Chapter

What Is the Future of the Lower Mekong Basin Struggling against Human Activities? A Review

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Abstract

The Mekong River (MR) is recognized the 12th biggest rivers in the world. The Mekong watershed is the biggest one in Southeast Asia (795,000 km^2), is densely populated (70 million people), is considered as the most productive one in Southeast Asia and is economically essential to the region. However, nowadays, the Lower Mekong River (LMR) and its delta are facing several emerging and critical anthropogenic stressors (dams construction, climate change, water poor quality, delta sinking). This review attempts to: (i) present the Mekong regional characteristics (geography, topological settings, climatic conditions, hydrology, demographic features and the anthropogenic activities), (ii) present the different factors that endanger the LMR, including the dam's impacts, the climate change, the delta subsidence, and the degradation of the water quality, (iii) make comparison with different big rivers around the world and (iv) promote future decisions in order to minimize the negative impacts and seek for a trajectory that assures well-being and sustainability. International consultation and cooperation leading to sustainable management is now of a pivotal importance to try to avoid the deterioration of the LMR and its delta.

Keywords: Mekong River, Mekong delta, dams, climate-change, delta sinking

1. Introduction

Rivers and deltas are highly populated areas and their ecosystems are highly vulnerable. Most of the deltas on earth are nowadays severely degraded due to anthropogenic activities [1]. Man-made delta degradation, in consequence, affects the livelihood of millions of people [2].

The Mekong River (MR) is known as one of the 32 largest river on earth [3], flowing through the largest watershed in Southeast Asia (795,000 km^2) and crossing six different countries (China, Lao PDR, Myanmar, Thailand, Lao PDR, Cambodia and Vietnam) (Mekong River Commission (MRC) [4]). This basin is densely populated with around 72 million inhabitants and it is about 52,000 km^2 [5]. The economy of the region and its population have been highly growing in the last decades, with an exponential need for electricity in China, Thailand and in Vietnam [6]. The Mekong watershed is very productive with a lot of aquatic economic activities [7], providing livelihoods for most of its population [8]. Along the Mekong Basin (MB), more than 60 million people are dependent of the natural resources [9]. This important productivity is mainly due to the natural hydrological cycle with an important flood pulse occurring during the monsoon season (from July to September). The large Cambodian floodplain and particularly the Tonle Sap Lake (TSL) is a highly productive ecosystem because of the sediments brought by the important flood pulse during the monsoon [7] and a reversed flow during the dry season.

However, the Mekong River is now threatened by different anthropogenic stressors and some considerable changes deeply affected the region over the last decades. Land use change, water infrastructures and regional climate changes are ongoing factors that affect the natural functioning of the basin and its population [10]. At the downstream ending of the Mekong River, the 20 million inhabitants are now threatened by the surrounding sea level rise (rising sea level and land subsidence) [11–13].

This chapter aims to answer the following questions: (i) What are the different stressors that threaten the MB? How these stressors evolve spatially and temporally? (iii) What are the future directions needed to minimize the different damages?

To answer the different research questions, the chapter will be articulated in different sections:

- Introduction of the Mekong regional characteristics
- Presentation and discussion of the different issues that the MR and its delta are facing to
- Comparison of the different stressors with different big rivers in the world
- identification of some future directions that should be taken in order to minimize damages even if some changes will not be recoverable (tipping point) for a sustainable water management and the research procedure that could adequately accompany these scenarios.

2. Mekong regional settings

2.1 Physical features

The Mekong Basin is the largest one in Southeast Asia (795,000 km^2), covering six countries (China, Laos, Myanmar, Thailand, Cambodia and Vietnam) [14]. **Figure 1** and **Table 1** of this paper present the main features of the Mekong Basin. The MR is 4800 km long (12th longest in the world), discharges 475 km^3 yr.$^{-1}$ of water (8th largest), and discharges 160 * 106 tons yr.$^{-1}$ of sediments (10th largest sediment load in the world) [16]. The Tibetan Plateau signs the start of the Mekong's journey, at an altitude of 4970 meters. There, the river flows through the Chinese provinces (Qinghai and Yunnan) which are a very steep topography. Across 2000 km, the average slope is 2 m km^{-1}. Then, the river marks the border between Myanmar and Lao PDR. In Laos and Thailand, less mountainous regions tuck the river. The Mekong Basin is usually divided into upper and lower parts where the geographical boundary is at Chiang Sean in Thailand [17]. Downstream Chiang Sean, the slope is moderated with an average of 0.25 m km^{-1}. The Khone waterfalls in Laos' Champasak province, the only waterfalls of the Mekong River mark the beginning of the Mekong's plains. Finally, the Mekong spills in the Cambodian and Vietnamese floodplains and ends its course into the East Sea [4].

