93 million tonnes, or 765 ± 203 $g.m^{-2}$ (baseline). As a combined consequence of climate change and hydropower development, floodplain sediment deposition is expected to decrease by 56 ± 3% from the baseline values. In 2010, Sarkkula and Koponen calculated that sediment trapping by dams would reduce bio-available phosphorus inputs into the Mekong floodplains by 10,000 to 18,000 tonnes each year, which corresponds to a 47-84% reduction (under the assumption of a 50% to 80% downstream sediment loss and a total amount of bio-available phosphorus of 21,500 tonnes). However, the role of phosphorus as a possibly constraining and limiting nutrient has not yet been fully established (Kummu *et al.* 2004, Ongley 2009, Holtgrieve *et al*. 2013).

Figure 21: Sediment rarefaction and clearer waters are likely to result in reduced fish productivity

Following dam construction and climate change, a 30-38% reduction in the average net primary production of the Mekong floodplains is predicted. Holtgrieve *et al.* (2013) estimate that the aquatic net primary production of the Tonle Sap Lake amounts to 2 ±0.2 grams of carbon per square meter and per day, i.e. 2.4 ±0.2 million tonnes of carbon per year. Similarly, Arias *et al.* (2014) calculate the average net primary production of the Tonle Sap open water and floodplains at 2.63 ± 0.13 grams of carbon per square meter of wet area and per day; this corresponds to an annual average net primary production of 1.07 ± 0.06 million tonnes of carbon in the open water and 3.67 ± 0.61 million tonnes in the floodplain. An exceptionally high percentage (up to 69%) of this aquatic net primary production enters the food web, explaining the unique productivity of the fishery. Arias *et al.* (2014) confirm the hypothesis of multiple authors that ongoing and future changes combining hydropower development and climate change will decrease ecosystem productivity in the Tonle Sap system, and they predict a reduction by 34 ± 4% of that average net primary production by 2030 (31% of the reduction being due to hydropower development). According to Sarkkula and Koponen (2010), fish productivity decline is expected to be relatively larger in the Mekong Delta and in the coastal zone than in the Tonle Sap Lake.

The extent and modalities of nutrient enrichment by agriculture and cities are not clearly assessed. The possible compensatory role of nutrient release from fertilizers in the 159,000 km^2 of rice fields (Hortle 2009), from 24 million head of livestock (Nesbitt *et al.* 2004) and from the untreated sewage produced by more than 60 million people (MRC 2003) has not been fully assessed. The Mekong River Commission believes that rapid development can be expected to accelerate nutrient enrichment, and reports significantly growing trends in concentrations of total phosphorus and ammonium in the Mekong mainstream, in particular at some urban hotpsots (e.g. Vientiane, Phnom Penh) and in the delta (MRC 2010). Liljeström *et al.* (2012) share this concern but find that the majority of the LMB nitrogen and phosphorus fluxes originate from agricultural areas (53% and 75% respectively), while urban areas contribute only 0.1% and 0.5% of total nitrogen and phosphorus.

4.2.2 Sediments and fish production in the Tonle Sap floodplains

The Tonle Sap Lake is by far the most studied component of the Mekong system (Campbell *et al.* 2009). Since the Tonle Sap floodplains represent more than 40% of the Mekong's total floodplains, the latter being a relatively homogenous ecological system, the Tonle Sap can be seen as a proxy for the Mekong floodplains in general. The relationship between the flood pulse and fish production levels in the Mekong floodplains has been widely discussed (Sarkkula and Koponen 2003, Lamberts 2006, Halls *et al.* 2008, Kummu *et al.* 2008b, Kummu *et al.* 2008c, Lamberts 2008, Lamberts and Koponen 2008, Sarkkula and Koponen 2010, Holtgrieve *et al.* 2013).

4.2.2.1 Tonle Sap floods, sediments and nutrients

The Tonle Sap and its floodplains retain 61 to 69% of the suspended solids they receive, and contribute 1.4 to 7 million tonnes of sediments to the Mekong Delta and coastal zone each year. It is estimated that the Tonle Sap Lake receives 5.1 - 6.3 million tonnes of sediments each year from the Mekong mainstream (Kummu *et al*. 2008b; Lu *et al*. 2014), plus 2 million tonnes from its tributaries (Lu *et al*. 2014). These 7.1 - 8.3 Mt/yr represent about 5% of the total original Mekong sediment load, i.e. 160 Mt/yr. Of its received sediment input, the Tonle Sap Lake retains 4.3 million tonnes (Eloheimo *et al.* 2002) to 5.7 million tonnes (Inkala *et al.* 2008) of suspended solids each year, and exports between 1.4 million tonnes (Kummu *et al.* 2008b) and 7 million tonnes (Lu *et al.* 2014) of sediments to the Mekong Delta and the coastal zone (see section 4.3.2). Sediment-related nutrients consist mainly of nitrogen (N) and phosphorus (P), the two most important elements for ecosystem productivity. Koponen *et al*. (2010a) assume that the system is not nitrogen-limited (considering inputs from plant nitrogen fixation and seasonal decaying of plant material), but underline that there is a need for a better assessment of the nutrient cycle, in particular in the dry season. Holtgrieve *et al.* (2013) confirm that it is unclear whether the limiting nutrient is nitrogen, phosphorus, or micronutrients, and underline that understanding which factors control aquatic photosynthesis is a critical next step in determining the likely impacts of dam construction on primary production.

The amount of phosphorus exported each year from the Tonle Sap system through fish migrations is similar to the amount retained by the lake. Sarkkula *et al.* (2010) estimate that the Tonle Sap Lake receives 21,500 tonnes of bio-available phosphorus each year, assuming a value of 130 mg of bio-available phosphorus per kilo of sediment. Of this, a certain amount is removed through export, in particular through the production of migratory fish that grow and absorb nutrients in the lake but migrate and die outside of it (Koponen *et al.* 2010b). Assuming that fish biomass is comprised of 0.5% phosphorus and 2.5% nitrogen, and that the lake produces 230,000 tonnes of fish annually (Baran *et al.* 2001), Koponen *et al.* (2010a) estimate that the amount of nutrients removed through fish biomass equals 1,150 tonnes of phosphorus and 5,750 tonnes of nitrogen each year. Koponen *et al.* (2010a) assert that ultimately 8,500 tonnes of dissolved inorganic nitrogen, 1,350 tonnes of total dissolved phosphorus and 850 tonnes of phosphate (PO_4^-) are retained by the lake each year. The authors underline that these figures are probably underestimates and that sediment accumulation could be facilitated by the vegetation cover and so be higher in the flooded areas than in the open parts of the lake.

Figure 22: "Dai" nets (i.e. bagnets) on the Tonle Sap River. The full fishery is made up of 63 such nets in the Tonle Sap River.

The "Dai" fishery

The "Dai" fishery is made of stationary trawls positioned in the Tonle Sap River to capture fish species migrating out of submerged areas in the Tonle Sap Basin towards the Mekong River. It operates between October and March, 4 to 35 kilometers upstream of Phnom Penh. The fishery was, until recently, composed of 64 units (Lieng *et al.* 1995, Ngor and van Zalinge 2002, Halls *et al.* 2013).

4.2.2.2 Analysis based on "Dai" fish catches

The catch of the "Dai" fishery in the Tonle Sap River is correlated with sediment inflows. The annual catch of the "Dai" (bagnet) fishery in Cambodia (see Figure 22) was long known to be correlated with the flood height, but Koponen *et al.* (2010a) have also plotted this fishery's catch as a function of sediment inflow over a decade (1999-2009) and shown a positive correlation between these two variables (Figure 23 and 24).

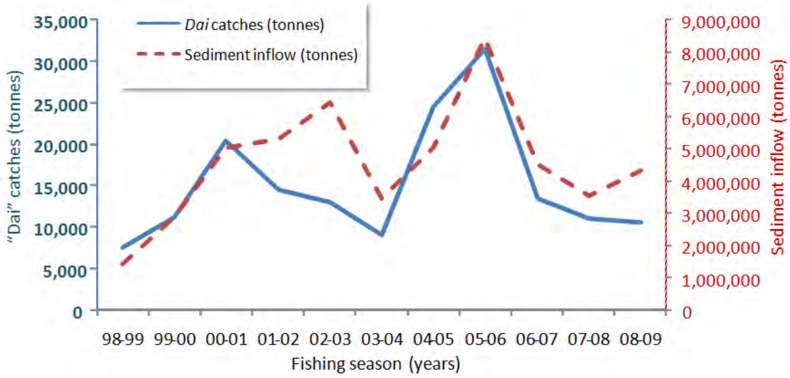


Figure 23: Dai fishery catch and sediment inflows into the Tonle Sap Lake.
Source: Redrawn from Koponen et al. *2010a*

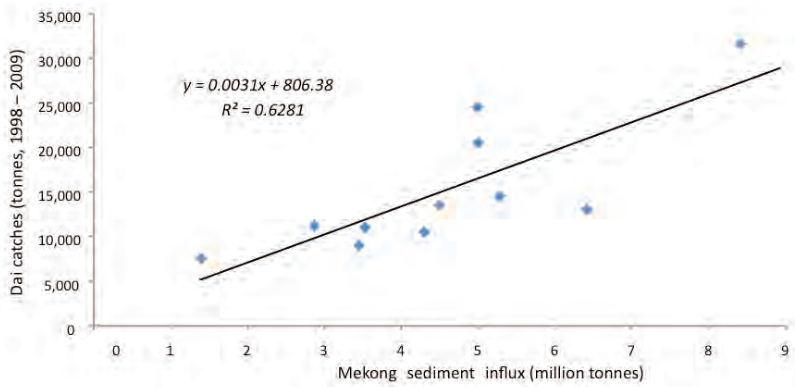


Figure 24: Dai fishery catch as a function of sediment inflows into the Tonle Sap Lake.
Source: Adapted from Koponen et al. *2010a*

4.2.2.3 Analysis based on primary productivity modeling

The fish biomass in the Tonle Sap depends on the primary production of the system. An 80% reduction in Mekong sediment input would result in a 36% decline of the total fish biomass. According to Koponen *et al.* (2010a), fisheries production ultimately depends on, and is limited by, the primary production of the ecosystem and the flood pulse process. According to Sarkkula and Koponen (2010), if the Mekong sediment input were to fall by 80%, the total fish biomass of the Tonle Sap would decline by 36% (compared to the 2004 baseline; see Figure 25). This model refers to the biomass, not the catch. The findings of this model reflect the work of Halls *et al.* (2010), who performed statistical analyses on available fisheries and environmental data and concluded: i) that the best single predictor of fish biomass in the Tonle Sap is the rate of sedimentation, explaining 95% of the variation in fish biomass available for exploitation, and ii) that this fish biomass could decline by up to 20 to 30% due to dam construction activities.

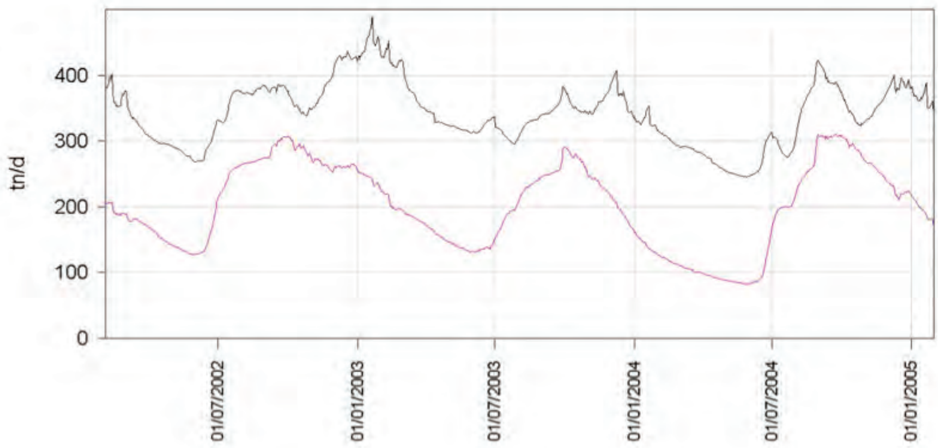


Figure 25: Modeled impact of an 80% reduction in sediment load on Tonle Sap fish biomass (Black line - before reduction; pink line - after reduction). Source: Koponen et al. *2010b*

Tonle Sap fish production is actually related to sediment inputs but also to several mixed factors. Sarkkula and Koponen's results focus mainly on sediment and do not reflect a number of other factors that activate or inhibit fish production. In a study focused on primary production, i.e. the origin of the food chain, Holtgrieve *et al.* (2013) note that the aquatic net primary production per unit area in the Tonle Sap Lake might increase with reduced sediment and higher light conditions for autotrophs, or conversely might decrease due to reduced nutrient inputs with flooding (see Figure 14 page 19). Halls *et al.* (2010) also note that sedimentation rates are inextricably linked to the extent and duration of flows (i.e. the flood index), and that the data available do not allow one to distinguish the relative importance of each factor (Figure 26). Koponen *et al.* (2010a) also point out that "nutrient inputs from fertilizers should be included in the model". These authors note that it is not clear to what extent the organic matter used for fisheries production is exogenous or endogenous (*"Unpublished data collected by the Mekong River Commission on organic matter concentrations in inflowing water suggest that the vast majority of the primary organic matter in the Tonle Sap is produced locally"*). Overall, the Tonle Sap fisheries harvest represents 7 to 69% of the total aquatic net primary production, depending on catch estimates and carbon transfer efficiency hypotheses (Holtgrieve *et al.* 2013). The middle scenario corresponds to a level of fisheries production exceeding the global average of 24% of aquatic net primary production for all freshwater and most marine ecosystems.

