京都大学防災研究所年報　第 60 号 B　平成 29 年
DPRI Annuals, No. 60 B, 2017

Study on the Impacts of River-damming and Climate Change on the Mekong Delta of Vietnam

Doan Van BINH, Sameh KANTOUSH, Tetsuya SUMI, Nguyen T.P. MAI(1), and La Vinh TRUNG(1)

(1) Faculty of Civil Engineering, Thuyloi University-Second Base, Ho Chi Minh City, Vietnam

Synopsis

Since the end of 2015, salinity intrusion and drought of different degrees hit the Vietnamese Mekong Delta (VMD). Between March and April 2016, China increased the released outflow discharges from Jinghong Hydropower station to the downstream reach of the Mekong River, following Vietnamese request after the worst drought event over the last 90 years. The released flow may mitigate the drought and high salinity intrusion occurred in several provinces in the VMD. This research aims at summarizing some damages information caused by drought event 2015-2016 and figuring out some possible impacts of six existed and eleven proposed dams in the mainstream Mekong River on the VMD. Water levels in the period of 2012-2015 is about 1m lower and two months shorter than that in period 1993-2001. This leads to salinity concentration increasing about 10-15 g/l in some locations. The timing and duration of salinity levels of the VMD at post-dam periods are shifted about 1 month earlier than pre-dam period. Eleven proposed mainstream dams along with 47 cm sea level rise will lead to a maximum reduction of about 15% and a maximum water level increase of approx. 220% in the VMD.

Keywords: Drought, Sea Level Rise, Hydropower dams, Salt Water Intrusion, VMD

1. Introduction

Since the end of 2015, the VMD has been suffered from the most severe drought event over the last 90 years, causing extreme salinity intrusion upland towards Vietnam-Cambodia border. It has caused damages to approx. 159,000 ha paddy fields (Kantoush et al., 2017) and thousands of people have been lacked freshwater for daily consumption. Such consequences are much over the endurance of the human and natural communities in the VMD. Following the request from Vietnam, China has promised to increase discharging water from Jinghong Hydropower Station as double as the same period last year to as much as 2,190 m^3/s from March 15 to April 10, 2016. Such increased release was expected to alleviate that drought in the VMD.

The Mekong River (MR) is the 8th largest river in the world in terms of mean water volume of about 475

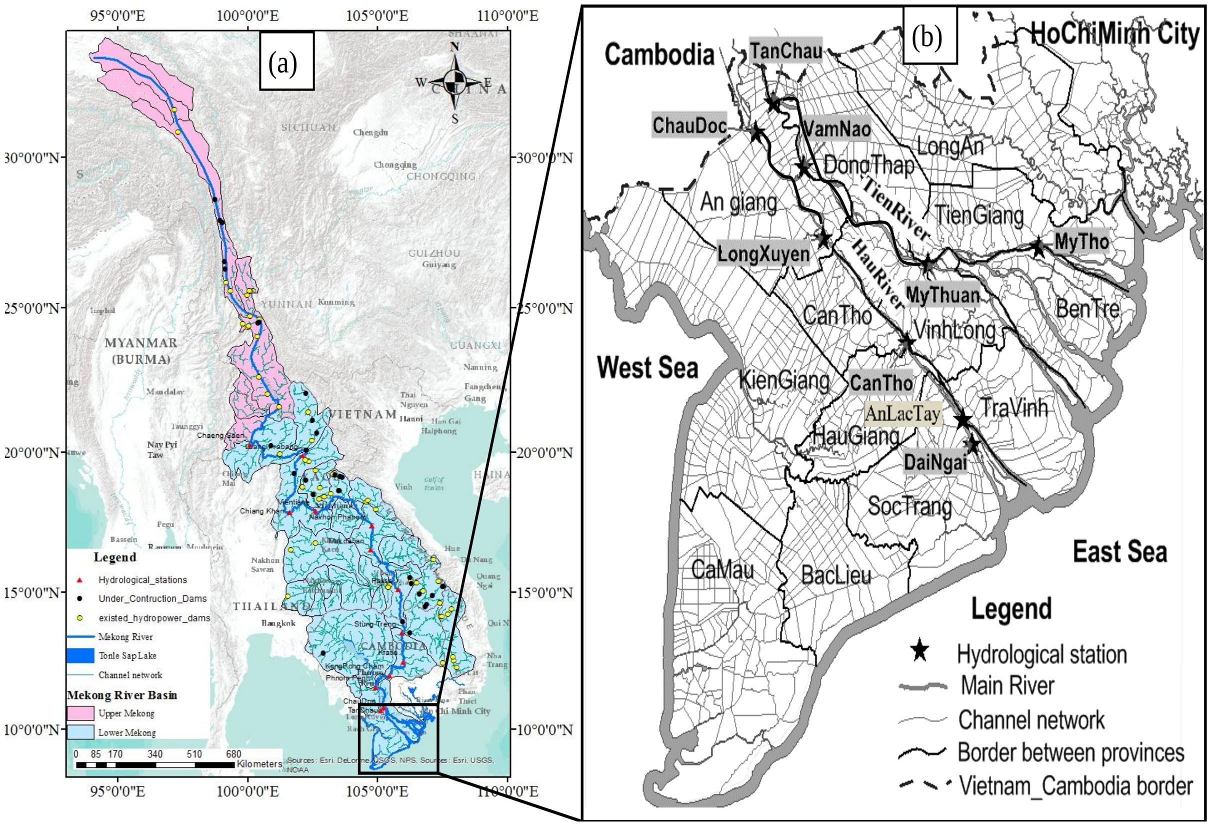

Fig. 1 (a) Mekong River Basin, (b) Vietnamese Mekong Delta(VMD)

km^3 (Grumbine et al., 2012). The Vietnamese Mekong Delta (VMD) is located at the furthest end of the MR, consisting of 13 provinces and cities e.g. LongAn, TienGiang, DongThap, VinhLong, BenTre, TraVinh, CanTho, SocTrang, HauGiang, AnGiang, KienGiang, BacLieu, and CaMau (Fig. 1). The total area of the VMD is 39,000 km^2, stretching from Vietnam-Cambodia border, several kilometers upstream of TanChau and ChauDoc gauging stations, to the East and West seas of Vietnam (Fig. 1b). The VMD which is known as *rice bowl* of Vietnamese (Ziv et al., 2012; Manh et al., 2015) is home of about 17 million citizens whose livelihoods based mainly on agriculture and aquaculture.