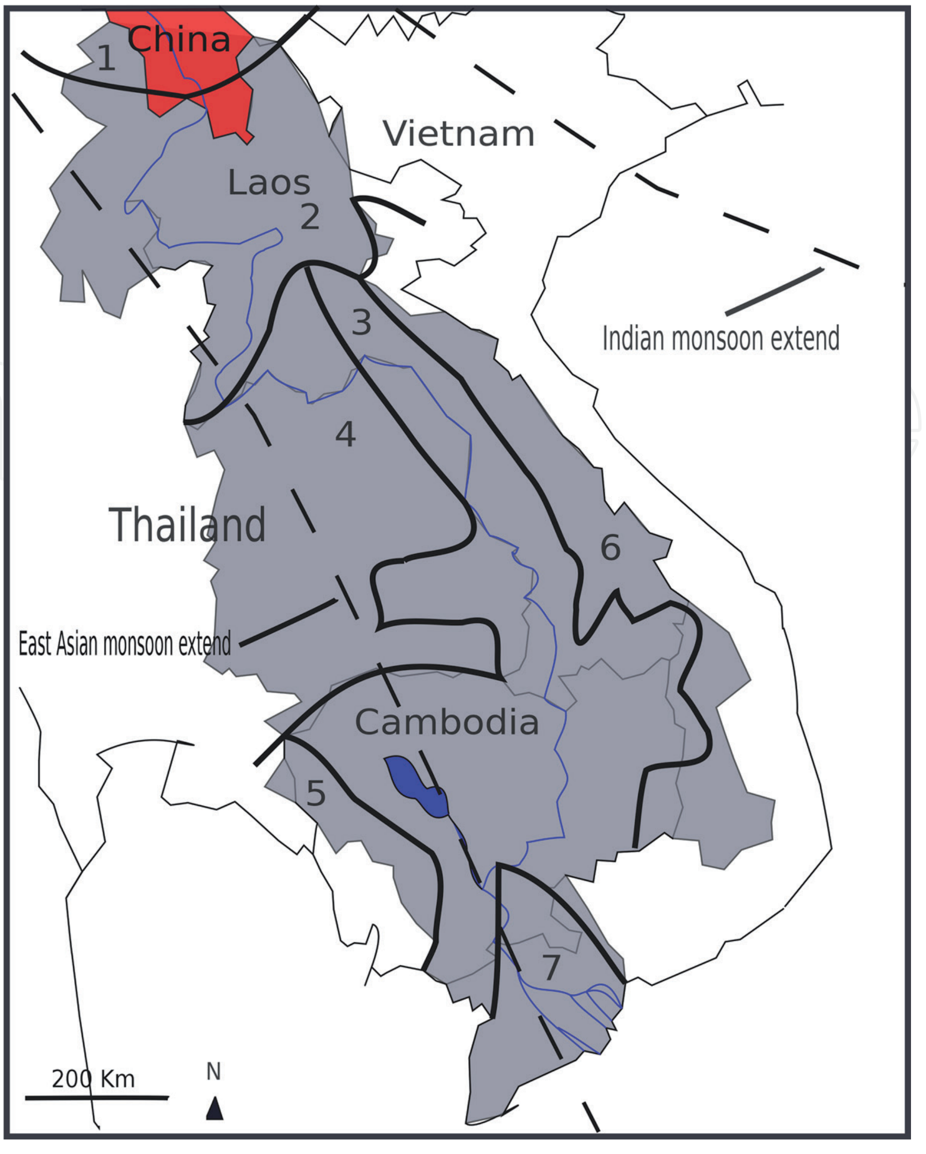

Figure 1.
Map of the Mekong River basin (MRB) showing the different countries, the upper Mekong Basin (red), the lower Mekong Basin (gray), the seven physical separations: the mountainous panhandle, the mountains of northern Laos and Thailand, the Mekong lowland, The Korat uplands, the Cardamon and Elephant hills, the Annamite mountain range and the Mekong Delta *(from [15]), the monsoon extends.*

Mekong River characteristics	
River length (km)	4800
Countries along the river	Cambodia, China, Lao People's Democratic Republic, Myanmar, Thailand, Vietnam
River basin (km^2)	795
Population (10^6)	58
Discharge ($Km^3.yr^{-1}$)	475
Discharge sediments (tons yr^{-1})	160 * 106
Annual suspended sediment load (10^6 tonnes)	150
Planned number of dams	123
Mean erosion rate (m yr-1)	12

Table 1.
Mekong basin characteristics.

According to physical features, Gupta [15] separated the MB into seven different units: the mountainous panhandle, the mountains of northern Laos and Thailand, the Mekong lowland, The Korat uplands, the Cardamon and Elephant hills, the Annamite mountain range and the Mekong Delta (MD) (**Figure 1**).

The Lower Mekong River is divided into four subsystems: Tonle Sap (lake and river), Cambodian Mekong delta (entire MD except the Tonle Sap), Vietnamese MD (Long Xuyen quadrangle, Plains of Reeds, region between Tien and Hau rivers) and coastal zones [18]. The Mekong Delta (**Figure 2**) has a total area of 52,000 km^2 [19]. The last 6 km (late Holocene) marked the fast growth of the delta [19]. The average progradation rate was 30 m yr.$^{-1}$ over the past 700 years [20] and 16 m yr.$^{-1}$ over the past 300 years [21]. In the last few decades, several authors reported instead of