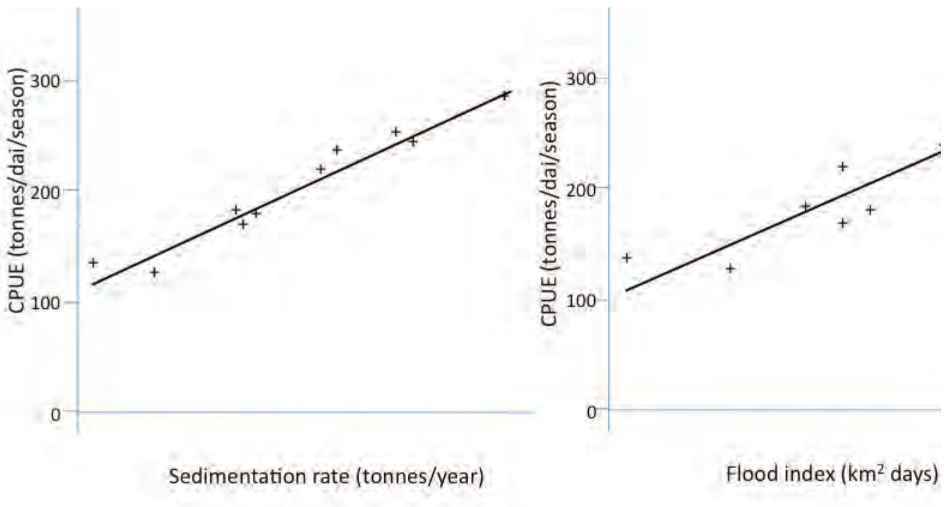


*Figure 26: Fish catch as a linear function of the rate of sedimentation (left), and the flood index (right). The Catch per Unit Effort (CPUE) is the fish yield per unit of "*Dai*" (=bagnet) fishery and per season. Source: Halls* et al. *2010.*

Overall, the main impacts of sediment trapping on fish resources are expected to occur in the delta and at sea rather than in the Tonle Sap, since only a very small fraction of the Mekong sediment load (around 5% annually) goes into the Tonle Sap. The impact of reduced sediments on coastal fisheries is reviewed in section 4.3.

4.2.2.4 The multiple factors influencing Tonle Sap fish production

The Tonle Sap's fisheries depend on a complex combination of inter-related variables that cannot be considered in isolation and require a multifactor approach. Despite their importance, nutrients are not the single driver of Mekong floodplains' fish productivity. As initially highlighted by Baran and Coates (2000), Baran and Cain (2001) and Kurien *et al.* (2006), fish production in the Mekong in general, and in the Tonle Sap in particular, depends on a number of factors, including habitats, flood characteristics, migrations, and fisheries. In a complex system of multiple drivers, the impact of reduced sediments on floodplain fish production cannot be assessed through the use of linear correlations and bivariate statistics alone, so we recommend as an alternative a multi-factor model, one which would allow an assessment of the relative weight of nutrients to be carried out in relation to other drivers, such as flooding patterns, floodplain habitat availability, connectivity or fishing pressure. The BayFish-Tonle Sap model of fish production constitutes a starting point for such an approach, although it does not include sediments at this point.

4.2.2.5 The BayFish model as a possible tool

The interaction of multiple drivers led to the development in 2005 of a multi-factor BayFish Tonle Sap fish production model, the purpose of which is to determine the impact of water and land use options on fish production, and so to assist with planning and decision-making. When building the model, there was not enough data available to properly quantify all the factors considered important, which was overcome through the use of a Bayesian approach allowing the available data to be combined with complementary expert knowledge (Baran *et al.* 2003). Using quantitative or qualitative information about fish, hydrological and environmental variables as inputs, the model can determine the probability of a certain fish production level occurring. The structure of the BayFish-Tonle Sap model is detailed in Baran and Jantunen (2005), and after its initial development, the model was further developed and strengthened over the years, up to 2007 (Baran *et al.* 2007d, Jantunen 2007). However, the BayFish-Tonle Sap model did not initially include a sediments component, since it was only a few years later that sediment issues became part of the research agenda in the Mekong (Lu and Siew 2005, Kummu *et al*. 2005b, Kummu and Varis 2007). In fact, the more specific sediment-fish relationship was not addressed until the MRC-led Detailed Modelling Support Project was implemented in 2009/2010. Despite its incompleteness, in particular in terms of sediments, the BayFish model is probably the most advanced multifactor model capable of providing a more comprehensive understanding of the interactions leading to a given level of fish production in the floodplains.

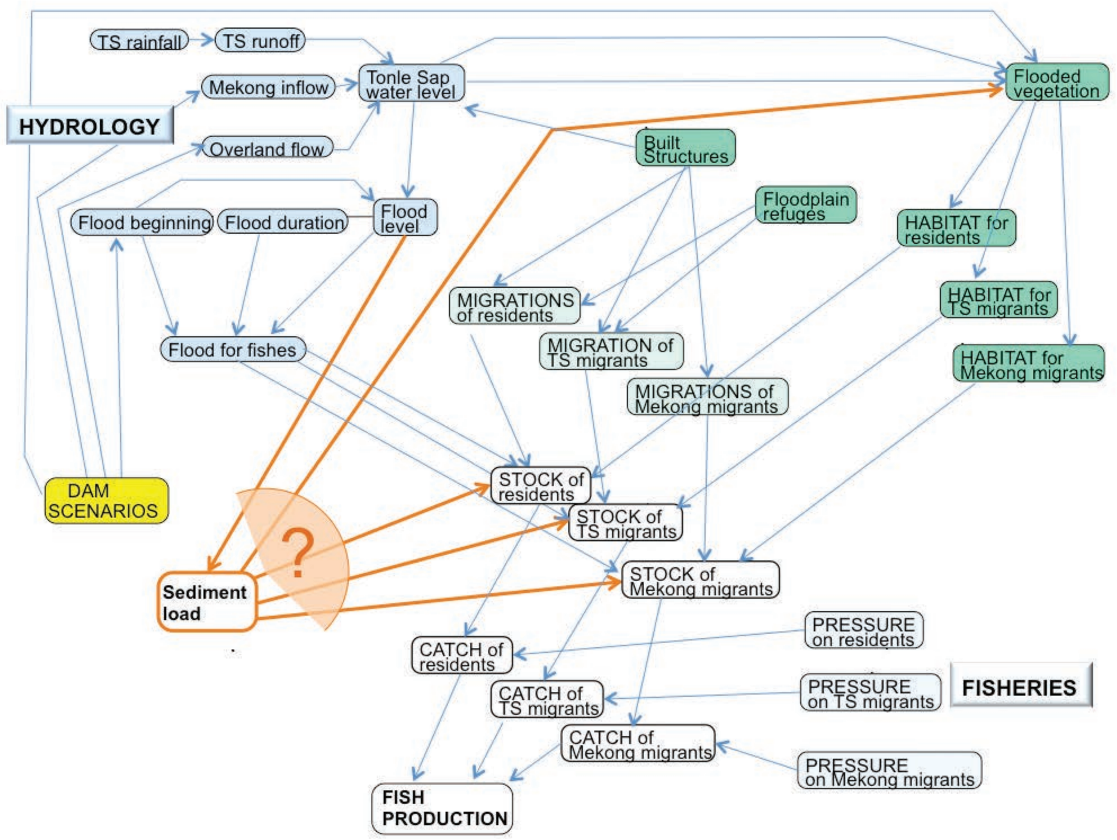


Figure 27: Main variables of the BayFish - Tonle Sap fish production model

The BayFish Tonle Sap Model

BayFish is a suite of decision-support tools that show and predict the impact of land and water use on fish production. The models developed are networks of interacting variables linked by probabilities (Bayesian networks); they reflect the best available knowledge about the major driving variables, and their known interactions. BayFish was initially developed for the Tonle Sap (Baran and Jantunen 2005) and the Mekong Delta (Baran *et al.* 2010). For the Tonle Sap, the network combines drivers such as flood levels, flood areas and flood durations, and influencing factors such as vegetation types, connectivity and fishing effort, and then calculates, based on these drivers, the probability of a given fish yield.

The Bayfish approach allows the integration of information from databases (hard data), scientific studies (science-based conclusions) and local knowledge (opinions elicited during structured consultations; Baran and Jantunen 2004), and this integration allows one to overcome the absence of data series, which is a common occurrence in tropical countries. Variables within the network model can be quantitative (e.g. “water level”) or qualitative (e.g. “fishing gear”). Ultimately, the model calculates trends resulting from the interaction of all probabilities within the system. The user can modify the parent variables and view the consequences of certain management choices made on the final outcomes. A sensitivity analysis can also be carried out to identify the variables that most influence the final outcomes (Baran and Jantunen 2005).

4.3 Influence of sediment loads on coastal fisheries

4.3.1 General features of coastal zones

The coastal zone is a variable and productive system under the influence of large rivers' outflows. The nearshore zone, located at the interface between freshwater and seawater, is a complex ecosystem dependent on combined riverine and marine influences. From a physico-chemical as well as a biological perspective, the nearshore area is an ecotone[7], but it should also be considered a true ecosystem characterized by its own specific environmental characteristics and fauna (Day and Yañez-Arancibia 1985, FAO 1995). This coastal system where the river nutrients meet the open ocean is usually characterized by very productive fisheries (Longhurst and Pauly 1987, Loneragan and Bunn 1999). The productivity of coastal systems depends on the relative influence of the river discharge and ocean currents, but never reaches stability. If the dynamics of freshwater and nutrient outflows influence the hydrology, biogeochemistry and productivity of the coastal zone (Milliman and Mei-e 1995, Cozzi *et al.* 2012), fluctuations in the coastal zone are the norm, and apply to salinity, turbidity, nutrient concentrations, temperatures and biological communities (Day *et al.* 1989).

Coastal ecosystems and fisheries, like their riverine counterparts, have been extensively studied, but surprisingly few studies have addressed the influence of rivers on coastal fisheries. In particular, southern hemisphere estuaries and coastal zones have been largely neglected by scientists; sediment processes in tropical coastal systems are especially poorly known (Blaber 2002). The extent to which fish rely on terrestrial organic inputs is also a knowledge gap in terms of tropical systems (Nagelkerken 2009). Thus, a literature search using Mendeley (7,200,000 science papers indexed) and the keywords "discharge" + "coast" + "fish" harvested only 140 documents, most of them dealing with pollution, estuarine fish, plankton or aquaculture, but not with the impact of river outflows on coastal fish or fisheries.

4.3.2 Features of the Mekong nearshore zone

The Mekong River contributes each year around 100 million tonnes (range: 67-145) of sediments to the coastal zone in Vietnam, and the Mekong dams to be built are expected to reduce this outflow by more than half. Ketelsen and Ward (2010) synthesized the work of Wolanski *et al.* (1996, 1998), Walling (2008, 2009), Wang *et al.* (2009) and Kummu *et al.* (2010) and concluded that, after discounting sediment deposition in the Tonle Sap and in the delta, about 100 million tonnes of sediments and 16,000 to 17,000 tonnes of attached nutrients reach the coastal zone each year at the mouth of the Mekong (Figure 28). Liu *et al.* (2013) value the long term sediment outflow in the coastal zone at 145 Mt/yr. Kondolf *et al.* (2014) note that the reduction in suspended sediment outflows and in floodplain sedimentation might start slowly in the first years due to increased erosion of the river on its bed and banks. Lu *et al.* (2014) measured the sediment flux entering the Mekong Delta from Phnom Penh (i.e. much lower downstream than previously assessed, from Thailand); they conclude from three years of data that the sediment flux into the South China Sea is much lower than previously estimated, reaching 67 million tonnes per year (65 Mt/yr from upstream and 2 Mt/yr from the Tonle Sap River). These authors explain the difference with previous estimates

[7] An ecotone is defined as a transition zone between two adjacent ecosystems

by the fact that in Cambodia the Mekong enters a floodplain depositional environment, "*resulting in a dramatic decline in the sediment loads from around 150 Mt/yr in Mukdahan [Thailand] to well below 100 Mt/yr in Phnom Penh*" (45% decrease in sediment loads between Mukdahan and Phnom Penh, then 20% decrease between Phnom Penh and the Cambodia–Vietnam border).