The VMD is low-lying area. The average elevation varies from 0.7m to 1.2 m above mean sea level (a.m.s.l), except for some high mountain in the Northern of AnGiang province. The highest areas are close to the Vietnam-Cambodia border, ranging from 2.0m to 4.0m a.m.s.l. As moving seaward, the VMD declines its altitude to about 1.0-1.5m a.m.s.l in the middle areas and 0.3-0.7m a.m.s.l when approaching the seas.

Average rainfall in the VMD is approx. 1,800mm with spatial temporal uneven distribution. The Western regions of the VMD (areas along the West Sea of Vietnam) receive the highest annual rainfall of approx. 2,000-2,400mm while the Eastern areas receive the least of 1,600-1,800mm. Approximately 90% of annual rainfall takes place during six months of rainy season (from June to November). The remaining 10% is scattered throughout the rest 6 months of the dry season from December to May of the following year. It is worth noting that, there is almost no rain in between January and March when farmers are cultivating the most important rice crop (Winter-Spring) of a year (Xuan, 1975).

Tien and Hau Rivers (names of Mekong and

Bassac Rivers in Vietnamese) are the two main rivers in the VMD. The length of the former is 250km while the latter is 220 km long. In addition, the VMD has a relatively dense channel and canal network, mainly constructed during the last century with the purpose of increasing irrigation capacity for navigation and agriculture expansion, with the total length of about 88,000 km (Hung et al., 2013). Tien and Hau Rivers conveys about 80-85% of flow entering the VMD while the rest 15-20% is from the overflow through Vietnam-Cambodia border. Using daily discharge in 1980-2015 period, the average flow volumes running through TanChau and ChauDoc stations (in the entrances of Tien and HauRiver Rivers) is 314.2 km^3 and 78.6 km^3, respectively. The year 2000 has the highest flow volume of 382.2 km^3 at TanChau and 105.1 km^3 at ChauDoc. The two most drought years have been experienced in the VMD are 1998 and 2015.

Seasonal flood in the VMD is usually from June/July to November/December while the dry season lasts for the rest half a year. The average discharges (1980-2015 time series) at TanChau station in flood and dry season are 15,600 and 4,200 m^3/s respectively. The highest peak discharge at TanChau station in between 1980-2015 was in the year 2000 of 26,000 m^3/s while the lowest peak discharge of 17,000 m^3/s was recorded in the year 1998 at the same station. Seasonal flooding has multi-functions on the development of the VMD. Annually, through flooding, the Upper Mekong (UM) provides an abundant amount of fine sediment with rich nutrients to floodplains, supplies freshwater for domestic, agriculture and aquaculture uses, provides diversified fishes for local citizens, and minimizes saltwater intrusion in the coastal zones (Hanington et al., 2017). The VMD is therefore one of the most productive agro-aquaculture and fisheries in the world (Manh et al., 2015; Ziv et al., 2012).

However, these plentiful resources are threatened due to upstream development, particularly dam construction projects along the main MR and its tributaries which have an electricity potential of 53,000 MW (ICEM, 2010; Keskinen et al., 2012). Currently, there are fifty-six existed hydropower infrastructures in the MRB of which eighteen in China, twenty-two in Laos, ten in Vietnam, and five in Thailand (Fig. 1a). Manwan hydropower dam is the first of eight hydropower dams in the middle and lower parts of Yunnan province in China (known as Lancang cascade) started construction in 1986 and filling reservoir in 1992 (Lu and Siew, 2006; Fan et al., 2015). Nuozhadu and Xiaowan are the two largest hydropower dams in the Lancang cascade, having active storage capacity of 12.2 km^3 and 9.9 km^3, respectively. In addition, Laos is constructing other twenty-two hydropower infrastructures for domestic supply and export, mainly to Thailand (Boer et al., 2016). In line with that, seven dams are under construction in China and two were commenced in Cambodia. That means thirty-one hydropower dams are under construction currently (Fig. 1a). Besides six existed hydropower dams in the maintream MR (Lancang cascade), eleven mainstream hydropower dams are under construction and planned in the mainstream of the Lower Mekong Basin (LMR) (Kummu et al., 2010; Li et al., 2012; Lu et al., 2014). Of these, seven are in Laos teritory, two are in Thailand-Laos border, and the rest two are in Cambodia state. Xayaburi is the first dam under construction in Laos.

Upstream development activities e.g., dam constructions; accumulating water in reservoirs; deforestation; irrigations schemes; urbanization; upstream flood protection and other forms of land use, have been directly impacting on the river current regime. Such upstream development are known having both positive and negative effects on downstream communities as summarized in Fig. 2. On the one hand, upstream development (e.g. dam constructions) reduces flows in the flood seasons while increases the dry season