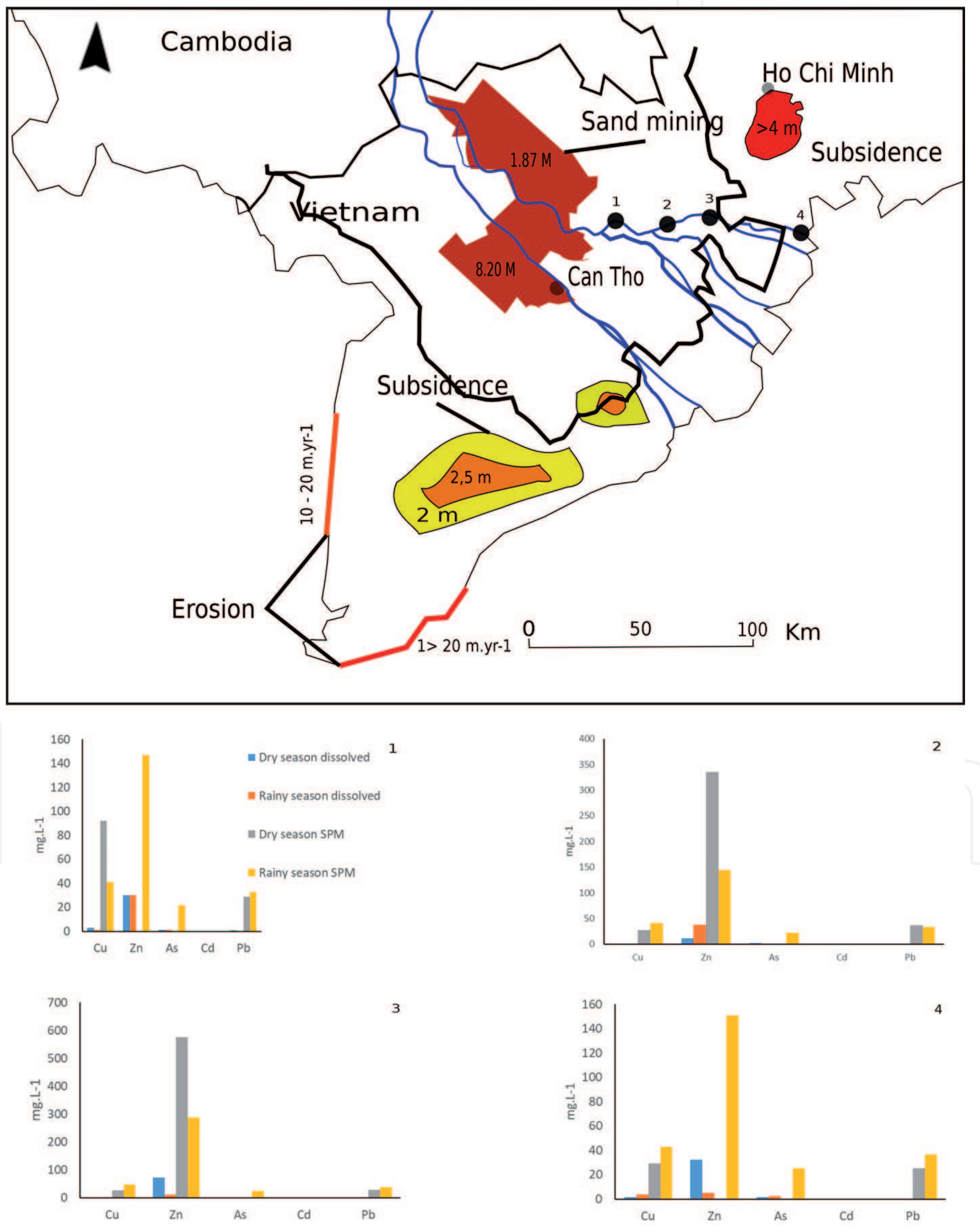

Figure 2.
Map of the Mekong delta showing the different issues in the region. Coastal erosion (m.yr.$^{-1}$), subsidence (m), sand mining (m^3), trace metal concentration in dissolved and SPM fractions (mg.L^{-1}) salt intrusion contour in 2010 (5 ppt).

gradual progradation, some serious shoreline erosion [22, 23]. The mean erosion rate was estimated to be at 12 m $yr.^{-1}$ [22] with some sub regions where erosion rates and driven factors are different [24]. The delta is constituted by two main geomorphological types: sandy beach-ridge and mud-dominated coasts westwards [10, 22]. The growth of the MD resulted in the formation of nine tributaries, so-called "Nine Dragon" and a dense man-made canal network, through the Tien River and Hau (Bassac) River, including: the Tieu, Dai, Ba Lai, Ham Luong, Co Chien, Cung Hau, Dinh An, Bat Xac and Tran De estuaries [25].

2.2 Climate and hydrology

In the basin, the climate varies from a cool to tropical weather. The Tibetan Plateau, where the MR takes its source, is mainly composed by high mountains, where the temperature is below 0 degrees during winter. There are also several glaciers with a total surface of 221 km^2 [26]. The summer precipitations are abundant. The lower basin is composed by tropical savanna and monsoon climate zones where the climate is seasonal. From November to February, the Northern monsoon brings dryness and cool temperatures whereas the hot wet season which lasts from June to September is dominated by the Southwest monsoon. The start of the wet season is marked by the beginning of the South West monsoon and later (August, September, October) during the wet season; the tropical cyclones also bring moisture to the region from the East Sea [4, 27].

Due to this dual climate variation, the hydrological regime is characterized by a monomodal flood pulse [28]. This annual flood pulse is the answer to the western North-Pacific monsoon and to the Indian monsoon and is a key hydrological characteristic of the basin. During the dry season, the water level is low whereas during the wet season, large areas of the MD are overflooded. The tributaries in the central and southern Laos contribute mostly to the Mekong flow in the lower basin, the mountainous topography permits the creation and the development of many rivers that pour into the Mekong River. In fact, 82% of the Mekong annual water discharge comes from four different sources: the mountains of northern Laos, the southern mountains, the Mun Chi system and the outflow of the Tonle Sap [15]. The upper catchment (China, Myanmar) represents 24% of the total catchment area and contributes in 18% of the total runoff [29]. However, this part of the basin is of a crucial importance for the lower basin, especially during the dry season. Indeed, from April to May, the upper basin represents 35% of the total runoff [30]. The Cambodian floodplains and the MD receive more than 90% of their available water resources from upstream [30]. In Vietnam, 95% of the Mekong water's discharge depends of upstream sources [31].

2.3 Socio-economic features

The Lower Mekong basin is the livelihood region of over 70 million people [27] and this number is probably going to reach 90 million by 2025 [10, 32]. Half of the total population lives within fifteen kilometers of the river banks [33, 34] and the delta hosts a population of nearly 20 million inhabitants [8]. The river remained relatively unexploited during the 20th century due to the wars that occurred in Indochina and the poor development of the Chinese provinces near the MB. The peace and the recent and fast development of China has led to the exponential economic development of the basin. The high demand for electricity and the mountainous landscape led to the construction of dams throughout the basin [35]. The agricultural sector is also well represented and a large proportion of the Laotian population relies on agricultural practices for their livelihood. Consequently, the Mekong River is intensively used for irrigation. The inventory of the diversions for agriculture is difficult

Figure 3.
Floating fish cages in the Tien River (Mekong River).

to make, but most of them are small diversions, directly connected in river channels and tributaries located in the Khorat Plateau of Thailand [36]. The MD is very dynamic and is the first area for agriculture and aquaculture production in South East Asia [37]. During the wet season, large areas of the lower basin are naturally flooded due to the rain and regulated for agriculture optimization [38]. These floods are making the lower basin highly fertile and create numerous ecosystems rich in biodiversity [39]. 781 species of freshwater fishes are known for living in the MR [40]. The MD detains the highest range of fish species (484) whereas the headwaters detains the lowest (24 species). Many people in the lower basin are dependent of the Mekong resources and especially fishes. In Cambodia, 80% of the population eats fish and it is the first source of proteins [41]. The lower MB has a big fishery industry (**Figure 3**) with 2.6 metric tons yr.$^{-1}$ and a total income of 7 billion USD yr.$^{-1}$ [8].