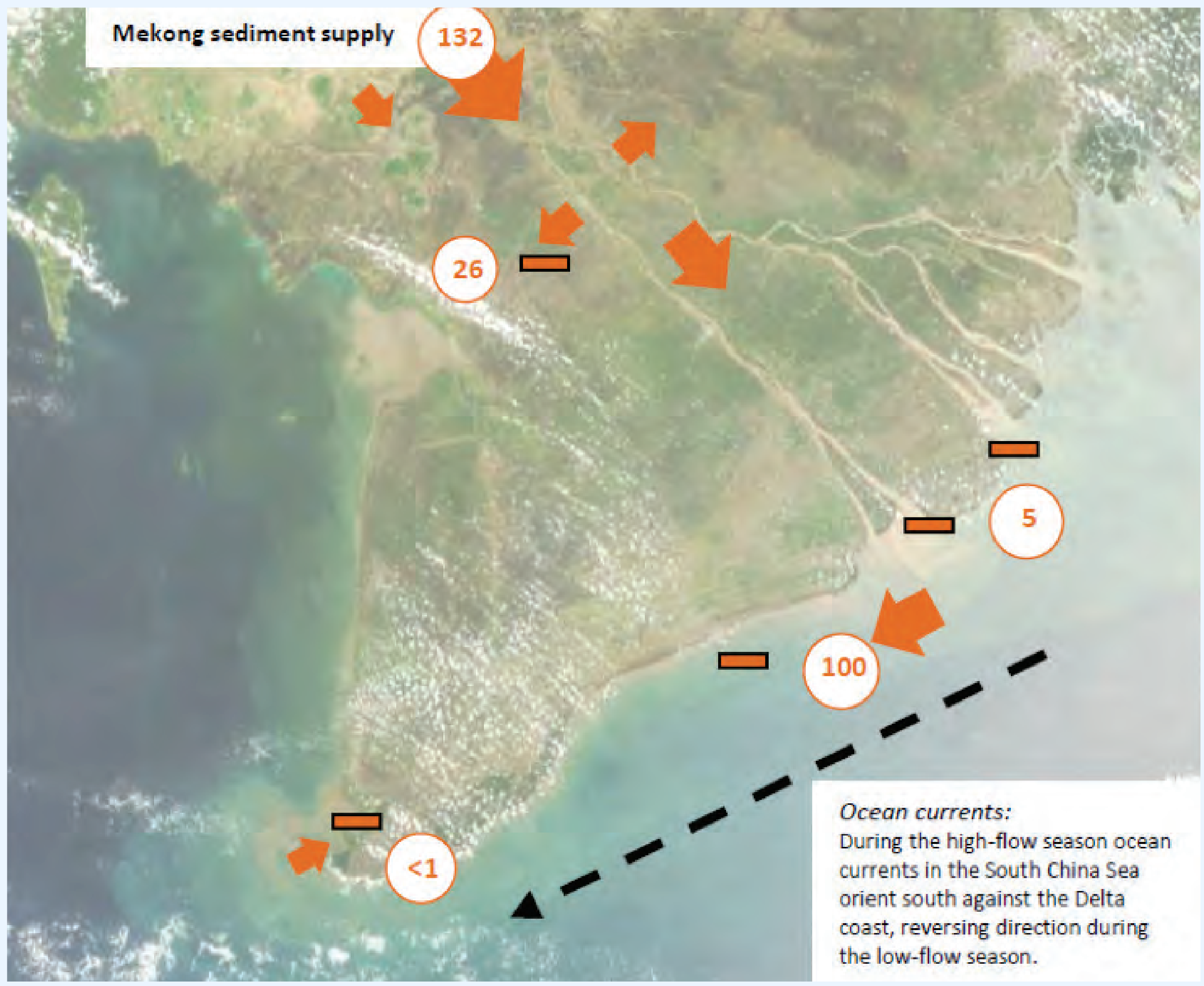


Figure 28: Mekong sediment supply in the delta (million tonnes in red circles). Source: ICEM 2010

By 2030, Mekong dams are expected to cause a 50% reduction in the arrival of sediments and nutrients at the coastal zone, a reduction aggravated by intensive sand extraction along all sections of the Mekong River (43.2 million tonnes in 2011; Bravard and Goichot 2012b). Anthony *et al.* (2015) confirm the erosion of the Mekong Delta coast (shift from massive growth over the last three millennia to a loss of nearly 2.3 km^2/year over 50% of the coast between 2003 and 2012) and the role of sediment retention by dams and sand extraction in this erosion, but they also include a third driving factor: subsidence due to groundwater extraction. Last, Nguyen *et al.* (2015) focused on the respective impacts of hydropower development, climate change (i.e. sea level rise) and deltaic subsidence on hydrology and sedimentation patterns in the delta; they find that the impact of hydropower development on floodplain sediment dynamics is larger than that of the other two factors. Under their "median changes" scenario, the sediment load to the South China Sea is expected to diminish to half of the current rate, while under the "maximum changes" scenario, a 95% reduction of the sediment outflow is expected by 2050-2060.

The Mekong's outflow into the South China Sea supports particularly productive coastal fisheries, and is characterized by a plume of sediments and brackish water which extends far and shifts seasonally from north to south, following the dominant winds and currents (Xue *et al.* 2000; Figure 29).

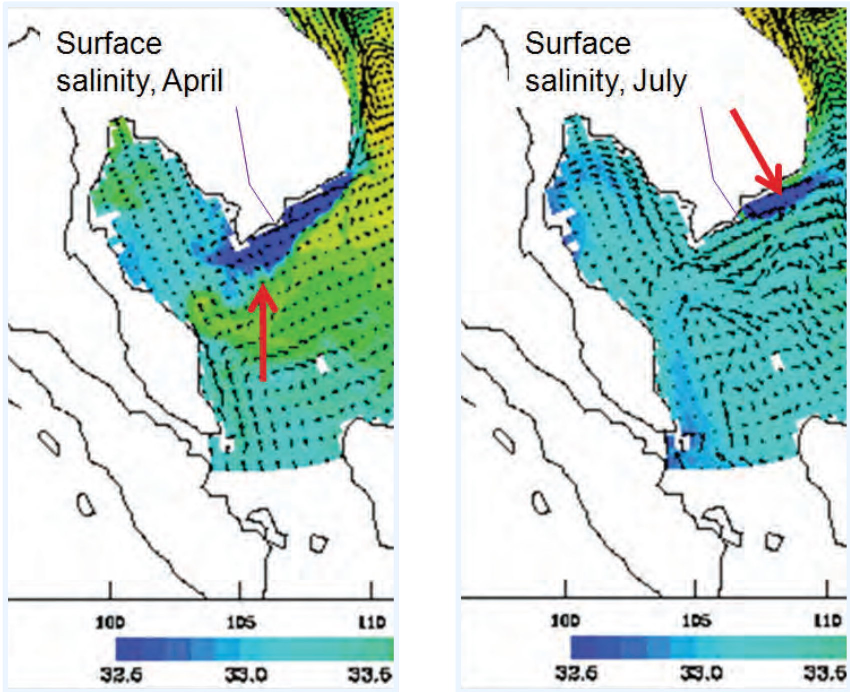


Figure 29: Mekong outflows into the South China Sea over two seasons - traced as brackish water.
Source: Xue et al. *2000*

With more than half a million tonnes of fish harvested annually, the southern Vietnam coastal fisheries are very significant. Nearshore fisheries in southern Vietnam generate 500,000 to 726,000 tonnes of fish per year, employ almost 6,000 fishing boats, constitute a significant component of the Vietnamese delta economy and have grown by 80% in the last 15 years (ICEM 2010). Fish constitute 80 to 90% of coastal yields and are supplemented with 10 to 20% of valuable invertebrates, such as penaeid shrimps, crabs, lobsters and squids (Silvestre and Pauly 1997). In 1976, a comprehensive assessment of Mekong fish resources estimated that Mekong capture fish production activities were comprised of 66% freshwater fish, 31% brackish and coastal fish, plus 3% reservoir fish (Lagler 1976).

The influence of Mekong outflows on coastal fisheries in Vietnam remains poorly understood. It was recognized as early as 1933 that the very productive coastal fisheries in this area were supported by the outflow of nutrients from the Mekong (Chevey 1933), and that fact was confirmed in later studies (Lagler 1976, Poulsen *et al.* 2002b). However, no hard data has been gathered regarding this relationship (ICEM 2010), and the connection between river outflows and coastal productivity is barely acknowledged in research and development agendas (Blaber 2002). Milliman and Farnsworth (2011) confirmed, in their global review of water and sediment outflows in coastal zones, that the Mekong is data-poor from a research perspective, even though a number of new studies have been undertaken in recent years (e.g. Bombar *et al*. 2011; Nguyen *et al.* 2014; Voss *et al.* 2014; Li and Bush 2015).

4.3.3 Coastal fish resources and river discharge

Although some promoters of irrigated agricultural development feel that "*water going to sea is wasted*" (Dugan *et al.* 2004), freshwater flows have a major influence on coastal zones, due to their impact on geomorphology, salinity and turbidity, as well as on the distribution and abundance of fish and crustaceans (e.g. Montague and Ley 1993, Whitfield 1996, Alber 2002, Kimmerer 2002).

4.3.3.1 Lessons learned from tropical coastal fisheries

The positive effect of river discharges on the production of coastal fisheries is widely acknowledged. In 1979, Kidd and Sander identified the correlation between the total annual volume outflow of Amazon River water and marine production in Barbados. Strong correlations have also been noted between river discharge and coastal fish catches in North America (Chapman 1966; Sutcliffe 1972, 1973; Rozengurt and Herz 1985; Grimes 2001), Central America (Yañez-Arancibia *et al.* 1985) and Australia (Growns and James 2005). Overall, the positive effect of river discharges on the production of coastal fisheries is widely acknowledged (reviews in Day *et al.* 1989; FAO 1995; Bunn *et al.* 1998; Loneragan and Bunn 1999; Dugan *et al.* 2004).

However, the dynamics of outflows are as important as the total discharge. Just as the volume of the freshwater inflow is known to be a major driver, timing is also recognized as an important factor in nekton[8] production, through its influence on spawning and recruitment (Kneib 1997; Piazza and La Peyre 2007, 2011). In their review, Loneragan and Bunn (1999) describe the influence of special high-discharge events as "*clearly the most important component of the flow regime for many species of commercial importance. The reduction or elimination of large flow events is likely to eliminate the associated high catches of fish and crustaceans*". This role of flow dynamics tends to blur the mere correlation between river discharge and coastal productivity (Dugan *et al.* 2004).

River discharge and associated sediment loads have an opposing influence on coastal primary production (Goldberg 1971, Parsons *et al.* 1977, Cadee 1978, Mann 1982). While nutrient inputs stimulate plant growth, turbidity generated by suspended matter diminishes available irradiance in the water and subsequently affects photosynthesis (Nixon 1981, Boynton *et al.* 1982, Kemp *et al.* 1982). Thus, coastal maximum production is often found at some distance from the mouth of a river, where light availability optimizes photosynthesis despite a lower concentration of nutrients (Parsons *et al.* 1977, Randall and Day 1987). Binet *et al.* (1995) assert that it is the high turbidity of the waters that explains the unclear correlation between the discharge of the Congo and Niger Rivers and the coastal production in these zones.

Although clear, the impact of flow reduction on the coastal zone has not been fully quantified. In their 2004 review, Dugan *et al.* concluded that although the importance of the relationships between river outflows and coastal ecology is acknowledged, "*few of the studies carried out so far in tropical and sub-tropical regions of Africa, Asia and Latin America allow quantitative analysis and clear prediction of the impacts of reduced water flow in coastal ecosystems*."

[8] Free-swimming aquatic animals independent of wave and current action

4.3.3.2 The case of the Mekong

Controlled flows resulting from dam construction will influence Mekong discharge in the coastal zone and modify the extent of the Mekong plume in the dry season. As early as 1976, Lagler predicted that fisheries around the Mekong plume in the South China Sea would also be subject to the impacts of the controlled flow regime. However, recent predictions about expected hydrological changes have varied substantially depending on the development scenarios considered, as described below.

Depending on the development scenario used, outflows in the Mekong Delta are expected to vary between -8% and +26% in the dry season due to dam construction activities, but to remain almost unchanged in the wet season. In 2009, Baran *et al.* (unpublished) reviewed for the MRC the conclusions of five studies regarding the hydrological changes expected to result from five development scenarios; these studies being the World Bank Mekong development scenarios (Podger *et al.* 2004), the Nam Theun 2 Cumulative Impact Analysis (Norplan and Ecolao 2004), the BDP 1 scenarios for strategic planning (MRC 2005), the Built Structures hydrological modeling study (Koponen *et al.* 2007) and the BDP 2 results (BDP 2008, Piman 2008). The scenarios used were: i) the "Baseline" (common to all studies), ii) the "Chinese dams" scenarios (World Bank and BDP 1), iii) the "Low development" scenarios (World Bank, BDP 1, Built Structures and Nam Theun 2 CIA), iv) the "Agriculture" scenarios (World Bank and BDP 1) and v) the "High development" scenarios (World Bank, BDP 1, Built Structures, Nam Theun 2 CIA, BDP 2).

The review concludes that in Vietnam (in Tan Chau), "Chinese dams" are expected to increase the discharge by 26% during the dry season and would have no influence in the wet season. In the case of the "Low development" scenarios, the discharge would increase by 5% in the dry season and would not change in the rainy season. Under the extractive "Agriculture" scenarios, the discharge would decrease by 8% in the dry season but the water level would not vary during the monsoon. For the "High development" scenarios, predictions include a 10% discharge increase in the dry season and a minimal 20 cm reduction in water level during the monsoon (Figure 30).

More recently, Räsänen *et al.* (2012) found that on average the cascade of dams in China increased the dry season (December–May) discharge by 34–155 % and decreased the wet season (July–September) discharge by 29–36 % at Chiang Saen, and that the dry season hydrological changes were significant all over the basin, as far as Kratie in Cambodia.