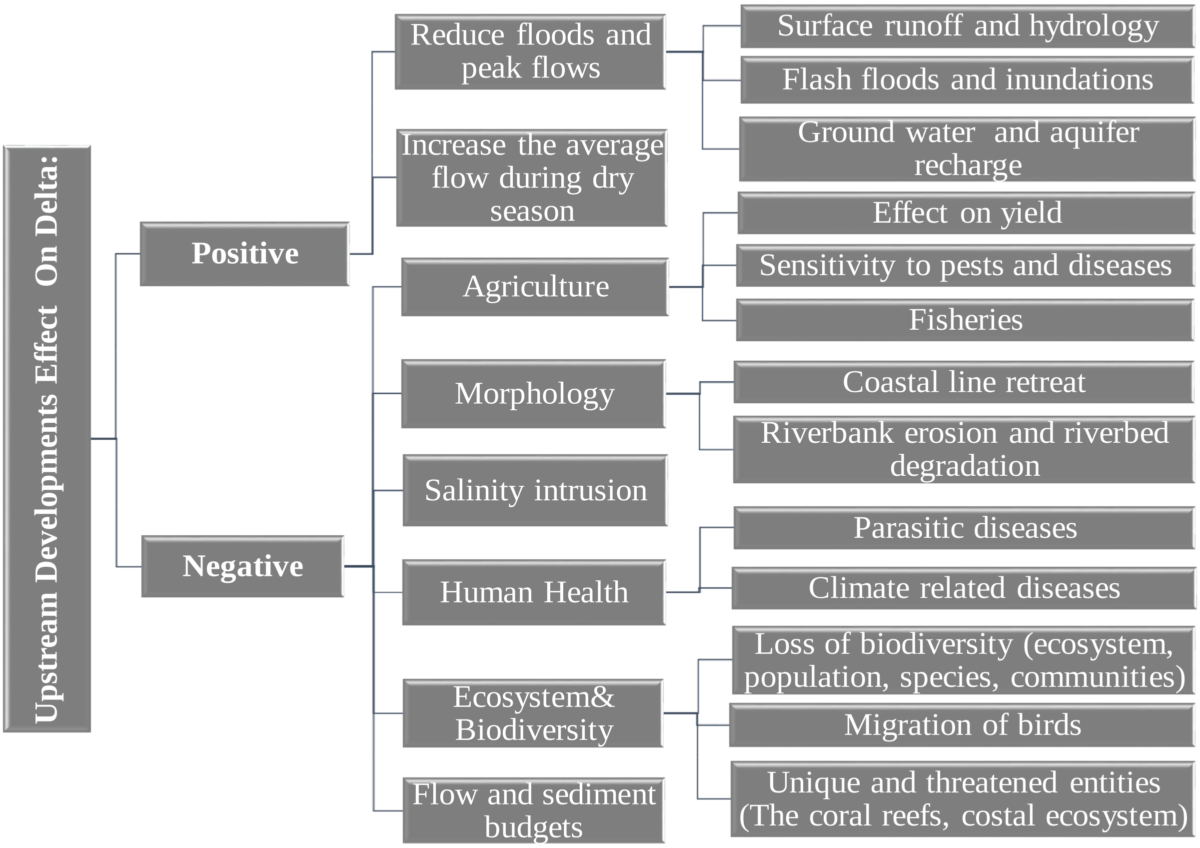

Fig. 2 Possible impacts of upstream development on the VMD

flow which helps eliminate saltwater intrusion in the coastal areas. However, on the other hand, upstream dams also cause many negative impacts on agriculture, fisheries, river and coastal morphologies, salinity intrusion, ecoystem and biodiversity, and sediment budgets (Fig. 2).

The VMD is vulnerable to salinity intrusion. Annually, salinity affects approx. 2.1 million ha in the coastal zones of the VMD during the dry season from December to May (Trung and Tri, 2014). The salinity concentration of 4 g/l affects about 1.4-1.7 million ha (Toan, 2014) while approx. 1.3 million ha is affected by saline water above 5 g/l (Smajgl et al., 2015). In 2013, salinity concentration of 4 g/l intruded 40 km upstream which is about 10-20 km further inland than average (Toan, 2014). It is obvisous that salinity intrusion is very sensitive to upstream development , population growth, urbanization, industrialization, and climate change induced sea level rise (Trung and Tri, 2014). The feature of salinity in the VMD is summarized in Fig. 3. Among them, hydropower dam development in the UMB is likely the most significant driver because of its great contribution on dry season flow to the LMB. (Kuenzer et al., 2013) revealed that 70% of low flow at Vientiane and 30-40% of low flow at Kratie are contributed by dry season flow in the Chinese parts which are currently dammed with six mainstream hydropower dams. As a result of dams, salinity intrusion in the VMD starts ealier and ends more lately than usual because of the storage of the reservoirs at the end of the flood season and the refilling of reservoirs in the onset of flood season. Such phenomena, consequently, leads to a shortage of freshwater for the Winter-Spring rice crop which is the most important crop in the VMD.

Rice takes up to 90% of crop planted in Mekong Delta (GSO, 2013). However, rice crop is extremely sensitive to salinity. According to Asch and Wopereis (2000) rice productivity would decrease by 0.4 – 0.6

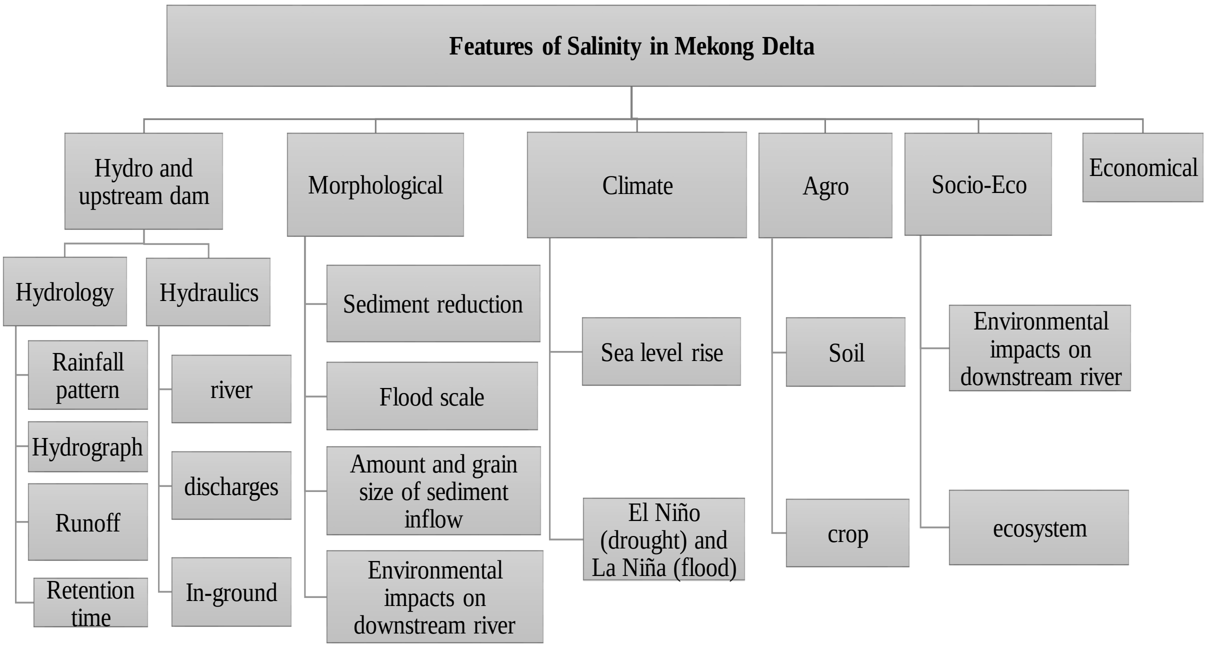

Fig. 3 Features of salinity in the VMD

Ton/Ha for every saline unit 1g/l increasing from 1.3g/l. In average, there are about 100,000 ha over 650,000 ha of annual rice crop endangered every year by salt intrusion (MARD, 2011).

There is limited comprehensive study to quantify the the impacts of all existed, underconstruction, and planned hydropower dams in the MRB on all aspects of water-related issues of lower Mekong countries, except for a work of Kondolf et al. (2014) who estimated the portion of sediment trapped in resevoirs of such dams. Recently, DHI and HDR (2015) evaluated the possible impacts of eleven proposed dams in the mainstream of the LMB on socioeconomic activities of downstream regions. Their results showed that these dams will cause a reduction in discharges in the dry season at TanChau and ChauDoc station (Fig. 1b) of 1.9 percent and 2.5 percent respectively in between January to May and 0.5 percent in June at both stations. As a result, downstream areas are likely to negatively affected.