3. Damming the Mekong Basin

3.1 General information on Mekong dam's

Prior 1990, hydro-power was undeveloped on the Lower Mekong River. The rapid development of the Southeast Asian region has increased the use of natural resources and is now accompanied by high a demand in electricity. The different governments of the Mekong Basin chose large-scale hydro-power projects because the region was so far limited in term of dam development infrastructures [42]. Consequently, the development of massive water infrastructures is now booming [35, 43]. The first dam directly built on the Lancang River (Chinese name of the Mekong) was the Manwan Dam, in 1986 and was fully operational in 1996 [44]. Other dams in the Chinese region were built rapidly: Dachaoshan dam (2001); Jinghong dam (2008); Xiaowan dam (2009); Gongguoqiao dam (2011) and Nuozhadu dam (2012) and some other dams are under now construction or being planned [44]. Lower on the MR, the Xayaburi dam (Laos) is almost only used for commerce. In total, 176 dams are now being built or planned through the MRB [16]. The MR has a total hydro-power capacity of ~60 GW [45], and about 20 GW is already being exploited [16]. These dams have considerable impacts on the ecosystem and on human life.

3.2 Sediment load changes

One of the firsts impact of dams is the changes of the sediment load as a dam traps up to 95% of sediments and consequently, reduces the amount of sediment downstream. The sediment discharge in the pre dam area was 160 million tons.yr.$^{-1}$ [46] and about 50% of the sediment load was provided by the Lancang River basin [16, 45]. The reduction of total suspended solid concentration was firstly observed in 1993 after the construction of Manwan dam in China [30]. The estimated sediment trapping for the entire cascade of the eight dams in the middle and lower Lancang River may reach 78–81% [44, 47]. However, incertitude between the data concerning the post dam sediment discharge has been observed (from 67 to 145 million tons) [14, 48–50].

Downstream the Lancang River and especially in the lower MB, the data concerning the sediment discharge remains uncertain and their improvement would require further efforts [50]. Actually, the dam's impact on sediment discharge can be noised by other effects such as climate change and land use [14]. Manh et al. [18] used numerical model to unravel the effects of dams and climate change. They showed that damming the Mekong exacerbates the sediment dynamics in the MD. Suif et al. [51] examined through modeling, scenarios analysis of 19 dams (existing, under construction and planned dams) and indicated that the annual suspended sediment load is largely reduced ranging from 20 to 33%, 41–62% and up to 71–81% for existing, construction and planned dams respectively.

The reduction of sediment load in the delta clearly depends on the position and quantity of dams in the mainstream and tributaries and hence, on political decisions [43]. The construction of all planned dams would have consequences on sediment transportation (95% being trapped), leading to a reduction of the amount of sediment in the delta at 9Mt.yr.$^{-1}$ [43]. Direct measurements on site revealed that from 2009 to 2016, severe drop of suspended sediment concentration have been observed in the MD [52]. Koehnken [48] suggested that the sediment load that enter the LMB was reduced from an average of 84.7 Mt. yr.$^{-1}$ to 10.8 Mt. yr.$^{-1}$ at Chiang Saen (1960–2002) and from 147 Mt. yr.$^{-1}$ to 66 Mt. yr.$^{-1}$ at Pakse. The dam's portfolio already in action upstream seems to impact the sediment load with their high trapping ability [53]. Concerning the Vietnamese delta, the future seems dramatic with a total sediment load into the delta about 16–40 Mt./yr., that is around 10–25% of the pre-dam sediment load of 160 Mt./yr. (MONRE VN, 2016).

3.3 Hydrological changes

Dam's impacts on the LMR hydrology have been studied in the literature using both statistical analyses from measured data in site and hydrological modeling [27, 54]. The results showed that the hydro-power operations have already altered the natural hydrological cycle with lower flood peaks and higher dry season flows. However, the different studies used different models, leading to the change of magnitude [55]. At Kratie the dry season flows are expected to be higher (25–160%)and the flood peaks lower (5–24%) if the projected dam's portfolio is realized [56].

Other studies showed that the presence of upstream dams did not affect considerably the flood hydrology or low flow hydrology and that the low flow water levels were firstly attributed to poor rainfall during the period of studies and deforestation in the catchment [50, 57, 58]. Downstream the Chinese dams, the monsoon water flows are now lower than those in the dry season due to the water storage in the hydro-power reservoirs [45]. Toan et al. [59] expect an increase of the number of years with a small flood, a decrease of the years with an important flood and a slightly decrease of years with a medium flood due to the hydro-power dam's development.

4. Climate change

4.1 Different models used to simulate climate change

Climate change is another stressor that could impact the basin. The IPCC studies projected an increase of the average temperatures in the MB by the mid and late 21st century but the precipitations projection are still unclear due to numerous uncertainties [60]. Climate change studies focused on the MRB are scarce and mostly use modeling to study the effects on hydrology [54, 56, 61–63]. Some studies only use one General Circulation Models (GCM) [54, 63] and projected that the Mekong's discharge will be impacted by climate change. However, Different GCMs have different sensibility, especially concerning the precipitations. It is then essential to use multiple GCMs to investigate the different climate scenarios that could occur and the various hydrological impacts.

Kingston et al. [62] used several GCMs down scaled to the MB and large uncertainties were observed (from −16% to +55% of monthly river discharge). Lauri et al. [56] used five GCMs and two emissions scenarios to project the hydro-logical response to climate change and the hydro-power development for the period of 2032–2042. They found that dams are expected to have higher impacts on MR hydrology than the projected climate changes. Hoang et al. [64] also expected a reduction in the frequency and magnitude of extremely low flows. Thilakarathe and Sridhar [65] showed an increase in drought risks in the Lower MR Basin.