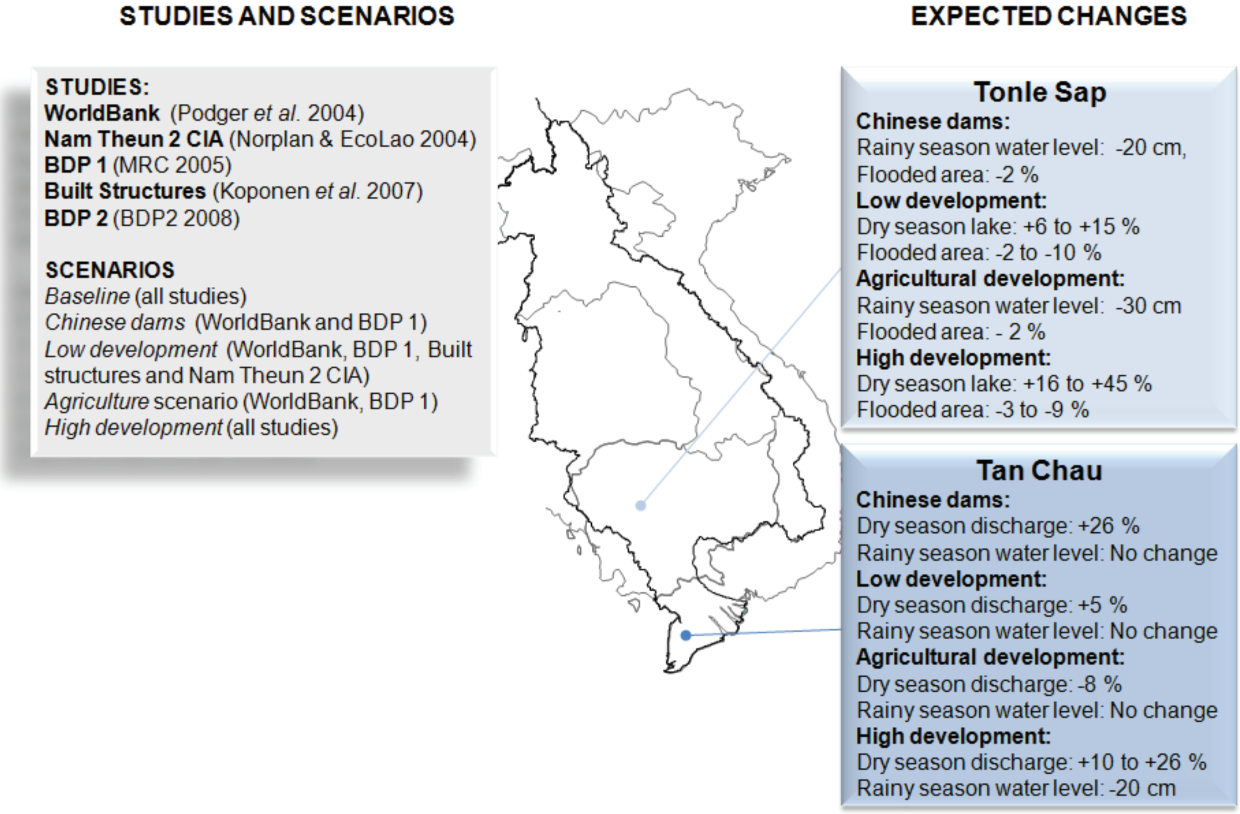


Figure 30: Predicted changes in Mekong outflows based on different development scenarios.
Source: Modified from Baran et al. *2009 (unpublished)*

4.3.4 Coastal fish resources and nutrient loads

Studies of riverine outflows in the coastal zone have tended to focus on turbidity or sediment load, without necessarily distinguishing these factors from nutrient load, organic matter or carbon concentrations, which are the actual drivers of coastal productivity. In the following section, we review the state of knowledge on the influence of turbidity, nutrients and carbon on coastal fisheries in general, before reviewing the case of the Mekong.

4.3.4.1 Lessons learned from tropical coastal fisheries

The role of nutrients in sustaining both primary production and fish production in the coastal zone is well established. The positive role of nutrients, in particular phosphorus and nitrogen, vis-à-vis primary production is widely acknowledged (reviews in Nixon and Buckley 2002, Dugan *et al.* 2004, Nagelkerken 2009), and so is the positive correlation between primary production and fish production or fisheries' yields (Nixon 1981, Nixon 1982, Day *et al.* 1989, Iverson 1990, Loneragan and Bunn 1999, Oczkowski and Nixon 2008, Blaber 2009). The correlation between primary production and fisheries' yields in a number of coastal environments worldwide is illustrated in Figure 31.

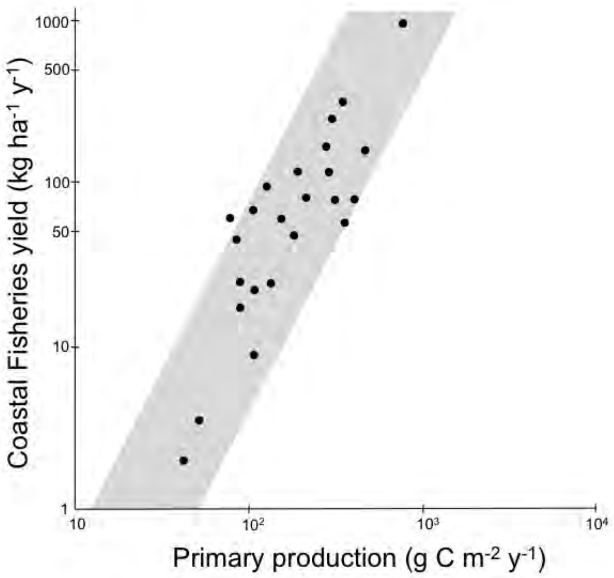


Figure 31: Relationship between aquatic primary productivity and fisheries' yields for a number of coastal systems worldwide. Source: redrawn from Day et al. *1989*

However, the effect of nutrients on coastal fisheries is influenced by a number of factors that modulate their role and impact (e.g. Hoeinghaus *et al.* 2011)**.** The presence of nutrients in water does not mean that they are systematically available for primary producers: nutrients can be temporarily adsorbed onto sediment particles or bound in refractory organic matter (Nagelkerken 2009), and this can blur the correlation between nutrient concentrations and catches. Nearshore production can also be partly driven by coastal upwellings, which are characterized by nutrient transfers from marine sediments carried upwards by currents. In the Ivory Coast, the floods coincide with the main upwelling season at sea, which has long obscurred the importance of continental inputs (Binet *et al.* 1995). In Morocco, sardine catches are higher during dry years because corresponding trade winds trigger stronger upwellings and higher nutrient inputs from marine sediments (Belvèze 1991). In Israel, phytoplankton blooms off the coast are usually associated with storm-induced turbulence (El-Sayed and Van Dijken 1995). However, in the case of the Mekong, the upwelling phenomenon might not play a major role, since the delta is located on the eastern side of Southeast Asia, while upwellings occur along the western coasts of continents. Also, primary production in tropical coastal systems is often limited by one nutrient in particular – either nitrogen or phosphorus – and this can also blur the overall correlation between yields and nutrient concentrations (Nagelkerken 2009).

A reduction in nutrient loads following sediment trapping behind dams leads to coastal fisheries yield depletion. Numerous cases of coastal oligotrophication and lower fish yields following dam construction have been documented. In Cuba, the reduction in sediment flows following a combination of river damming and reduced fertilizer use caused a dramatic decrease in the catches of estuarine species (Baisre and Arboleya 2006), while in Brazil, a cascade of dams on the Sao Francisco River trapped 95% of the suspended sediments, reduced nutrient concentrations in the river plume by 90%, and caused the estuary to become transparent, oligotrophic and unproductive (Knoppers *et al.* 2012). In Egypt, oligotrophication due to sediment trapping by the Aswan Dam had a catastrophic effect on coastal fisheries at the mouth of the Nile River, with annual sardine catches falling from 15,000 tonnes prior to the dam being built, to 550 tonnes afterwards. As a result, the overall fish catch declined by 75% between 1962 and 1969 (Aleem 1972, El-Sayed and Van Dijken 1995, Bebars *et al.* 1996).

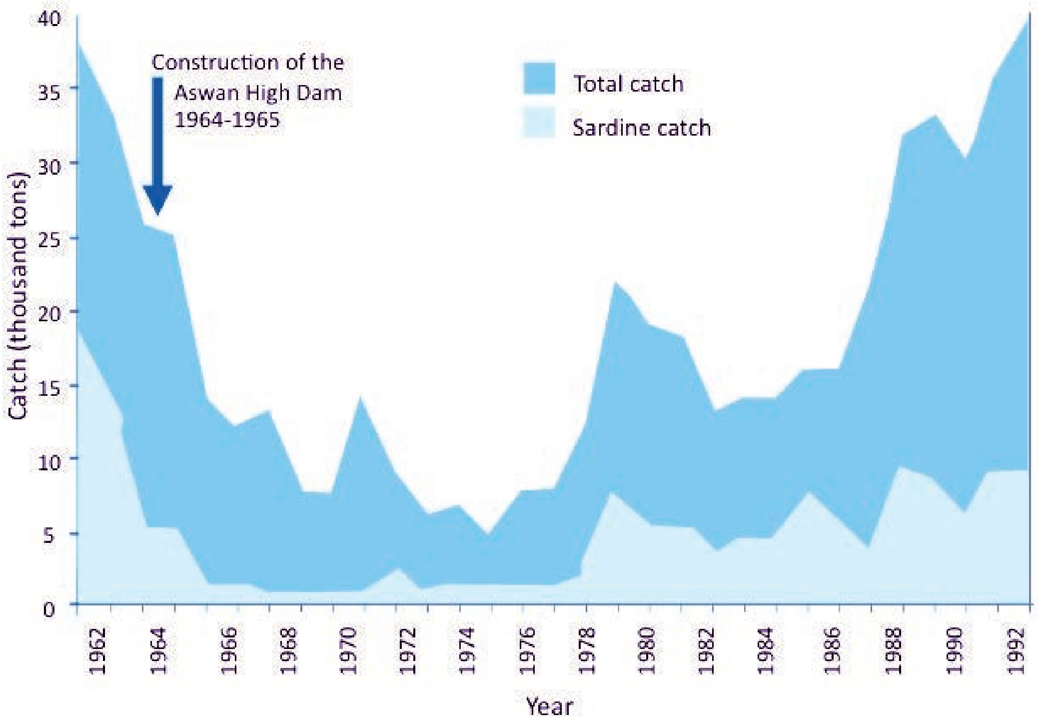


Figure 32: Catches in the Egyptian coastal fishery. Source: El-Sayed and Van Dijken 1995

Could anthropogenic effluents compensate for the loss of natural nutrient inputs?

There is strong evidence worldwide that anthropogenic effluents can stimulate coastal productivity and enhance fishery production in coastal ecosystems (Nixon and Buckley 2002). This appears to be the case, for example, with the Mississippi River (Grimes 2001). In Egypt, the coastal fishery recovery since the mid-1980s (Figure 32) coincides with large increases in fertilizer application along the Nile, and it was recently demonstrated using nitrogen isotopes (δ15N) that 60 to 100% of current fishery production may be from primary production stimulated by nutrients from fertilizer and sewage runoff from Cairo, a city of 16 million (Oczkowski and Nixon 2008, Oczkowski *et al.* 2009).

However, the anthropogenic influence on coastal productivity oscillates between enhancement and pollution. This means that increasing nutrient loads via agricultural fertilizers and sewage might initially increase ecosystem productivity up to a threshold, beyond which a decline is expected from eutrophication, algal blooms and hypoxia (Oczkowski and Nixon 2008). In the coming decades, the supply of agricultural fertilizers must also be considered in the context of the foreseeable global phosphorus supply crisis (Roberts and Stewart 2002, Vaccari 2009, Cordell *et al.* 2009, Rosemarin *et al.* 2009). Actually, the resilience of coastal production systems is still unclear; for example, 30 years after the completion of the Aswan Dam, the coastal ecosystem at the mouth of the Nile has not yet reached a new ecological equilibrium (El-Sayed and Van Dijken 1995).

The response of coastal ecosystems to river nutrient deprivation is complex and varies depending on local characteristics. Stratification, water depth and marine sediment inputs vary dramatically among systems, and there is no generic response of coastal fisheries to flow regulation and sediment load reduction (Howarth and Marino 2006, Oczkowski and Nixon 2008). For decades, the eutrophication (an excess of nutrients) of rivers and coastal zones was the main concern; however, oligotrophication (nutrient depletion) is now emerging as a new, global issue (Cozzi *et al.* 2012).

River flows also provide carbon inputs to the coastal zone, but the relative role of this riverine carbon versus that of coastal vegetation is unclear. It is largely recognized that riverine flows provide estuaries and coastal zones with carbon that is readily assimilated by primary and secondary consumers such as fish (Rose and Summers 1992, Houde and Rutherford 1993, Lane *et al.* 2004, Wissell and Fry 2005, Piazza and La Peyre 2007, Kimmerer *et al.* 2009). However, little evidence is available regarding the direct contribution of that terrestrial carbon to coastal food webs and the overall value of this riverine carbon subsidy (Loneragan and Bunn 1999, Piazza and La Peyre 2011). Along tropical coasts, this discussion is complemented with a debate about the role of mangroves, salt marshes and coastal vegetation as a source of carbon. The role of mangroves in supporting coastal fisheries is undisputed (reviews in Baran and Hambrey 1998, Kathiresan and Bingham 2001, Dugan *et al.* 2004), and numerous articles have agreed about the positive role of mangroves as a habitat (Robertson and Blaber 1992, Blaber 2002), but others have disputed the fact that these mangroves export organic matter to the coastal zone (Haines and Montague 1979, Peterson and Howarth 1987, Newell *et al.* 1995, Loneragan *et al.* 1997). Overall, it seems that mangroves do produce a lot of organic matter, but that the relationship between mangroves and coastal production is strongly modulated by coastal morphology and energy, which drives the export rate of that organic material (John and Lawson 1990, Baran 2001, Manson *et al.* 2005, Vorwerk and Froneman 2009, Blaber 2009, Bouillon and Connolly 2009).

4.3.4.2 The case of the Mekong

The Mekong River releases each year at least 16,000 to 17,000 tonnes of nutrients into the coastal zone. The MRC estimates that 225,000 tonnes of nitrogen and 37,000 tonnes of phosphorus are washed into the Mekong mainstream each year (MRC 2010). Liljeström *et al.* (2012) alternatively value this annual riverine nutrient flux at 288,000 tonnes of N and 55,000 tonnes of P. However, all these nutrients do not necessarily reach the sea, given the importance of deposition processes in extensive downstream floodplains. According to Ketelsen and Ward (2010), the Mekong River releases each year at least 16,000 to 17,000 tonnes of nutrients into the coastal zone, which results in the creation of an extensive turbid area extending as far as 400 km beyond the mouth of the river into the South China Sea, as shown by remote sensing turbidity measurements of the Mekong plume (Figure 33).

In Vietnam, coastal fisheries in the Mekong provinces yield 500,000 to 726,000 tonnes of fish per year. Baran (2010) reviewed coastal fisheries' statistics in the Vietnamese provinces adjacent to the Mekong plume, and found that the catch in these eight provinces grew from 312,000 tonnes in 1995 to 544,000 tonnes in 2007, and had reached 726,000 tonnes by 2009. This is actually an underestimate, since Mangin and Loisel (2012) have shown that the Mekong plume extends northwards to additional provinces in Vietnam (Ba Ria-Vung Tau and Binh Thuan provinces), and as far as Kampot and Sihanoukville provinces in Cambodia, so the coastal fisheries statistics of these provinces should also be included (Figure 34).