2. Previsous studies

Impacts of hydropower dams in the MRB on downstream areas have been studied by some researchers. Most of previous researches have studied the impacts of hydropower dams on downstream hydrology (Lauri et al., 2012), aquatic ecosystem productivity (Kummu and Sarkkula, 2008; Lambert and Koponen, 2008), and riverine transport (Kummu et al., 2006); some researchers have investigated the influence of dam construction in the Lancang cascade on sediment load from the UMB to Cambodia Mekong Delta (Fu and He, 2007; Fu et al., 2008; Kameyama et al., 2013; Kummu and Varis, 2007; Liu and He, 2012; X. X. Lu et al., 2014; Lu and Siew, 2006; Walling, 2008; Wang et al., 2011); several studies have focused on estimation of trapping efficiency of reservoirs and its impact on downstream areas (Kondolf et al., 2015, 2014; Kummu et al., 2010; Rubin et al., 2014) and only few researchers paid attention on evaluation the impact of upstream hydropower dams on the VMD (Binh et al., 2017; Hoa et al., 2007; Kantoush et al., 2017; Manh et al., 2015).

A GIS-linked hydraulic model HydroGis was employed by (Hoa et al., 2007) to study the impact of local man-made structures, sea level rise, and dams upstream the MR individually and in combination on the flooding in the VMD. Flow velocities in the main rivers and channels are increased in areas protected by dyke systems. River banks and beds in those areas are then vulnerable to be eroded, leading to a deeper and stronger flow, which in turn may cause catastrophic failure of dykes in the protected areas. Unprotected areas will suffer from bigger inundation due to the propagration of flood wave from protected regions. In addition, dams in the MRB result in an increase in estuarine siltation in the VMD, enhencing the flooding in the delta, especially under the impact of sea level rise. A closer cooperation in transpoundary water resources management between countries in the MRB was then recommened to sustainably share limited water of the transboundary MR. They also recommended to authorities of the VMD that flooding in the VMD which not only is necessary for agriculture but also help prevent catastrophic flooding in unprotected areas should be allowed.

(Manh et al., 2015) used sensitivity-based approach supported by a quasi-2D hydrodynamic model of suspended sediment dynamics to investigate the future flow and sediment dynamics in the VMD under the impacts of hydropower dams, climate change and sea level. They found that hydropower dams upstream of the VMD has the highest impact on the flow and sediment dynamics in the delta, followed by climate change and sea level rise. Hydropower dams reduce sediment supply to the VMD. They also reduce the flow in the rising and high stages of flood season in the delta, which declines the sedimentation in the VMD’s floodplains. On the other hand, climate change causes an increase in the flood discharge which makes more areas in the VMD be inundated with a prolonged duration. Climate change also increases sediment input to the MRB and sedimentation in the VMD. However, such increase is far less than the reduction caused by hydropower dams. Having the lowest impact, sea level rise will magnify the flooding in the VMD caused by the main MR. Such extra flooding then expands the sedimentation area in the delta. The combination of three driving forces (hydropower dams, climate change, and sea level rise) leads to a slight increase in inundation extent, but a huge sedimentation in the VMD’s floodplains and sediment load to the East Sea of Vietnam.

Given the damage in the VMD caused by drought event in 2015-2016, (Kantoush et al., 2017) conducted a research to investigate the possible impacts of eleven proposed hydropower dams in Thailand, Lao PDR and Cambodia and climate change on the VMD in case if such drought event happens in the future. One dimensional hydrodynamic model was established for the whole VMD from Vietnam-Cambodia border to the seas. The results showed that eleven proposed dams may lead to a decrease in the discharge in the VMD, maximum of about 15% at CanTho. On the other hand, the combined effect of eleven dams and 47cm sea level rise due to climate change may cause an increase in water level up to 220% at MyTho. Such phenomena are more likely to result in an increase in salinity intrusion, coastal flooding, and lack of fine sediment and natural nutrients to the VMD’s floodplains.

Based on their research, (Binh et al., 2017) then further investigated in impacts of existed and planned hydropower dams in the mainstream of the MR and climate change induced sea level rise on the VMD by analyzing the historical data and numerical simulation. They found that six existed hydropower dams in the Lancang cascade in China reduced the water level at TanChau station by approx. 1m compared to the 1993-2001 period when only one dam was in operation. Two dimesional depth averaged model was developed by using Telemac2D for the whole VMD with a mesh of more than 6.5 million nodes using space steps of 10m and 50m in rivers and channels and a space step of 100m in the floodplains.

3. Recent drought event (2015-2016)

River-damming along with the effect of El Nino, have caused the most severe drought event in 2015-2015 over the past 90 years. All 13 provinces of the VMD are severely affected by this drought event. Discharge in the upstream of the MR reduced by 900 m^3/s (CGIAR, 2016). The measured water levels were at their lowest values since 1926, even much lower than those measured in drought year 1998 (Fig. 4). The figure shows a reduction of 3m by comparing water level on 22 of September 2000 and 2015. Correspondingly, sediment concentrations in 2015 were lower compared to precedent years (one fourth of 2011) (Fig. 5).

The drought event in 2015-2016 was accompanied by saltwater intrusion in the VMD. Saltwater has intruded 45-65km in Tien River and 55-60km in Hau River (CGIAR, 2016), which is 20-25km further than seasonal average values. Salinity concentrations at AnLacTay (Fig.1) in 2015 and 2016 are much higher than recorded values in previous years (Fig. 6). The figure indicates that salinity concentration of 2016 is about 6 g/l higher than that of 2005 and 2007. As a consequence, approximately 159,000 hectare (ha) paddy fields were damaged; around 195,217 households lacked fresh water for daily consumption by the end of 2015. Finally, this drought event damaged around 400,000 ha rice crop, 13,000 ha cash crops, 25,500 ha fruit gardens, and 14,400 ha aquaculture and caused shortage of freshwater for 208,394 households (CGIAR, 2016).