4.2 El Nino southern oscillation and extreme climatic events

El Nino Southern Oscillation (ENSO) is a climatic event that connects the ocean and the atmosphere in the tropical Pacific Ocean [66]. The Mekong Region is known as being influenced by three monsoon systems, including: the East Asian Monsoon, the South West Asian Monsoon and also the Western North Pacific Monsoon [67]. This ENSO also impacts the precipitations and discharges in the watershed [68]. A study of the Mekong discharge data showed that the combination of the ENSO and the runoff may have increased during the 1993–2005 period in comparison to the 1950–1993 period [69]. Rasanen et al. [27] also studied the relation between ENSO and the Mekong hydrology. They observed that the ENSO dependence was the highest in the Southern part of the basin. They also concluded that the precipitation and discharges decreased and the annual flow was shorter during El Nino. Ha et al. [52] also showed a decrease in water and sediment supply during El Nino.

Extreme climatic events such as tropical cyclones can impact the precipitation regime and lead to more sediment transport through the watershed. Darby et al. [58] combined, suspended sediment load data with hydrological model simulations in order to better understand the role of tropical cyclones on precipitations and sediment load. They found that 32% of the suspended sediments that reach the delta are generated by tropical cyclone rainfalls.

4.3 Regional Sea level rise

Regional sea level rise (RSLR) is currently about 4.0 mm $yr.^{-1}$ along the Mekong coast [70]. Vu et al. [71] estimated SLR using the RCP 6.0 emission scenario. They projected an increase of SLR between 25 to 30 cm by 2050. Relative Sea Level Rise associated with delta subsidence will have inundation consequences in the MD which has an average elevation of less than 2 m [11, 12]. This RSLR will affect rice production yield, up to 50–60 km into the river and approximately 30,000 ha of agricultural area may be affected. Currently, up to 40 km of the river mouth is affected by the intrusion of saline water [72]. RSLR due to climate change is one of the consequences of the delta sinking. Subsidence is another consequence of the delta sinking and is 10 times higher than the sinking due to RSLR.

5. Delta sinking

With 20 million inhabitants, the MD is recognized as one of the largest populous deltas in the world [8] and is considered as the "rice bowl" of South East Asia, providing 50% of the Vietnam's food. It is a very active area in term of agricultural development and is the second most important rice exporter (Vietnam [73]).

5.1 History of the Mekong Delta

5300 to 3500 years ago, the Mekong estuary increased rapidly due to high sediment supply transforming it into a delta. However, since the past few years (2005 seems to be the transition year), the delta is experiencing high riverbank and coastal erosion (**Figures 2** and **4**). Anthony et al. [22] quantified the shoreline erosion using high-resolution satellite images. They found that between 2003 and 2012, the erosion affected over than 50% of the 600 km long delta shoreline. However, the erosion is not the same for all the delta shoreline and three sections are observed: the sand dominated delta distributing mouths, the mud-dominated South China Sea coast and the mud-dominated Gulf of Thailand coast. Recently, Marchesiello et al. [24] undertook a comprehensive numerical exercise, coupling field surveys, laboratory experiences and remote sensing data, to assess natural against man-induced coastal erosion processes. While sediment trapping by dams and sand mining for construction is clearly identified as factors of risks enhancing coastal erosion, this later could also be largely attributed to other processes, such as shore sediment redistribution by the ocean forces (waves, currents and tides), mangrove squeeze and/or subsidence.

5.2 Incision of the Mekong Delta

Brunier et al. [19] studied the channel changes morphology in the MD. Computed data from 10 years comparison period showed that the channels changed with significant incision, expansion and deepening of numerous pools. The authors explained the morphology channels changes by the large extraction of construction materials. The regional exponential socio-economic development engendered a high increase in the demand for sand mining [74]. The United Nations Comtrade Database (UN [75]) revealed that Singapore demands a high amount of sand with 80 Mt. bought from Cambodia and 71 Mt. from Vietnam for the 2000–2016 periods (**Figure 5**). Bravard et al. [76] estimated sand extraction to be approximately 54 My. $yr.^{-1}$ which is around one third of the natural flux of sediments. This extraction causes serious impacts on the environment and on human's livelihoods, regularly reported in national newspapers ([74] among others). Le et al. [77] pointed out that a critical value of 0.4 $g.L^{-1}$ of suspended sediment concentration must be maintained in the Mekong estuary for sediment processes. If a SSC beyond this value is measured, the deposition rate will be strongly reduced and the erosion rate will probably increase.

Figure 4.
(a) Sand extraction in the Mekong Delta, used as construction material in Ho Chi Minh City (photo from the Saigoneer, published on Monday, 19 March 2018). (b) Photo of Sim Chi Yin in National Geographic showing the erosion effects in the Mekong Delta (photo from the Saigoneer, published on Monday, 19 March 2018). (c) Photo showing the erosion effects in the Mekong Delta (photo by Vo Le Phu).

Figure 5.
Photo showing sand extraction in the Mekong delta (photo from the Saigoneer, published on Monday, 07, August 2017).

5.3 Dikes implementation and delta subsidence

The MD has the capacity to produce three rice crops per year, and even to supply the whole region. This important production is possible because of the implementation of irrigation, drainage channels and flood protection infrastructures [38, 78, 79]. However, these infrastructures also change flows and sediment transports. Triet et al. [80] observed that high-dykes permitted to decrease local flood risks but, on the other side, increased downstream flood risks. In addition, high dikes removed high fertility sediments delivered by the floodwaters balance [81].

The recent literature [11, 82, 83] clearly highlighted that subsidence exacerbates the delta sink and associated risks of coastal erosion, extended duration of flooding and salinization. This salinization will have impacts on the MD fisheries. The *Pangasius* needs freshwater to survive. An increase of 0.73 m of the sea level, combined with a decrease of 29% of the Mekong River flow, a scenario expected in Vietnam by 2100, will impact the area dedicated to the *Pangasius* farming by 11% [84]. Erban et al. [82] estimated the subsidence rate at 1.6 cm $yr.^{-1}$. This subsidence is due to over exploitation of the groundwater with a decline of 0.3 m $yr.^{-1}$ of groundwater level. A continuation of this pumping at the present rates, due to population increase, might result in a 0.88 m of land subsidence by 2050. Minderhoud et al. [12] alarm on the possible drown of the Mekong delta if water extraction is allowed to increase continuously. However, a limitation of the water extraction could result in limiting future elevation loss.