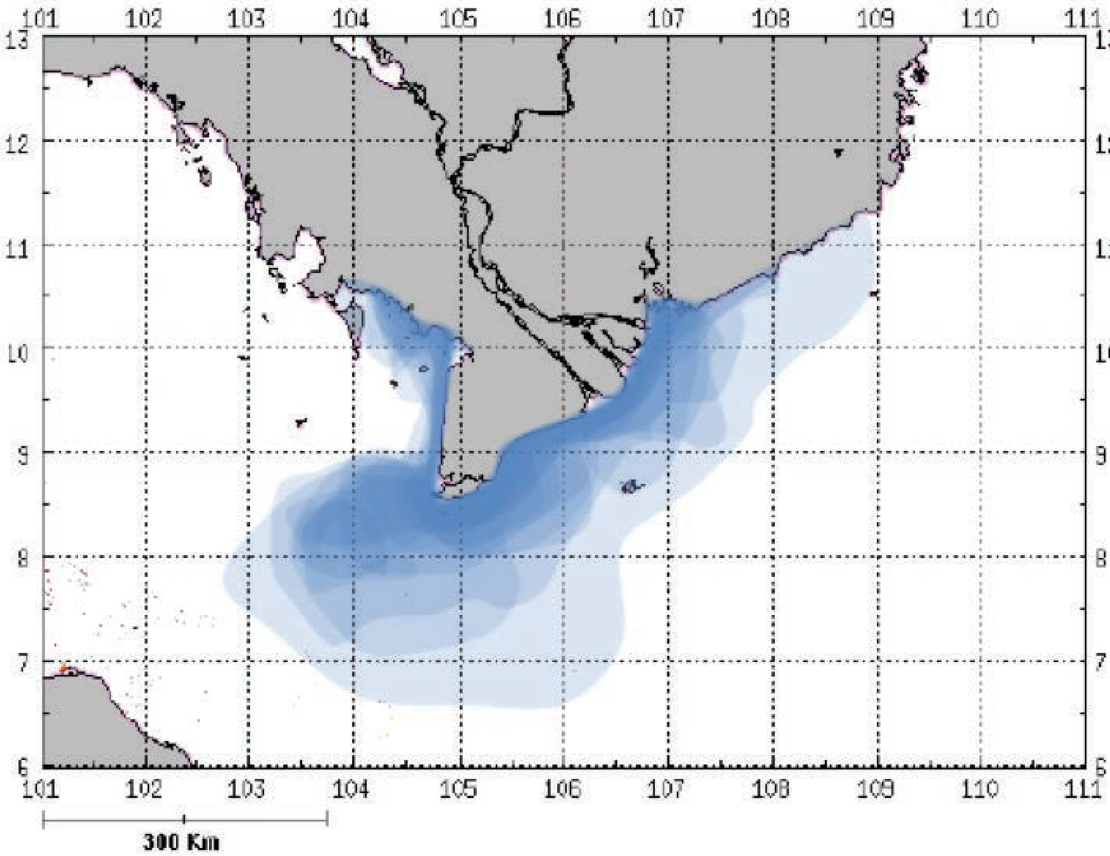


Figure 33: Annual extent of turbidity concentrations measured in the Mekong plume in 2005 - a representative, average year. Source: Mangin and Loisel 2012

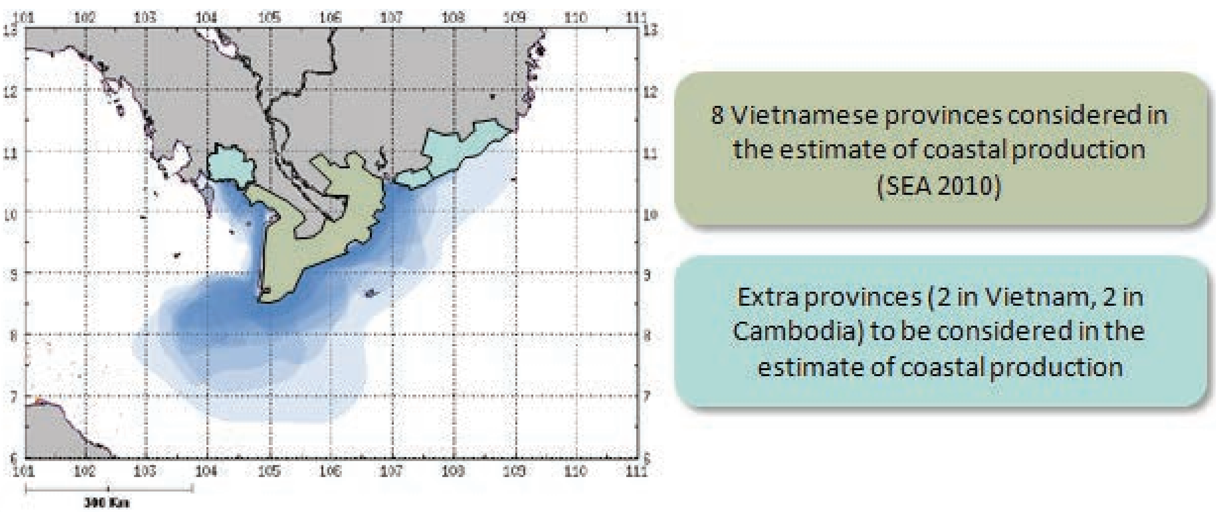


Figure 34: Area to be considered for any evaluation of coastal fisheries influenced by the Mekong discharge, based on the extent of the Mekong plume. Source: adapted from Mangin and Loisel 2012.

Currently, very little is known about the possible impact of reduced nutrient loads on coastal fish resources in Vietnam and Cambodia. Yoshimura *et al.* (2009) predict an increase of 13–25% in nutrient levels in the Mekong mainstream by the 2020s, but their model does not integrate nutrient retention by dams. Sarkkula and Koponen (2010) state that the main impact of sediment trapping will be felt in the Mekong Delta and at sea rather than in the Tonle Sap area, since the Tonle Sap receives five million tonnes of upstream sediments only, compared to 100 million tonnes that feed the Mekong plume in the South China Sea. Sediment/nutrient trapping will result in reduced turbidity at sea, but more specific studies are required to quantify the reduction in turbidity, in nutrient concentration and in surface area of the river plume. In economic terms, the sediment reduction would impact coastal fisheries as well as the aquaculture sector, which is dependent on the supply of protein from marine "trash-fish", which are used to feed high-value carnivorous farmed fish.

In the South China Sea, fish relying on the Mekong River's nutrients can be found as far as 500 km from the river's mouth (MRC 2003); however, the role of the terrestrial carbon outflow vis-à-vis the coastal system is not well known yet. Few studies so far have quantified the flow of carbon or nutrients from the river to the coastal zone (Voss *et al.* 2014, Li and Bush 2015), and none have assessed the possible reduction in carbon flows in the event of large-scale dam construction activity. The relative importance of this carbon input compared to that of effluents from coastal cities and of the (residual) mangrove forests also remains to be assessed.

A relationship between coastal fish production and Tonle Sap outflow—rather than Mekong outflow—was already pointed out 80 years ago. In the coastal zone of Vietnam, 68% of the fish species display ecological features linked to the coastal zone rather than to the ocean, in particular spawning grounds in shallow waters along the coastline (Vu 1997). In 1933, Chevey noted that "*a remarkable concentration of fish can be noticed at the mouths of the Bassac and Mekong Rivers […] at the beginning of the dry season […]. Their scales do, in fact, carry the very clear mark of a rhythm of acceleration and diminution of growth, when normally no rhythm should be marked on them in this particularly tropical region of the China Sea. It is to the enormous quantity of nitrogenous material in all forms brought down from the Great Lake of Cambodia that this bank of sea fish owes its temporary existence. The animals which compose it, attracted by the influx of nutrient material, migrate and concentrate there and their scales register the sharp acceleration of growth that results*". Interestingly, both Chevey (1933) and Nguyen (1995) note that it is in summer, at the time of the flood, that coastal fish disperse and their growth slows down, while the fast growth period is related to increased food abundance at the time of decreasing water levels; this relates nutrient abundance to the emptying

of the Tonle Sap rather than to the Mekong mainstream peak outflow. This phenomenon can also be related to the findings of Lu *et al.* (2014), who find that on a yearly average, the sediment load from the Tonle Sap contributes only 15% of the sediment flux to the delta, but its share reaches 58 to 88% during the December–April period. Chevey explicitly concludes that "*it is really by an induced influence that the Great Lake of Cambodia succeeds in imposing its rule and its rhythm on a distant population of the sea"*. This calls for a comparative analysis of the respective role of inorganic nutrients (from the runoff) and of organic matter (from flooded vegetation in particular) on fish production in the coastal zone.

The relationship between outflows and coastal productivity was later confirmed by Lagler (1976) who foresaw that "*the loss of nutrients, either dissolved or in organic silt, from the plume of the Mekong/Bassac will certainly diminish productivity in the nearshore areas and to a lesser extent in the off-shore areas*" but recognized that "*while the characteristics of the fishery are anticipated to change, little is known scientifically of the migratory patterns of fish to and from the plume*".

4.3.5 Coastal fish resources and fishing

4.3.5.1 Lessons learned from tropical coastal fisheries

Fish production in the coastal area is influenced by multiple factors whose relative influence cannot be easily distinguished. Along the coastal zone, the fish stock is influenced by physical dynamics (for example, hydro-dynamic convergence, water column stratification, transport and retention of fish larvae), chemical dynamics (such as nutrient fluxes, carbon inputs and turbidity), biological dynamics (including recruitment success and natural mortality) and human factors (fishing pressure and mortality) (Grimes 2001, Blaber 2002, 2009). We briefly review below the fishing factors that also influence or skew the correlation between sediment outflows and coastal fish production.

Sediment discharge/plume influence fish catchability. In the river plume, a higher fish yield can result from the higher productivity levels stimulated by nutrient inputs, but it also reflects the concentration of fish in certain areas – where they are more accessible to the fishery (Whitfield 1996, Loneragan and Bunn 1999). Conversely, in some coastal zones or estuaries where fish are concentrated in the dry season, river flushes result in reduced yields; this phenomenon being the consequence of lower fish catchability when fish migrate or get distributed over a larger area on the continental shelf (Cadwallader and Lawrence 1990, Lowenberg and Kunzel 1991, Binet *et al.* 1995).

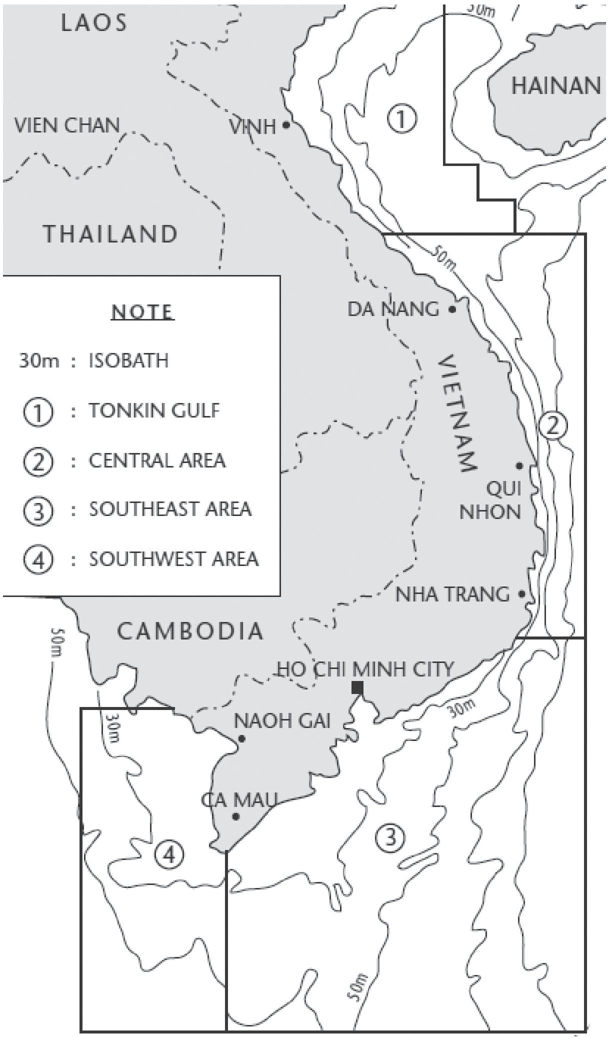


Figure 35: Exclusive Economic Zones (EEZs) around Vietnam. Sectors 3 and 4 correspond to the zone under the influence of the Mekong outflows. Source: Son and Thuoc 2003

Variable fishing effort blurs the correlation between sediment outflows and fish catches. Fish yields result from a combination of fish stocks, fish catchability and fishing pressure, with the latter parameter depending on several factors, such as the local technological level, access rights and market demand. Thus, the status of the fishery sector introduces a very significant bias in any assessment of the relationship between sediments/nutrient flows and coastal fish yields: increasing catches might reflect increased fishing effort rather than growing stocks, and conversely a decline in the fish stock might not be immediately visible, as in most cases it changes in inverse proportion to the fishing effort. In Egypt for instance, it is not clear whether the increasing fish catch off the coast since the late 1980's has been due to growing fish stocks or intensification of fishing efforts (El-Sayed and Van Dijken 1995, Bebars *et al.* 1996).

4.3.5.2 The case of the Mekong

Any study of the correlation between coastal fish catches and sediment outflows is hampered by fisheries data issues. In Vietnamese fisheries statistics, the South China Sea coastal fishing grounds under the Mekong's influence are not distinguished from other fishing grounds. If marine fisheries' catches are recorded by the marine sector at the commune level, then compiled at the district level at monthly intervals, they are later on aggregated at different administrative levels and thus, lose the original resolution necessary for biological research and management (Van Zwieten *et al.* 2002). Although it is acknowledged that most pelagic stocks are found off the coasts of southeast and central Vietnam (Nguyen 1995, Vinh and Thu 1997) in a zone under the influence of the Mekong plume, we could not find published information with a higher resolution than the two Exclusive Economic Zones (EEZ) 3 and 4 around the Ca Mau peninsula (Figure 35). Nguyen (1995) published more detailed maps of fish catches per coastal sector in the dry and wet seasons, but data at the mouth of the Mekong are missing for the dry season, which prevents pattern interpretation.