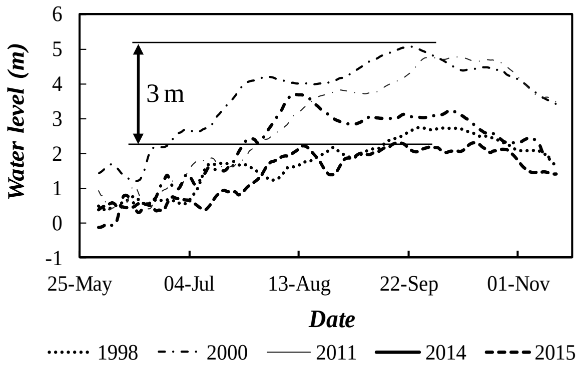

Fig. 4 Measured water level in flood season at Tan Chau

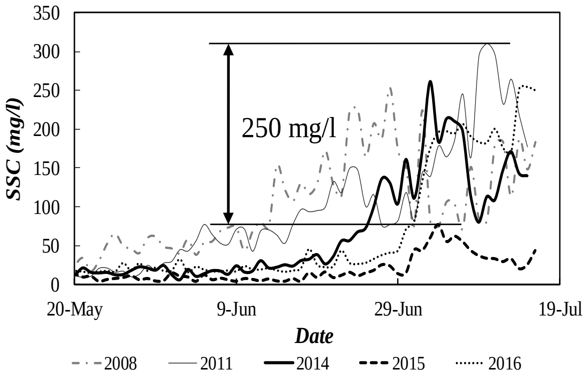

Fig. 5 Suspended sediment concentration at Vam Nao

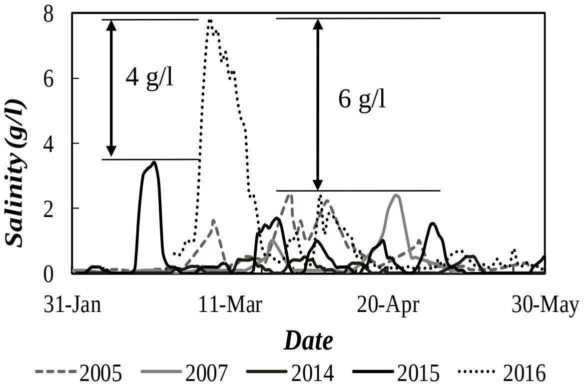

Fig. 6 Salinity concentration at AnLacTay

Obviously, the impacts of a similar drought event 2015-2016 in the future will be more severe if accompanied by building more dams upstream and increasing sea level induced by climate change. The possible impacts of the former are demonstrated elsewhere in section 1. For the latter, sea level rise will lead saltwater intruding more deeply inland which in turn will result in an increase in the affected extent. Particularly, sea level rise may cause the loss of cultivation land as a result of increasing flooding inundation in the coastal areas, the lack of fresh water due to increased salinity intrusion, and the difficulty of livelihoods of million local people in the delta (Hoa et al. 2007; MONRE 2009; Tri et al. 2013; Thu and Wehn 2016). Sea level in the VMD has already risen by 20 cm since 1901 (CGIAR, 2016). Given that the average increase in sea level is around 3 mm per year (CGIAR, 2016).

Taking the above mentioned into consideration, the objectives of this research are to evaluate the (1) impacts existed upstream dams on the VMD and (2) impacts of eleven proposed dams in Thailand, Laos and Cambodia on the VMD under seas level rise induced by climate change.

4. Turbidity and salinity monitoring campaign

(1) Measurement campaigns

Apart from the certain effect of El Nino causing less rainfall than average, our hypothesis is that the existing hydropower dams in the Upper Mekong (UM) have exacerbated the severity of the drought 2015-2016. Operations of hydropower dams in such a way of maximizing electricity generation have caused the shortage of base flow in the VMD. For such consideration, in the framework of JASTIP project

(Japan-ASEA Science, Technology and Innovation Platform http://jastip.org/en/project/disaster_prevention/) we established a project to study the impacts of hydropower development in the UM on hydrology, sediment, and salinity changes in the Lower Mekong (LM) with special focus on the VMD.

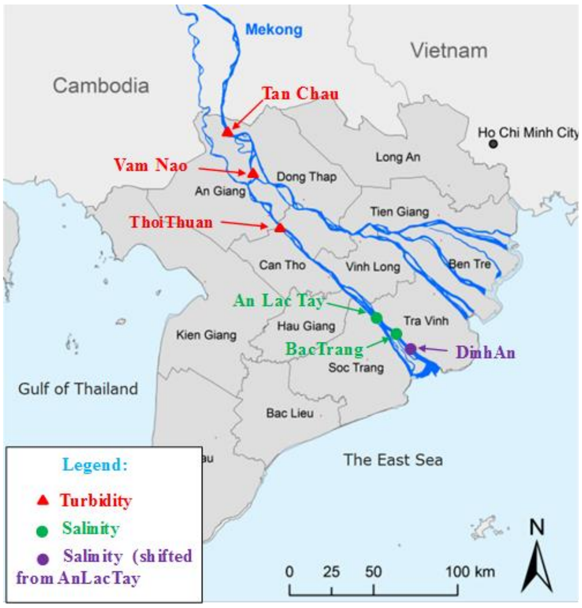

Fig. 7 Location map of measurement instruments

Under this project, we conducted two campaigns to install instruments for turbidity and salinity measurement outspread over the delta. Turbidity meters were installed in the upper part of the VMD while salinity meters were set up in the lower part of the delta (Fig. 7). In the first campaign taken on February 26-28, 2016, two turbidity meters were installed at TanChau and Vam Nao stations and the location of a salinity meter was in AnLacTay station (Fig. 7). As described above, TanChau station in Tien River is one of the two main entrances of the VMD which is several kilometers from the Vietnam-Cambodia meter. VamNao station is about 30 km downstream of TanChau station, locating in VamNao river which is the secondary channel diverting water from Tien River to Hau River. AnLacTay station locates in Hau River on the right bank looking downward. It is about 50 km from the East sea (Fig. 7).

The second campaign was conducted on February 10-11, 2017, about one year after the first campaign. One turbidity and one salinity were installed. Turbidity meter was placed in Hau river in ThoiThuan commune, ThotNot district, CanTho city (Fig. 7). It is about 120 km downstream of ChayDoc station (the entrance of Hau river to the VMD). Installation location of salinity meter was on the left bank of Hau River, about 25 km from the river mouth and around 25 km downstream of AnLacTay station (Fig. 7). However, the salinity concentration at AnLacTay station was too small in 2017, therefore it was shifted downstream to DinhAn station also in Hau river to be able to continuously measure salinity concentration. DinhAn station is about 20 km from the estuary (Fig. 7). Installation activities of all instruments can be typically seen in Fig. 8.

The turbidity and salinity meters used in this project are Infinity-ATU75W2-USB and Infinity-ACTW-USB, respectively (Fig. 9). The instruments used 4 pieces of one-time-use battery which can be used up to 5 months of continuous measurement.