6. Water quality degradation

6.1 General information

Compared to temperate watersheds, the Mekong River is not well monitored, despite a clear warning on threats [31]. In the early 1990, the mainstreams of the delta were already too contaminated for drinking [85]. However, in the MD, surface water is used by the population for irrigation, aquaculture and for drinking [86]. In the MD, more than 50,000 Km of man-made canals were reported [87].

Studies made by Wilbers et al. [86] showed that pH, turbidity, ammonium, arsenic, barium, chromium, mercury, manganese, aluminum, iron, and *Escherichia coli* in the canals exceed the thresholds set by Vietnamese quality guidelines for domestic purposes [88]. Strady et al. [89] analyzed trace metal concentrations in water, SPM and surface sediments in the Tien River. They showed relatively low concentration ranges in the different phases.

6.2 Groundwater

Groundwater is a main water supply source for domestic purposes and is tapped wherever the salinity level is not too high [90]. Groundwater resource quality has been exacerbated by trace metals and other pollutants, in which Arsenic contamination became an emerging concern. Stanger et al. [91] was the first study to alarm about arsenic (As) groundwater contamination in the MD and showed that As concentrations from 100 to 120 m deep was extremely high and exceeded WHO standards (10 μg/L) [92]. As groundwater was recorded in the Kandal province (Cambodia) and also in Vietnam [93]. The high concentration of As in water leads to serious health issues in the population [94]. The highest As concentration recorded in the MD was 1610 $\mu g.L^{-1}$ (100 times higher than the WHO standards) [95], which is about one-hundred times higher than the WHO drinking water standard. Furthermore, during a groundwater sampling campaign, Buschmann et al. [96] observed that 37% of the samples exceeded the WHO standards and 26% of the samples had an As concentration over 50 $\mu g.L^{-1}$. However, Guédron et al. [97] reported, for the Laotian capital (Vientiane), low total Hg concentration in the MR close to the city, which is due to the low industrialization of the city.

6.3 Dams impact on water quality

Dams also lead to eutrophication and pollution of the water resources locally and downstream, as a result of the regulated water flux and water stagnation [98]. The closure of Manwan dam led to the decrease of heavy metal concentrations at downstream parts. The nutrients in the reservoir showed variations of concentrations between 1993 and 2004, and the total amount of phosphorus consistently increased [44]. The water temperature was also recorded and the overall mean surface temperature in the reservoir increased due to the dam closure. Downstream the dam, the temperature is now cooler during summer and warmer during winter [44]. Chanta and Sok [99] studied the impacts of a Dam on the Sesan River, a major tributary of the Mekong River, located in central Vietnam and north-east Cambodia. They showed a decrease of water quality downstream the dam with an increase of the suspended particulate matter concentration, total phosphorus, nitrogen and ammonium.

6.4 Water pollution due to human activities

As previously above-stated, the population in the MB is rapidly growing and the estimations report over 100 million inhabitants by 2050 [100]. This growing population already has impacts on the land use with a deep transformation of agriculture over the last 15–20 years [101]. Water pollution in the Mekong due to human activities is relatively low compared to other tropical catchments [102]. However, the increasing amount of industrial, agricultural and urban (Vientiane, Phnom Penh) wastewater could have potential concern in the future [102]. In the lower MB, contamination could become the main issue through irrigation, wastewater, fuel or coal combustion [103]. A recent report of the World Bank, stated that water pollution is a great threat that could cost Vietnam up to 3.5 percent of GDP each yearby 2035 [31]. Nutrients, pathogens and pharmaceuticals can be encountered as waste from livestock. In Vietnam, two third of the 84.5 million tons of this livestock waste is not treated [104].

Spatial water quality variability studies can be done using self-organizing map (SOM). With this technique, Chea et al. [105] classified more than 117 monitoring stations. They found that the Laos, Thailand and Cambodia had good water quality with low nutrient and high dissolved oxygen levels. Two other clusters including the MD (Vietnam), Northwest of Thailand, Tonle Sap Lake and Vientiane urban center in Laos showed moderate to poor water quality indexes, with high nutrient load and low dissolved oxygen levels. They explained that these differences are due to human activities and especially to population growth and agricultural development in the man-made canals in the lower delta in Vietnam.

7. Comparison with other world big rivers

The Mekong River is ranked 12th biggest river in the world and the Mekong watershed is the biggest in southeast Asia. Other rivers and watersheds on earth also struggle against human activities. The objective of this section it to make an inter-comparison between the MR and other different big rivers around the word.

7.1 Dams in the world

A new hydroelectric portfolio has been developed on different earth big rivers since 2000 with a craze for the construction of megadams (dams with a height superior to 15 m). Worldwide, hydropower capacity has increased by 55% from 2000 to 2015 [106, 107]. The construction of megadams is the response of the world electric demand. However, this high level of construction can lead to several risks such as: downstream sediment and nutrient reductions, changes of the annual flood pulse and reservoir siltation [107, 108].

The Amazon River is one of the most dammed river in the world. Effectively, 62 dams are localized in the Andes, 76 dams on the cratonic rivers of the Amazon basin, and 2 on the Madeira River. Additionally, up to 286 dams are planned in the basin [109]. The Dam Environmental Vulnerability Index (DEVI) is a method permitting to assess the impacts of damming, using different parameters. The results for the Amazon basin reveals high vulnerability for several sub-basins with large potential changes.

Another example of negative dam's impacts can be illustrated by the Haung He (Wellow) River in China. This river was characterized by the highest total sediment flux of any river on earth (1.6 Gt year^{-1}) [110] due to deforestation and agricultural development. The implementation of dams resulted in a decrease of the sediment deposition in the lower Huang He River. Between 2000 and 2002, the sediment deposition passed from 111 × 106 m^3 yr.$^{-1}$ to a channel incision with a net erosion of up to 361 x 106 m^3 yr.$^{-1}$ [111].