The most accessible time series about fish yields is that of the ADB/WorldFish TrawlBase project. The results presented by Son and Thuoc (2003) were actually compiled during the TrawlBase project (http://trawlbase.worldfishcenter.org; Silvestre *et al.* 2003). Vietnam data cover the 1977 to 1995 period, but accessing them for new analyses in relation to sediment loads during the same period would require the agreement of the Vietnamese line agencies in charge. Nguyen (1995) details the multiple biological research and monitoring programs implemented in this zone prior to 1977 (1959-1962, 1963-1968 and 1968-1973) but data are not readily accessible. More recently, Van Zwieten *et al.* (2002) detailed the statistical collection system for coastal fisheries in Vietnam, and highlighted the intricacies and pitfalls of that system – in which catches and fishing effort are recorded independently by different agencies. An extensive literature search surprisingly harvested no recent publications in English about coastal fisheries in Vietnam.

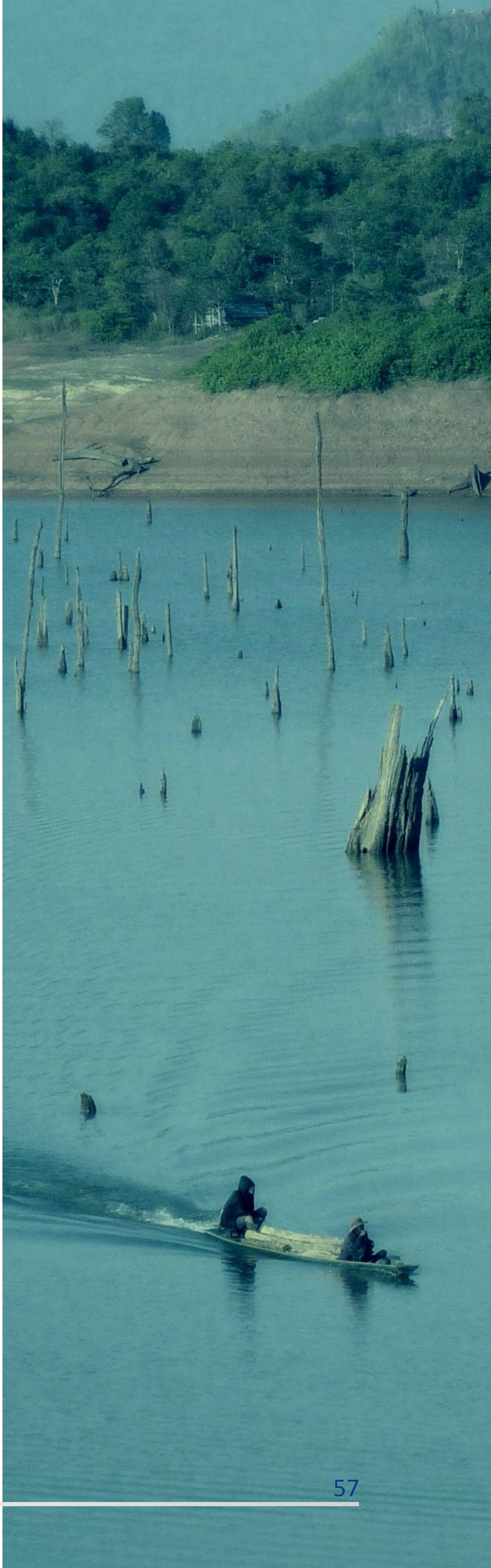
Any assessment of the relationship between sediment outflows and fish catches would absolutely require fishing effort to be factored in. Between 1981 and 1999 in southern Vietnam, marine capture fisheries' production levels increased three-fold, but the fishing pressure (expressed as total horsepower) increased more than five-fold (Son and Thuoc 2003). The overfishing of Vietnamese coastal waters mentioned by Stobutzki *et al.* (2006), and the subsequent changes in fish sizes and species composition that have taken place, have introduced further bias into that relationship.

4.4 Conclusion

We reviewed in the previous chapters the components of sediments, the ecological connections between fish and sediments and the relationships between sediment loads and fisheries production in tropical rivers in general and in the Mekong in particular.

In the present chapter we reviewed the current level of knowledge about the Mekong fish production, as well as the influence of sediment loads on fish resources in the Mekong's floodplains and in the coastal waters of Vietnam, taking into account the experiences gained from other river systems around the world. In particular, we looked at the influence of sediment trapping by dams and the influence of the river's discharge on coastal fisheries production.

In the next, concluding chapter, we will summarize the main findings of this book by first describing the most influential sub-basins and as a result, identify the most influential dams from a fish production perspective. Drawing from Chapter 3, we will then review the most important drivers of the fish production, of which sediments are only a part, and the links between sediment load and fish production. At the end, we draw all these elements together by proposing a comprehensive model to be used for any future assessment of the impacts of changes in sediment loads on Mekong fisheries.



5

SEDIMENTS, FISH PRODUCTION AND THE WAY FORWARD

5.1 Ecological zones from a fish yield perspective

Three main fish production zones can be distinguished in the Mekong. From a fish yield perspective and given the current level of knowledge of fish production, of habitats distribution and the resolution of sediment-related data, we believe a detailed study of the relationship between sediments and fish production in the Mekong should focus on three main ecological zones (Figure 36):

- ***The nearshore zone*** – corresponding to the coastal area of the South China Sea influenced by the Mekong discharge, i.e. the Mekong plume;

- ***The downstream zone*** – including all the floodplains (Mekong Delta, Cambodian lowlands and Tonle Sap) and ending upstream at the Khone Falls at the border between Cambodia and Lao PDR, and

- ***The upstream zone*** – corresponding to the Mekong River section between the Khone Falls and the source.

The coastal zone is part of the Mekong fish production area, and the section from Tibet to Khone Falls can be considered a single zone. This zoning system reflects to a large extent, the fish migration zoning proposed by Poulsen *et al.* (2002b) and the MRCs ecological zones (MRC 2005), but differs from all previous zoning attempts due to:

- the inclusion of a coastal zone as a part of the Mekong area of influence, and
- the inclusion of one single upstream zone from the Khone Falls to the Mekong source. This reflects: i) the fact that the upper limit of the Lower Mekong (i.e. the Chinese border) is a political and administrative boundary, but not a hydrological or ecological one; ii) the findings of Kang e*t al.* (2009 a, b) regarding the similarity in Lower and Upper Mekong fish faunas up to Jinglinqiao; iii) the fact that the Lancang section of the Mekong does not feature any significant fishery nor significant contributions of migratory species to Lower Mekong fisheries; and iv) the fact that the Vientiane to Khone Falls section produces around one million tonnes of fish a year, while the Chinese section of the Mekong generates only 60,000 tonnes per year, and so does not justify being a special case from a fish production perspective.

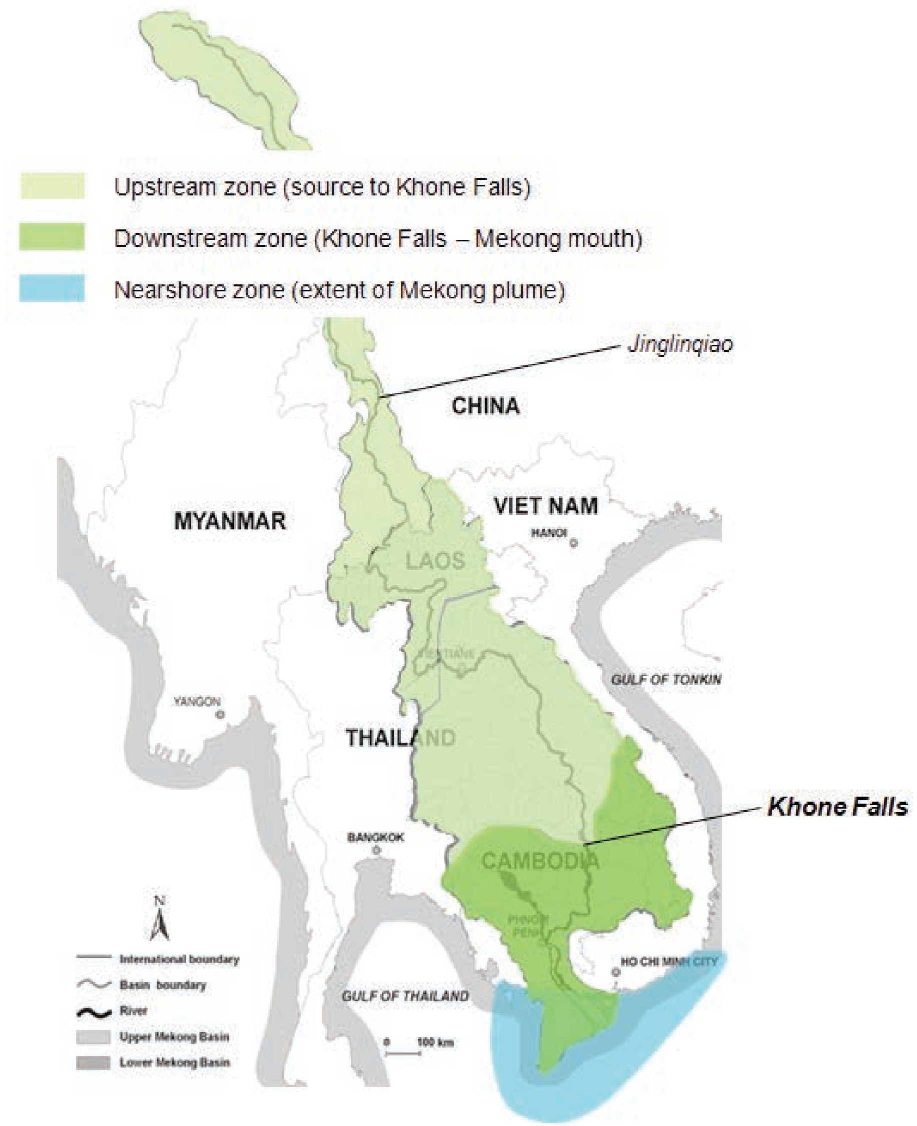


Figure 36: The three zones proposed for studying the relationship between sediments and fish production

5.2 Most significant Mekong sub-basins

The Srepok, Sesan, Sekong, Mun/Chi and Lao PDR tributaries, and the Upper Mekong itself, are the most significant sub-basins or sections from a fisheries sustainability perspective. To our knowledge, only one published study has tried to assess the relative importance of the different Mekong sub-basins for sustainable fish production[9]. Ziv *et al.* (2012) compiled 70 lists of fish species in 23 sub-basins or mainstream segments, and modeled the carrying capacity of migratory fish in each sub-basin (Figure 37).

This approach, aimed at forecasting the impact of dams on tributaries, highlights the biological importance of:

- The 3S area, which includes the Srepok, Sesan and Srepok Basins and is very rich in biodiversity (Baran *et al.* 2014);
- The Mun/Chi sub-basin, which is rich in biodiversity and also the largest Mekong sub-basin (Poulsen *et al.* 2002b, Baran 2010). This watershed represents the Thai part of the Lower Mekong Basin but is already heavily blocked by multiple irrigation dams;
- The multiple Lao PDR tributaries, which are used as breeding sites by a number of migratory species which then feed in the lowlands (Poulsen *et al.* 2002b); these can be collectively referred to as the Lao PDR sub-basins, and
- The upstream Mekong in Yunnan province, China, which is characterized by insignificant fish production levels, but has a cascade of large dams and so plays an important role in terms of sediment supply and sediment retention (Plinston and He 1999, Kummu and Varis 2007, Zhai *et al.* 2010).

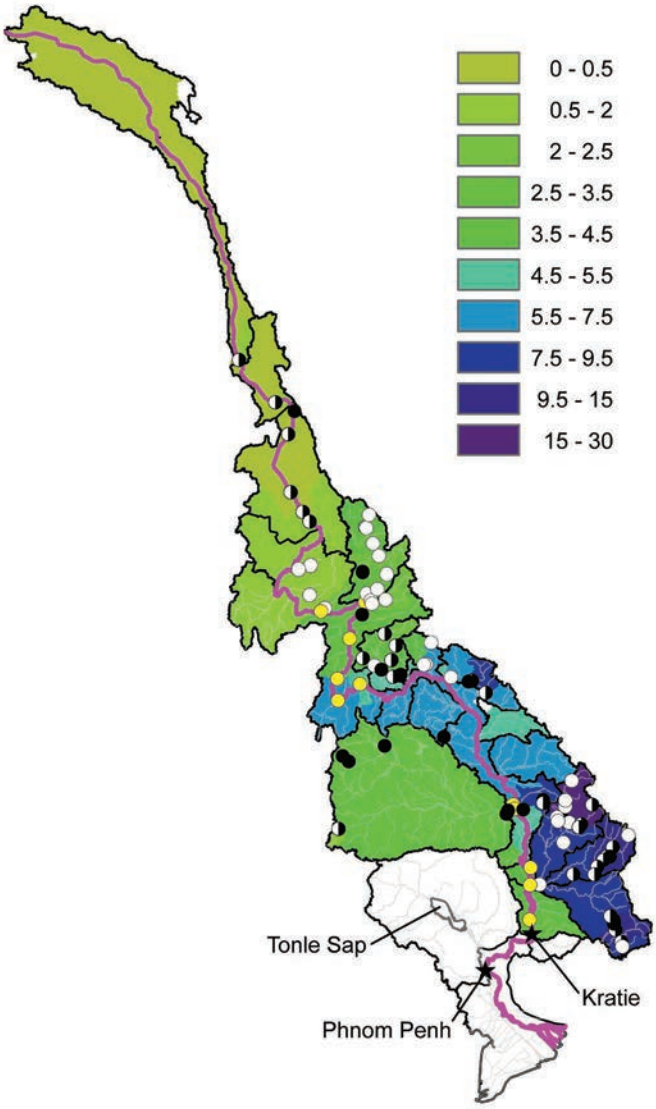


Figure 37: Dry-season carrying capacity of Mekong sub-basins for migratory fishes. Darker blue colors indicate a higher carrying capacity in migratory fishes; units are arbitrary and only reflect proportions. Source: redrawn from Ziv et al. *2012*

[9] The results of the MRC IBFM (Integrated Basin Flow Management) project and the details of the BDP works on the significance of tributaries have never been publicly released.