Fig. 8 Instrument installation activities

Fig. 9 Salinity (left) and turbidity (right) meters

The turbidity meters record the measured values once every 15 minutes and 30 minutes were set up for salinity meters. To overcome the possible error of the reading, ten values were recorded in each time of a measurement within 10 seconds, then averaged. Periodical field investigations (3 times a year) are implemented to collect measured data and observe real changes by photographs. The first time is in the dry season in January/February. The second time is at the rising stage of the annual flood, usually in June/July. The third time is during the high stage of the flood flow, normally in September/October. Part of data from our measurement campaigns were included in Fig. 5 and 6 as well.

(2) Suspended sediment and salinity concentration measurement at existed main hydrological stations in the VMD

Suspended sediment and salinity concentrations in Tien and Hau Rivers have been monitored annually by some governmental agencies. In the upper part of the Mekong and Bassac Rivers, suspended sediment concentrations (*SSC*) have been measured at five main national hydrological gauging stations, including TanChau and MyThuan in Tien River, ChauDoc and CanTho in HauRiver, and VamNao in

Fig. 10 Ships used for *SSC* measurement

VamNao River which connects Tien and Hau Rivers (Fig. 1). At these stations, *SSC*s have been continuously measured since 1999. Before 1999, they were randomly measured. The measurements are conducted by ships (Fig. 10). Measurements of the *SSCs* in the dry season are conducted twice a day at the representative position of each cross section (normally this representative position is around the middle of the river), one in the rising phase and one in the falling phase of the tide. On the other hand, four times per day are considered to measure *SSCs* in the flood season, two in the rising and two in the falling of the tide. Daily *SSCs* are obtained from averaging values of measurements within a day.

Fig. 11 Station of salinity concentration measurement

Agriculture, especially rice fields, and aquaculture are extensively developed in the VMD. These two sectors are sensitive to salinity concentration. It is therefore extremely important to monitor salinity concentration penetrating to rivers and channels in order to have proper actions. Some salinity stations were established along main rivers and its branches such as Dai, Tieu, HamLuong, CoChien branches in Tien River and DinhAn and TranDe in Hau River. In one branch, several some location for salinity concentration measurement in track the pathway of saltwater. Most of stations measure salinity manually, but few station now use the automatic salinity meter, fixed in a bridge house as in the Fig. 11. For such automatically measured apparatus, hourly salinity concentrations are recorded.

(3) Strategy in selection of monitoring sites under our project

As stated above, the main method for the measurement of *SSC* and salinity concentration at existed stations in main rivers in the VMD have been recently done manually. Such manual measurements are not accurate enough in guaranteeing providing full picture of variation of these parameters. Our measurement campaigns were therefore launched under JASTIP project for which both turbidity and salinity concentrations are continuously monitored.

(a) Turbidity measurement

Approximately 80% of water from the upstream of the MR flows through Tien River and the remaining 20% is conveyed by Hau River. The flow budget is then balanced thanks to VamNao river playing as the diversion channel from Tien to Hau River. Simultaneously, Tien and Hau Rivers transport about 85% and 15% of sediment load to the East Sea, respectively (values calculated at TanChau and ChauDoc stations from (Manh et al., 2014)). Similar to the flow, about one third of sediment in Tien River is diverted to Hau River through VamNao river. As a result, the sediment ratios between Tien and Hau Rivers become 61% and 39%, respectively (again these values are calculated from (Manh et al., 2014)). It is worth noting that suspended sediment in the VMD is prominent by fine grain size with d_{50} = 2.5-3.9 μm in the freshwater near the estuary of Hau River, of which most sediment is fine silt and small amount of clay (15%) (Wolanski et al., 1996).

Stemming from the sediment budget consideration in the VMD, our strategy for selecting the measuring locations has twofold: (1) to use our continuously measured data (once in every 15 minutes) to check the reliability of existed data provided by the National Hydro-meteorological Data Center, and (2) to investigate the sediment dynamics and then sediment budget in the VMD. Hence two turbidity meters were installed at TanChau and VamNao stations (Fig. 7) in Tien River and another one was leaved at ThoiThuan station (CanTho City) in Hau River (Fig. 7).

The measurements of *SSC* at five existed main hydrological stations in Tien and Hau Rivers as indicated above are standardized under the framework of the Mekong River Commission (*MRC*); therefore, the comparison of our new measured data with theirs at TanChau and VamNao stations will allow us to justify whether existed data at other stations are reliable to use or needed to have further transformation before utilized. Moreover, the selection of TanChau and VamNao stations for installing our instruments derives also from the fact that the river section between these two stations is very dynamic. Severe erosion happens every year, especially in some islands. By comparing our new high-frequency measured data at these two stations (15 minutes' interval), we can understand the sediment dynamics which determines the erosion or deposition patterns at specific locations.

A question then arises that what is the role of VamNao River in balancing sediment between Tien and Hau Rivers? To make this question answerable, ThoiThuan station was chosen in placing a turbidity meter. Giving the known *SCCs* at ChauDoc station (obtained from the National Hydro-meteorological Services), at VamNao station, and at ThoiThuan station, it is straightforward to understand the contribution of VamNao River in diverting sediment from Tien to Hau River.

(b) Salinity monitoring

In drought event 2015-2016, salinity has intruded up to 55-60km in Hau River, which is about 20-25km deeper than as usual (Kantoush et al., 2017). We then decided to establish a station to monitor salinity at AnLacTay station (Fig. 7). The reason behind was to track such abnormal salinity pathway to understand how long and how high of the salinity concentration in that drought event. Our obtained data reveal that the maximum salinity concentration was 7.8 g/l at this station on March 6, 2016 which is much higher than those values of 2.4 g/l in 2005 and 2007, and 0.5 g/l in 2014. However, salinity concentration in 2017 is very small. It is noticeable that detection of saltwater at AnLacTay lasts for only about 6 months from January to