7.2 Climate change

As we detailed in the previous section, the prediction of the impacts of the climate change on a big river such as the MR is difficult. In addition to the sediment mining, and the damming of the basin, variation of the climate will have consequences on the future delivery of sediments to the Mekong Delta.

The modeling of climate change and the impacts on rivers is difficult to predict and depends on the characteristics of the basins [112]. Some studies show that the intensification of the hydrological cycle is mainly due to the increase of extreme events during short time [113]. In addition, the increase in the magnitude and return period of floods is observed in different rivers such as the Amazon, Congo, Niger and also big rivers in Southeast Asia. Decrease in flood magnitude and return period is also predicted in the Nile, tigris-Euphrate, Danube Volga, Ob and parts of the Mississippi basin [114].

Atmospheric rivers are narrow ribbons of large moisture flux from the tropics to mid latitude [115]. These rivers are susceptible to see their flow regime change with the global climate change. Some atmospheric rivers will have large influence in high flow contribution (Zhuiang, Volga, Tigris-Euphates rivers) whereas other rivers will not be influent (Amazon, Congo, Magdalena, Nile rivers) [116].

The rivers where the flow is based on the monsoon rainfall and snowmelt could in the future suffer from the diminution of their flow in consequence to the reduction of the glacier size such as the Indus and Brahmaputra [117, 118]. Other rivers such as the Huang he River, where the meltwater is a small percentage, the increase of precipitations will enhance water availability [118].

The russia's great Artic rivers (Ob Yenisey and Lena) flood hydrograph is controlled by the snow and ice melt [119]. A warmer climate will increase ice melting resulting in an increase of the flow regime in the polar zone. In addition, the permafrost, logically permanently frozen will start to melt, leading to a change in the water pathway with an increase of the groundwater proportion in the river flow [120].

7.3 Water pollution, sand mining, shoreline erosion

Water pollution is an omnipresent subject when dealing with big Rivers. This review stated that the MR water is relatively preserved compared to other rivers. Indeed, excepted some Rivers, such as the Danube, where better management practices during the last two decades [121], resulted in better water quality, most of big rivers are still suffering large pollution. Best [3] stated that 80% of the world's transboundary rivers are severely polluted by nutrients (nitrogen, phosphorus) that can lead to eutrophication and/or wastewater (human waste) (UNEP-DHI, 2016). One of the most polluted river, The Gange River, India, faces to several problems such as untreated fecal waste, pesticides and heavy metal pollution [122]. Macro and micro plastic pollution is another problem encountered in big Rivers. Seventy-four per cent of the world plastic pollution is coming from large Chinese rivers such as the Changjiang, Indus and Huang He. Eighty-six per cent of the global plastic waste is coming from Asian rivers [123].

Sediment mining is a big issue for the Mekong River that has been documented in this review. The MR sediment extraction is 55 Mt. yr.$^{-1}$, representing 47–95% of the total annual suspended sediment load [124]. Other rivers in the world are also impacted by this activity that can, *in fine*, considerably decrease downstream sediment fluxes, change channel morphology, increase salt intrusion. The Zhujiang river, China is affected by this phenomenon with the removal of 60 Mt. yr.$^{-1}$ of sand, equivalent to the annual sediment load, engendering large channel incision [125]. The Changjiang River is also impacted with the removal of 40 Mt. yr.$^{-1}$ representing 17% of the total annual suspended sediment flux [126].

This paper revealed shoreline erosion of the Mekong delta (**Figure 2**). Other tropical rivers also show erosion of their coastal shorelines. The Irrawaddy River is considered as a major tropical river in the world [127]. The Irrawaddy basin covers 60% Myanmar's country [128]. Its delta is highly populous with about 15 million people living in an area of 35.000 km2 [129]. Chen et al. [130] showed that the delta's front accreted by 10.4 m. yr.$^{-1}$ between 1974 and 2018. In addition, 42% of its shoreline was subjected to erosion. However, the repartition of the erosion is disparate with a predominance of the erosion on western coastline and an accretion on the Yangon lobe. However, the mainstream of the Irrawaddy became increasingly straightened since 1974 suggesting the influence of dams and sediment extraction reducing sediment supply.

8. Future directions

As reported in this review, the Mekong River is currently facing profound transformations that lead to several issues, some emerging and some already critical (**Figure 6**). This basin is unique, with an exceptional productivity and a dense population depending on it. It is hence necessary to face these issues in order to reduce impacts, with the goal of sustaining the Lower Mekong river resources and services [5].

8.1 Local and regional strategies

The issues are multi-level and need strategy at both local and regional scales like, for example, groundwater resources. In 2007, Ho Chi Minh City encouraged the diminution of the groundwater pumping. This regulation permitted to decrease the subsidence [131]. Groundwater pumping could also be attenuated by connecting the Vietnamese