Figure 38 below shows the most significant sub-basins in fish generation terms (see Figure 11 on page 17) and their links to the key fish yield zones.

Figure 38: Most significant sub-basins/watersheds for fish generation purposes, and key fish yield zones

5.3 Most influential dams

From a fish perspective, the dams having most impact basinwide are the Lower Sesan 2, Stung Treng and Sambor Dams. The impact of a given dam on fish resources depends, not only on the characteristics of the dam, but also its location and the ecological significance of the tributary river it is built on. Recent analyses (Wild and Loucks 2014a, 2014b; Kondolf *et al.* 2014; Rubin *et al.* 2015) show that the 3S (the Srepok, Sesan and Sekong Rivers) are among the top five rivers for their contribution to the sediment load of the Lower Mekong Basin, the latter influencing the fish production basinwide (Figure 39).

A number of studies have also identified the Mekong mainstream between Khone Falls and Kratie as being an important fish migration corridor linking downstream feeding zones and upstream breeding sites (Sao and Dom 1955, Roberts and Baird 1995, Poulsen *et al.* 2002b, Timmins 2006, Bezuijen *et al.* 2008). The most influential dams along these ecologically significant river stretches are detailed below:

- ***Lower Sesan 2 Dam (LSS2):*** located just downstream of the confluence between the Sesan and Srepok rivers. This dam alone will alter 16.4% of the sediment flow (Thomas 2012) and 9.3% of the fish biomass (Ziv *et al.* 2012) of the Lower Mekong Basin;

- ***Stung Treng Dam:*** located just upstream of the Mekong's confluence with the 3S rivers, this mainstream dam will block access to 646,000 km^2 (79.9%) of the Mekong Basin for migratory fish present in lowland floodplains in the wet season (Baran 2010), and will alter sediment flows within sub-basins that contribute at least 39.9% of the total sediment load in the Lower Mekong Basin. However, this dam will not alter fish migrations and sediment flows from the 3S sub-basins; and

- ***Sambor Dam:*** located on the mainstream near Kratie, downstream of the 3S rivers confluence, the Sambor Dam will block access of migratory fish to 81.3% of the Mekong Basin (potentially impacting 37% of the Mekong fish biomass), and will also alter the sediment flows in sub-basins, which contribute at least 66.2% of the total Lower Meking Basin sediment load.

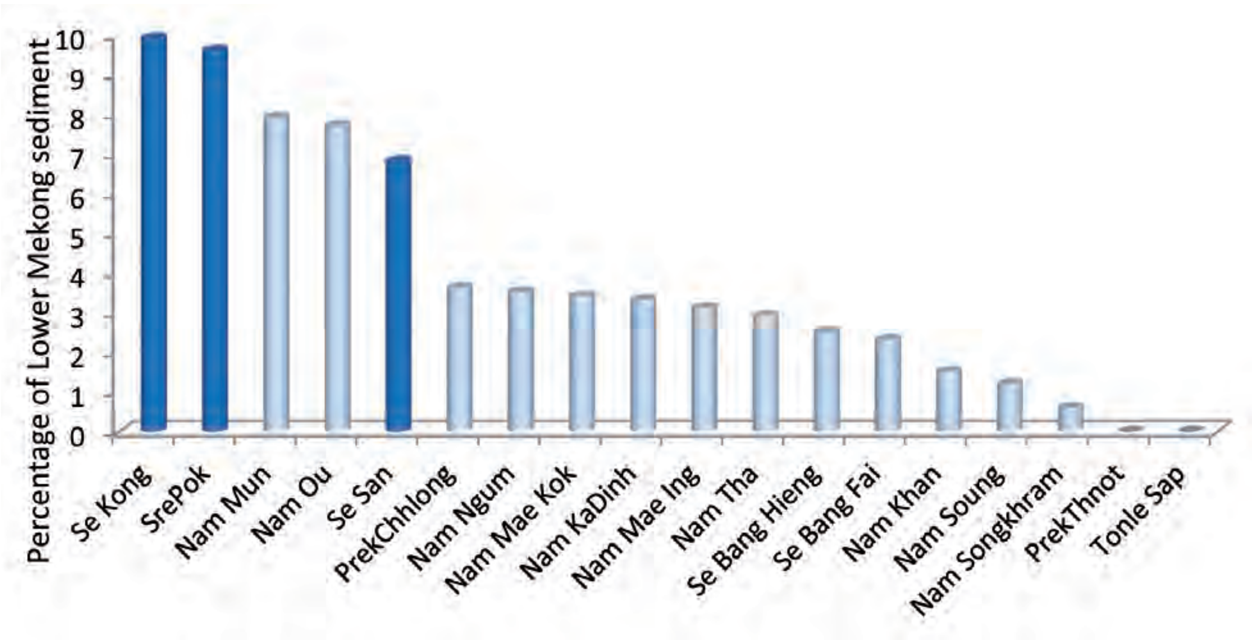


Figure 39: Contribution (in percentage) of Lower Mekong sub-basins to the sediment load in the Lower Mekong Basin. Source: Thomas 2012

Thus, an analysis of the combined influence of these dams and others on sediment loads and fish resources should initially focus on the components of the system whose role or influence is clear and distinct, including in particular: (i) the upper Mekong, the Mun/Chi River, all of Lao PDR tributaries and the Srepok, Sesan and Sekong Rivers, and (ii) the Lower Sesan 2, Stung Treng and Sambor Dams (Figure 40).

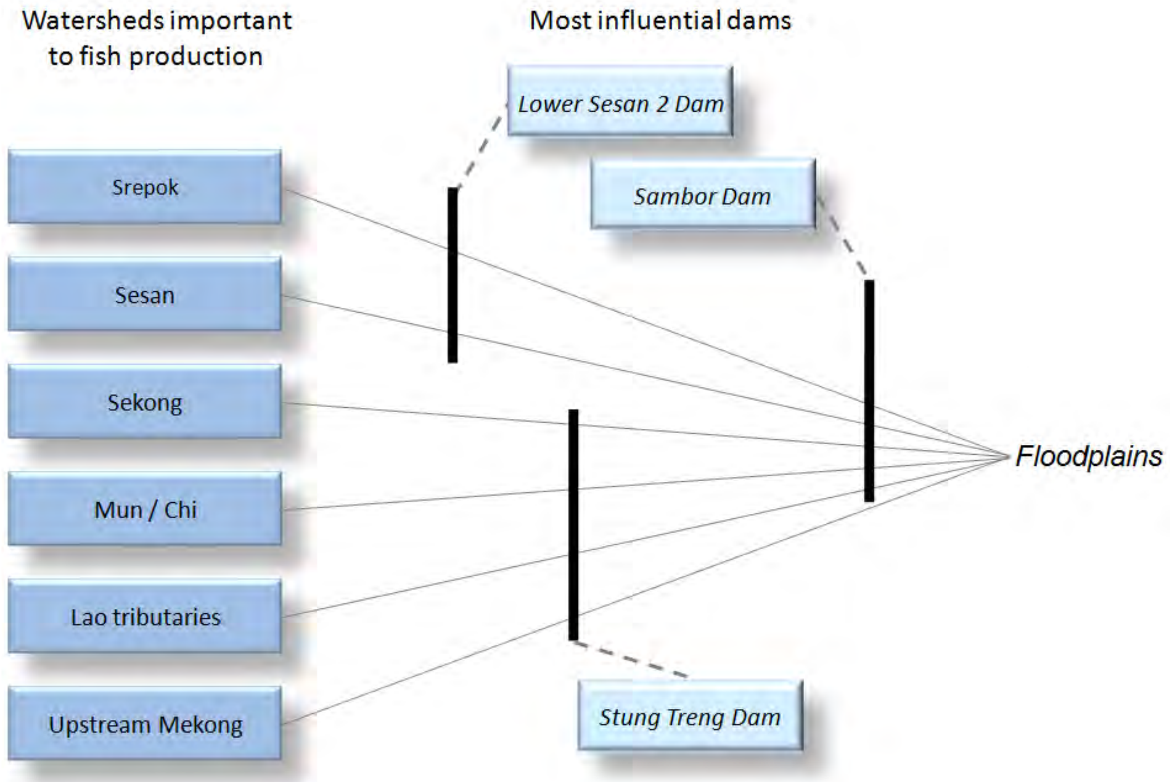


Figure 40: Key sub-basins for fish production and dams with the greatest impact on fish

5.4 Most significant factors and drivers

Overall, fish production in the Mekong is a multi-factor phenomenon and is not related to sediments alone. It is clear that dam developments will reduce the downstream sediment concentrations, but a change in sediment loads is only one among several dam-related factors which can affect fish resources. Dams reduce downstream sediment and nutrient loads, which in turn alter the river's geomorphology, habitats and productivity, but will also reduce the flood pulse, alter water quality and obstruct fish migrations (McCartney *et al.* 2000, Marmulla 2001). Thus, nutrient loads, the flood pulse, fish migrations and water quality can be considered the four most important factors influencing fish production in tropical systems (Junk 1999, Welcomme 2001, Arthington *et al.* 2004 and Figure 41).

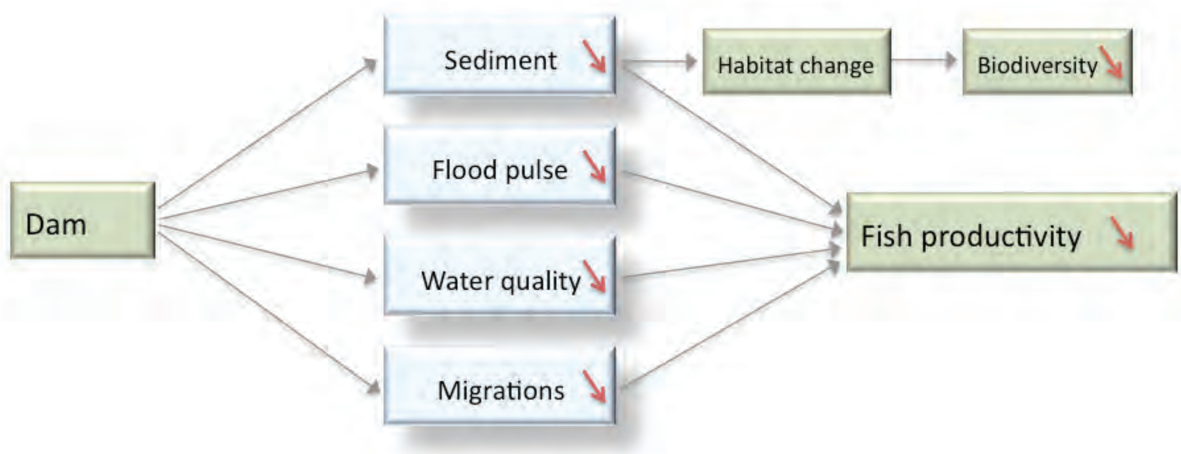


Figure 41: Relationship between dams, environmental or biological drivers and fish productivity

Mekong fish resources are also influenced by sand extraction and fertilizers used in agriculture. Furthermore, dams are not the only anthropic factor influencing Mekong fish resources – other factors include:

- *Massive sand extraction* – estimated to reach 27 million m^3 or 43 million tonnes a year (Bravard and Goichot 2012b); this will modify the riverbed and riverine habitats;

- *Cities and urban effluents*, which negatively influence water quality and aquatic biodiversity (but not necessarily fish productivity), in particular downstream of large cities such as Siem Reap and Phnom Penh, and in the delta (150,000 to 170,000 tonnes of organic effluents are discharged annually from urban areas; MRC 2008);

- *Agricultural developments* in the Mekong Basin result in the intensive use of fertilizers (e.g. 378 kilos of NPK - nitrogen, phosphorus, potassium - per hectare per year on average in the delta from 2 million hectares of rice fields; Huan *et al.* 2005) with these nutrients partly contributing to the nutrient load of the Mekong's flows (225,000 tonnes of nitrogen and 37,000 tonnes of phosphorus from agricultural fertilizer run-off into the Mekong River each year; MRC 2008). Liljeström (2007) shows that in the Mekong, most nutrients of agricultural origin come from the highlands and from the delta in Vietnam, from China, and to a lesser extent from the Issan region in Thailand.

Thus, a number of interactions take place between the multiple drivers of fish production, as shown in Figure 42.