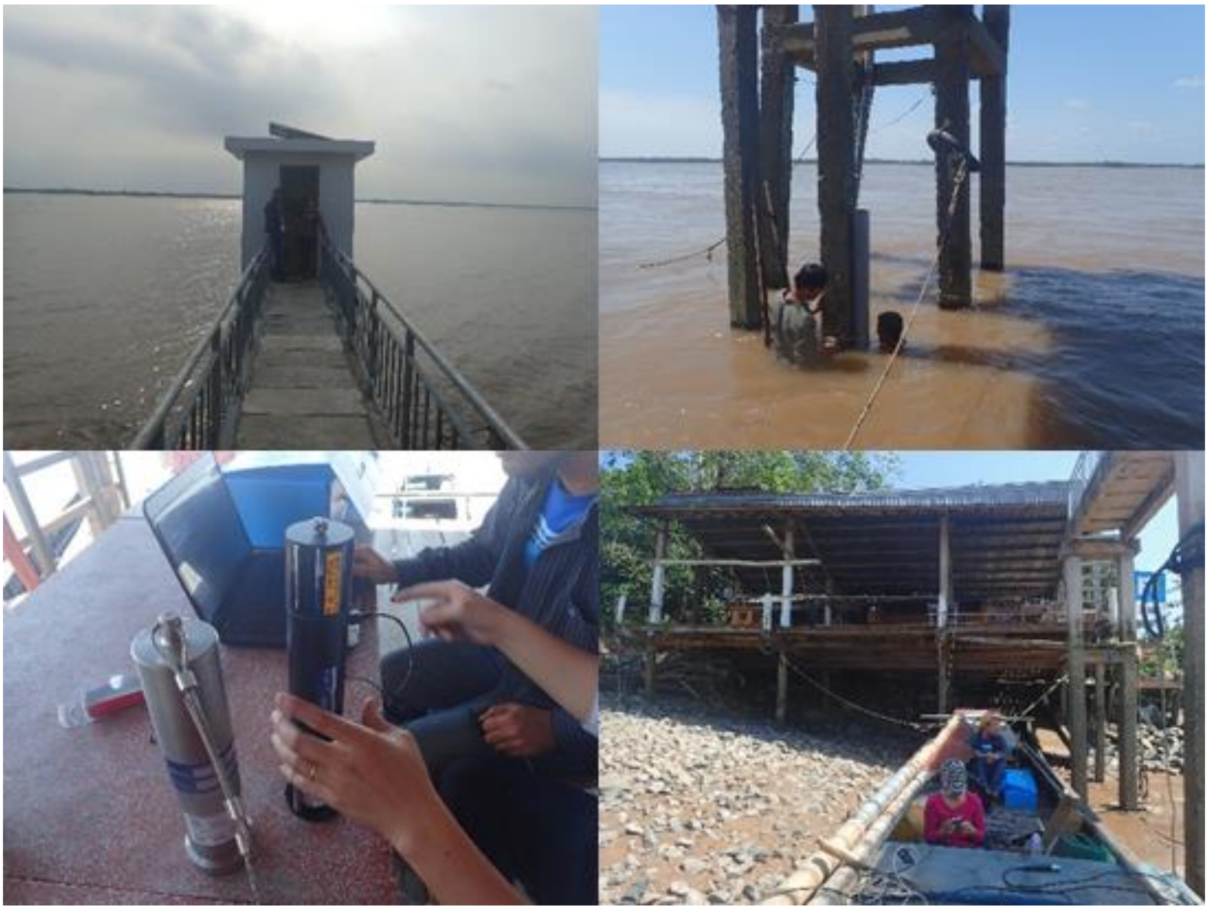

Fig. 12 Installation of salinity meter at BacTrang

June when water levels are at their low values. In flood season from July to December, salinity is undetectable. Given that we decided to shift our device from AnLacTay to DinhAn station which is about 35 km downstream of the former (Fig. 7) in order to be able to track salinity concentration all year round. The installation at DinhAn station was done in April 2017.

Another salinity meter was installed at BacTrang station (Fig. 7) in February 2017. Fig. 12 shows our installation activities in this station. Actually, there exists a salinity station there under the management of Department of Agriculture and Rural development of TraVinh province. Unluckily only daily salinity concentrations were shared, therefore, the monitored data from our side at this station later on can be compared with theirs. The strategy of this location selection is also similar with that of turbidity. Firstly, we later on can compare our monitored data with theirs to cross check the reliability of such data sets. Next, when confirmed the reliability of their data sets, we can use existed salinity data at other stations under their management which have been monitored in the same manner.

The continuous monitoring with high-frequency recorded data (30 minutes' interval) at BacTrang and DinhAn stations (DinhAn is 10 km seaward from BacTrang) will be the mean of investigating the dynamics of saltwater intrusion in Hau River. It is expected that such continuous measurements will help us to understand how fast saltwater moves landward by comparing salinity concentration at DinhAn and BacTrang at the same time. We next can also know the evolution of salinity over time. Moreover, inter-annual variation of salinity concentration related to dam construction upstream of the MR will also be detected.

5. Impacts of Lancang hydropower cascade on the VMD

(1) On the hydrodynamics

Manwan is the first hydropower dam in the Lancang cascade constructed in 1986 and started filling the reservoir in 1993 (Lu and Siew, 2006; Fan et al., 2015). Then a series of other 5 hydropower dams began successive operations: Dachaoshan (Nov. 2001), Jinghong (Apr. 2008), Xiaowan (Dec. 2008), Gongguoqiao (Sep. 2011), and Nuozhadu (Nov. 2011) (Fan et al., 2015). Among these, Nuozhadu and Xiaowan are the two biggest dams in terms of reservoir capacity. Given the reservoir filling time into consideration, the assessment of the impacts of Lancang cascade on the VMD from 1980 to 2015 in considered in 5 periods (Fig. 13). The pre-dam period is from 1980 to 1992 in which there was no dam constructed. The flow regime in this period was anthropogenic undisturbed. The post-dam period consists 4 sub-periods according to the completion of each dam (Fig. 13) to assess the possible impacts of individual and group of dams separately.

Daily water levels of each period are averaged and plotted together. Fig. 14 shows that in flood season (from July to December), both flood peak and duration are decreased with increase the number of hydropower dams upstream. Till 2008, there are 4 dam completed but their reservoir capacities are small. The second largest dam, Xiaowan, started filling its reservoir in December 2008. Therefore, although Xiaowan dam is in the period 2002-2008 but its full impacts on flow downstream is properly from the next period, 2009-2011. Given that, the impacts of Lancang cascade is not necessary until 2008.

Since 2008, the impacts of hydropower dams on flood flow regime in the VMD are obvious. As a common rule of reservoir operation, it fills the water in the beginning and discharge water at the end of flood season. Therefore, from July to September (Fig. 14) the water level significantly reduced compared to pre-dam period. Especially, period 2011-2015 (including drought year 2015) is abnormally smaller than other periods, about 0.5m smaller than pre-dam period and 1m smaller than 1993-2001 period. Because the owners of Lancang cascade are not willing to share data related to their dams to public, therefore it is too difficult to understand what is the reason for such abnormally small water levels. The possible explanation is that these lancang cascade were trying to kept almost water generated in Chinese part for their own use for maximizing electricity generation. Another possible reason is that there was likely a water diversion from Lancang cascade to other catchments other than the MRB to help Chinese overcome the water shortage in 2015. This explanation is also reasonable because in 1998 (in period of 1993-2001), there was a similar drought event (total flow volume in TanChau and ChauDoc stations in 1998 is even smaller than that in 2015) but the water levels in 1993-2001 period is still highest among 5 designated periods.