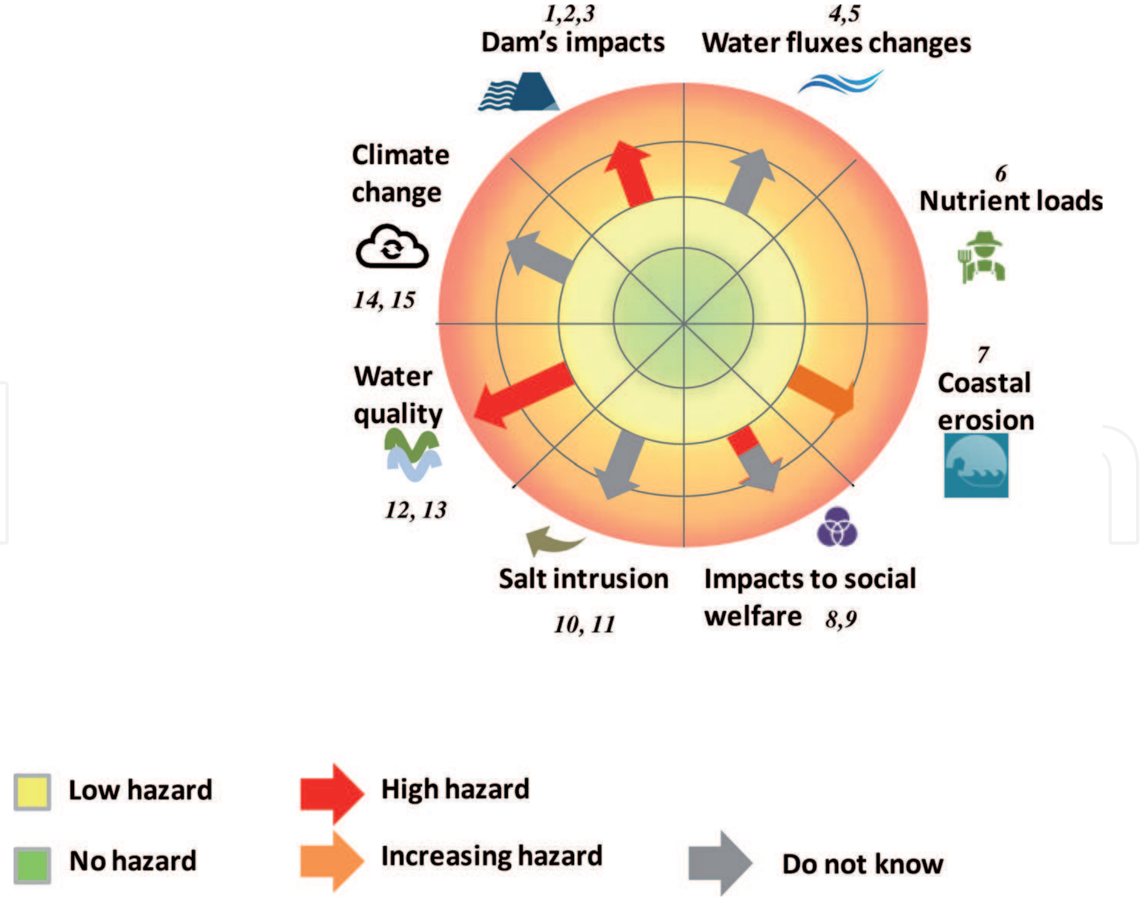

Figure 6.
Sketch representing the hazard level of the different issues that the Mekong River is facing to. Numbers are referring to the publications in the review: 1. Schmitt et al. [43]; 2. Suif et al. [51]; 3. Manh et al. [18]; 4. Koehnken [48]; 5. Pokhrel et al. [55]; 6. Toan et al. [59]; 7. Chanta and Sok [99]; 8. Minderhoud [11, 12]; 9. Trieu and Phong [84]; 10. Nguyen The Hinh [104]; 11. Chea et al. [105]; 12. Minderhoud [11]; 13. Trieu and Phong [84]; 14. Buschmann et al. [90, 96]; 15. Chanta and Sok [99]; 16. Hoang et al. [64]; 17. Darby et al. [58].

population to safe public water [132] or by accompanying farmers to less demanding freshwater production modes and agricultural activities, such as brackish aquaculture, and mangrove associated aquaculture [133]. The subsidence in the delta could also be reversed by using organic residues from rice production [134] or by restoring the mangrove to prevent coastline erosion [135, 136].

Among the other major issues introduced in this review, most of them need political agreements between the different neighbor countries so they can be tackled. For instance, the ongoing development of dams, at regional scale, seems to be irreversible, but there is a clear benefit to develop a culture of dam's portofolio for the strategy of implementation, as recently proposed by Schmitt et al. [43]. While dams have and will have impacts in the basin in the next decades; the best efficient development will probably make the difference, in terms of cost/benefits balance. The data concerning the construction of megadams is clearly insufficient [137]. Too little data is nowadays available concerning big rivers the flux of sediments, nutrients and water to guide decisions. Sediment flux modeling evolves rapidly and the advances made can help decision makers to find the best site for future infrastructure as dam's position is of a pivotal importance [138]. A strategic dam position for the environmental flow of the Mekong is a position with little impact on the sediment budget and fish habitats [139]. Some studies showed that the presence of smaller dams in cascade with equivalent energy production is better than very large dam in term of sediment budget [140].

The use of satellites in order to precisely measure the water level could permit to understand better hydrological dam's impacts. In 2020, the Surface Water Ocean Topography (SWOT) mission will launch a satellite to pursue this work [141]. Satellites observations permit to provide unbiased, spatially explicit and repeated data permiting to better understand the processes in action in the MR and delta [142]. Sand extraction is another regional issue that could be attenuated by implementing regulations. Banning sand extraction could reduce change of channel morphology and reduce long term sediment starvation [143]. Downstream, the lack of sediment is regularly reported as a main issue for coastal dynamic and risk of erosion. The recent results of Marchesiello et al. (2019) unfortunately showed that the impact of sediment reduction may not have yet affected the shore, and may accentuate risks of erosion in the coming decades. The reforestation of the mangrove is a simple measure that should be seriously considered to ensure the preservation/restoration of the coastal areas. Indeed, during tidal inundations, the sediment particles flocculate and form larger flocs. The mangroves just act as a passive scavenger of mud and trap the suspended sediments [144, 145].

8.2 International actions

International actions also come from international organizations. The Mekong River Commission (MRC) was created in 1995 and aims to share scientific data, promote the sustainable development of the basin and promote the communication between Laos, Thailand, Cambodia and Vietnam. The MRC reviews projects in relation with potential development impacts. Other big rivers in the world, such as Nile, has an international powerful management [146]. This kind of management could be copied to improve the Mekong's management.

The MR is currently confronted to several anthropogenic stressors that impact the environment, with some feedback effects on the population and its well-being. Some of these impacts could be irreversible in the next years or decades, even if sustainable solutions are being settled up now. The time to initiate a network of collaborations, as stated by the Vienna declaration on the Status and Future of the World's Large Rivers is over and it is now time to act. Sustainable development can still reduce the impacts. This development must integrate different actors from scientists to decision makers in order to take into account the scientific information in the future decisions.

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