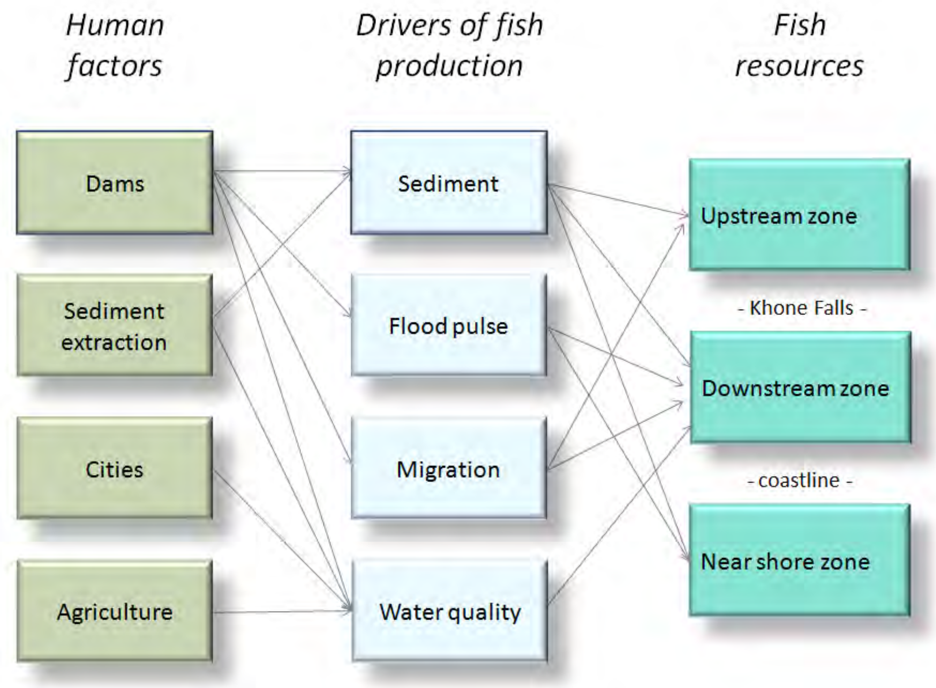


Figure 42: Key factors influencing fish resources in the focus zones. The two boxes with a black frame reflect the focus of the present review - dams and sediments; the other boxes correspond to factors which also influence fish production in the three main focus zones

5.5 From dams to fish yields

Having discussed the relationship between sediments and fish in general, here we discuss the relationship between sediments and fishery production.

5.5.1 Sediments, fish stocks, fishing and fish production

Assessing fish production through fish yield is complicated because of varying fishing intensity. In the absence of any detailed assessment of Mekong fish stocks, the relationship between sediments and fish production needs to be assessed using fish yields as a proxy for fish production. However, the variability of fishing intensity introduces a substantial bias in the relationship (example in Castello *et al.* 2015). As detailed in the previous chapters, sediment and nutrient loads influence several biological functions among fish, nutrition and growth being the most obvious ones. This in turn drives the fish stock, i.e. the biomass of fish in water. That biomass is extracted thanks to the fishing sector, whose effort and efficiency can substantially vary over time. It is the combination of fish stock and fishing that generate fish production, in other words the fish biomass measured at landing sites or at markets (Figure 43). Any future assessments of the relationship between sediments and Mekong fish production will have to focus on these descriptors of fishery yields.

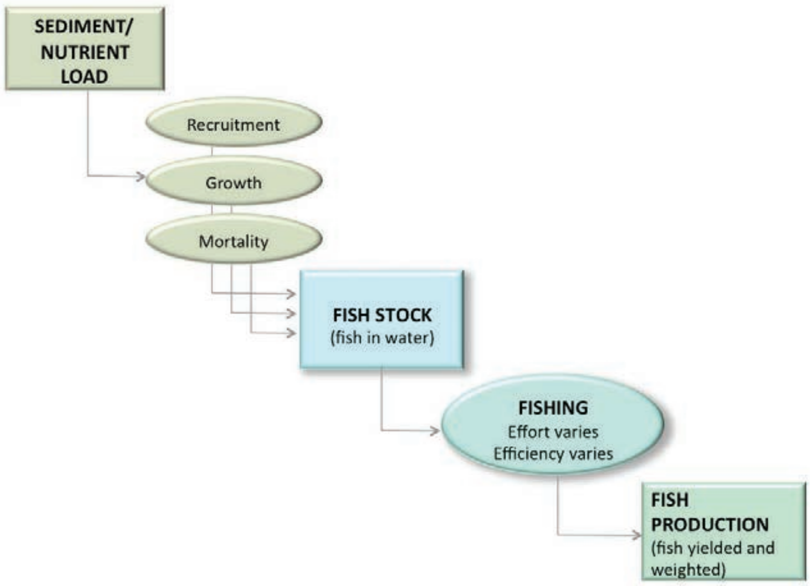


Figure 43: Fish resources, biological components and data availability

5.5.2 Weak links between sediment load and fish production

Fish recruitment, growth and mortality: **the lack of knowledge about fish recruitment, growth and mortality weakens the assessment of the relationship between sediment load and fish production.** Without entering into detailed fishery biology, one can consider that at a given time, the size of the fish stock depends on the birth rate (recruitment), on the development of individuals (growth) and on the death rate (mortality) in the fish population. We detail what is known in the Mekong about these parameters:

- *Fish recruitment:* with more than 781 fish species identified but quasi-undocumented in terms of their recruitment dynamics, and more than 100 long-distance migrants – representing almost 40% of the total yield – having recruitment areas that are geographically disconnected from their main feeding and growth zones, fish recruitment in the Mekong Basin can be considered unknown.

- *Fish growth:* the growth of some native species cultured in ponds or cages is documented, but in general, little is known about the growth of Mekong fish species in the wild, which is most probably dependent on nutrient loads and on the flood pulse.

- *Fish mortality:* this parameter is a combination of natural mortality (unknown) and man-driven mortality due to fishing and environmental changes (e.g. pollution in floodplains, mortality at dam passages, etc,). Fish mortality is the only component for which a loose proxy exists (i.e. fish catch data).

Fishing effort and Fishing efficiency: **the variability in fishing effort and efficiency is not known.** Two important factors influencing the yield (or fish production) of the fishing fleet are the fishing effort and the fishing efficiency:

- *Fishing effort* represents a combination of the number of fishing boats present in an area, the surface area of the nets used and the time spent using each type of gear. Neither the amount of gear nor the time spent fishing so far has been monitored in the Mekong.

- *Fishing efficiency* is a complex factor that is permanently evolving thanks to new technologies aimed at maximizing catches. This is illustrated by the spread in Vietnam, among coastal fishing boats, of sonar systems used to locate fish shoals, or the use of electrified bottom chains increasing the catch of bottom fish in the Tonle Sap trawl fishery. A boat newly equipped with such devices will harvest more fish, even though its recorded fishing effort (e.g. gear category and time spent fishing) will not have changed. Fishing efficiency in the Mekong has never been studied or monitored.

Fish production figures: **fisheries' yield is not a good proxy for the fish stock.** In the Mekong, the lack of an extensive and long-term monitoring program prevents an assessment of the annual variability of the fish production (see sections 4.1 and 4.3.5.2); furthermore, the fish catch is not an accurate proxy for the fish stock, for two main reasons:

- The catch results from a combination of the fish stock and fishing intensity; an increase in fish yields may reflect a change in fishing activities rather than in the stock, such that the overall catch can keep growing while the stock decreases (case of early overfishing). In fact, fishing effort has never been quantified in the Mekong, resulting in an under-valuation of the fish stock in areas of low fishing pressure, such as in Lao PDR.

- As described previously (Figure 11, page 17), there is a disconnect for long-distance migratory fish between upstream breeding zones – where juveniles are created but not caught – and downstream feeding zones – where adults are caught but not created. Thus, an estimate of the standing stock per zone based on catch data would result in an undervaluation of the ecological role of upstream breeding zones in the sustainability of overall production levels.

- In conclusion, the current absence of information on fisheries descriptors, or on biological parameters for the Mekong fish populations, does not allow a characterization of fish production levels to take place, which poses a significant challenge to the assessment of the relationship between Mekong fish production and changes in sediment loads.

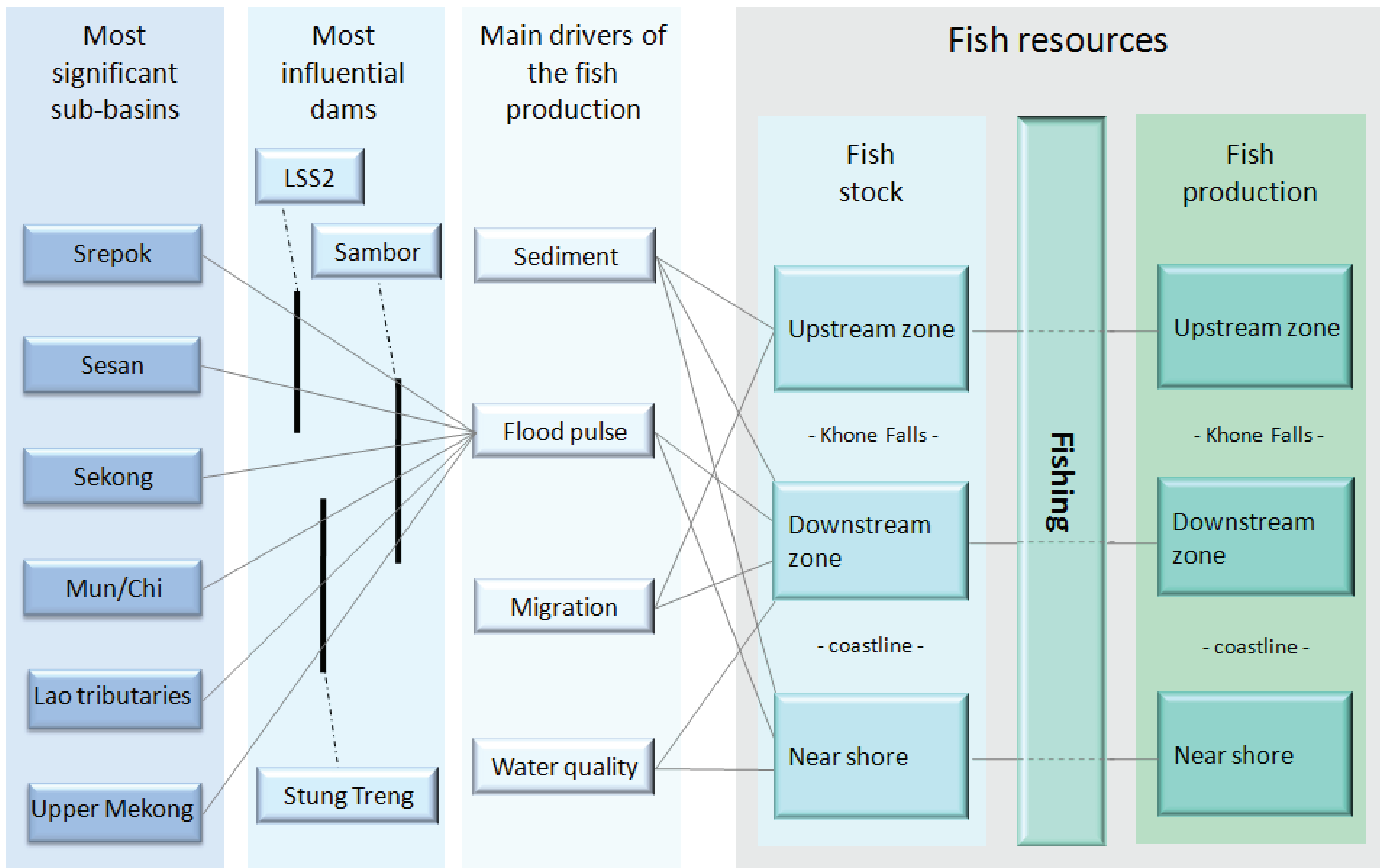


Figure 44: Conceptual model for an assessment of the impacts on fish of sediment changes due to dam construction activities

5.6 Putting the parts together

In light of the elements described above, we recommend that in order to fully assess the impacts of dam construction activities on sediment loads in the Lower Mekong Basin, and subsequently on fisheries, the framework outlined in Figure 44 be used as the basis of any research activities.

In the nearshore zone, fish resources depend on sediment loads, the flood pulse and water quality, and on the relationships between these factors, which have been reviewed in section 4.3. Sediment loads determine nutrient inputs into the coastal zone, as well as the turbidity of the plume. The influence of river floods on coastal fish production has been clearly established, with both volumes and flood dynamics being important, and this means that flood regulation by dams will definitely have an impact on coastal fish resources. Further to this, water quality is mainly dependent on the input of organic matter from cities and fertilizers from agriculture; however, fish migrations are not considered quantitatively important in this zone, and will not be significantly affected by upstream dams.

In the downstream zone of the Mekong Basin, fish resources depend mainly on sediment loads, the flood pulse, migrations and water quality. As described in Chapter 4, the flood pulse plays a major role in floodplain productivity, and river discharge regulation by dams is expected to change the timing and intensity of the flood – impacting floodplain productivity. In this zone, sediments also contribute to the exceptional productivity of the floodplain system. Migration is another important aspect of the fish resources in this zone, and dams will largely block the transfer of long-distance migratory fish between this downstream zone where they feed, and the upstream zones where they breed (at least 37% of the Mekong fish biomass will be affected by this alone). In the absence of substantial pollution in this zone, water quality refers mainly to dam effluents and agricultural fertilizer outflows.

In the upstream parts of the Mekong Basin, fish resources depend mainly on sediment loads and migrations, while the influence of the riverine flood pulse is less pronounced than in the floodplains and coastal areas. Sediment loads become all the more important here and determine nutrient inputs into the food web. As a result, dam construction activities will also affect fish migrations here, though water quality will be more of an issue downstream of this zone.

In all zones, an assessment of the fishing effort is required in order to relate fish catches to fish stocks before the latter can be related to fish production drivers, including sediments. The impact in the three focus zones will also depend on which of the three most influential dams (i.e. the Sambor, Stung Treng, Lower Sesan 2) are built, and subsequently which of the six most significant areas (i.e. the Upper Mekong, the Mun/Chi sub-basin, the Lao PDR tributaries, the Srepok, Sesan and Sekong sub-basins) are disconnected from the downstream floodplains.

Overall, dams are likely to impact fish resources in a number of ways that will not be related to sediments only, and damming is just one among several human activities that impact fish resources. Assessing the impact of changes in sediment load on Mekong fish production levels will require the quantification and integration of the majority of these factors, before an assessment of the relative role of sediments can be made.

6

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