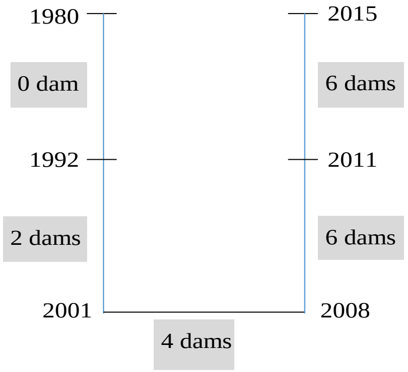

Fig. 13 Assessment periods and number of dams accordingly

Fig. 14 also reveals that duration of flood season in post-dam periods are reduced compared to that of pre-dam period. Flood duration in the VMD is not sensitive to two periods 1993-2001 and 2002-2008 when there were 2 dams and 4 dams (Fig. 13), respectively. In others words, the impacts of the first four dams in Lancang cascade are not much influencing

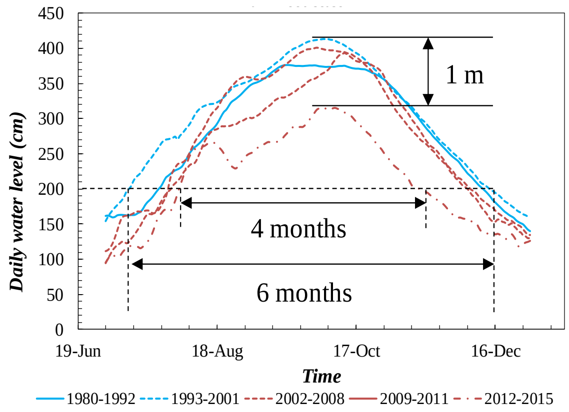

Fig. 14 Water levels at TanChau station in flood season

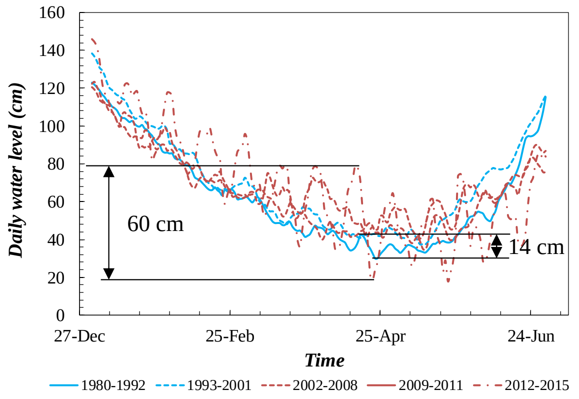

Fig. 15 Water levels at TanChau station in dry season

the flood duration in the VMD. However, the period 2012-2015 when six dams in Lancang cascade in operation significantly reduces the flood duration in the VMD. If taking water level at 2 m as a reference line, flood duration reduces from 6 months in pre-dam period to 4 months in post-dam period of 2012-2015. It is worth noting that flood season is extremely important for the development of the VMD. The VMD needs normal flood for getting natural nutrients attached with fine sediment provided by the upper part of the MRB of which 50% comes from the Lancang basin (Milliman and Syvitski 1992; Ta et al. 2002; Fu and He 2007; Gupta and Liew 2007; Walling 2008; Kondolf et al. 2014).

In the dry season (from January to June), water discharges in the VMD are increased. The maximum increase in discharge at TanChau station is about 2,000 m^3/s. It is likely thanks to the regulation of Lancang cascade. However, plotting of the water levels in pre-and-post dam periods (Fig. 15) may guide us to another story. The figure shows that the fluctuations of water levels in post-dam periods are increasing with the increase in the number of dams constructed. Such fluctuations are in the form of tidal circle. In other words, the tide has increasingly intruded to the upper parts of the VMD in post-dam period, which is less in pre-dam period. The tidal amplitude has increased 46 cm at ChauDoc station in post-dam period in comparison with pre-dam period (Fig. 15). Therefore, the increase in the discharge in the dry season in the VMD is more likely because of the increased influence of the tide rather than Lancang cascade dam operation. Increased tidal influence is more likely to be accompanied by increasing salinity intrusion to the VMD which will cause many serious problems to livelihood of thousands of local people as seen in drought event 2015-2016 in section 3.

(2) On the saltwater intrusion

The VMD is affected by tides with two different regimes. The semi-diurnal tide in the East sea influences large areas including estuaries of Tien and Hau River. The tide rises and retreats twice every day. The diurnal tide in the West sea influences a smaller area in the west of the VMD. The tide reaches its peak and bottom once a day. The semi-diurnal tide in the East sea is stronger than the diurnal tide in the West sea. The magnitude of the former is about 2.5-3m while the latter has smaller magnitude of around 0.5-1m. The boundary of saltwater moves along the rivers accordingly to the variation of the tides. The average tidal-affected area in main rivers is about 40-45 km from the river mouths. People in tide-affected areas have been adapting to such environment by earning their livings from aquaculture (fish and shrimp farms). However, they are very sensitive to the changes of salinity

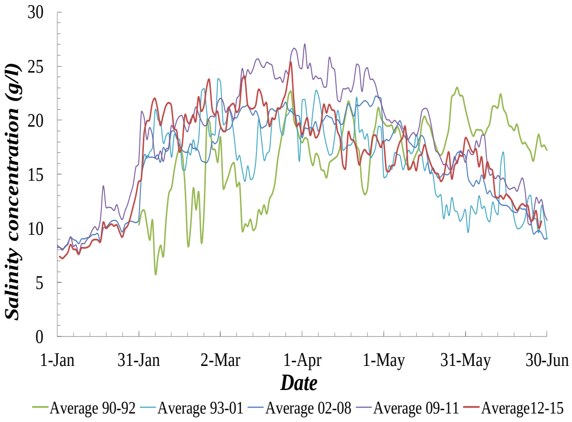

Fig. 16 Salinity concentrations at AnThuan station in dry season

concentration, caused by upstream development, especially hydropower dam expansion.

Salinity concentration in main rivers in the VMD is sensitively responded to the construction of Lancang cascade hydropower dam construction. The typical changes of salinity concentration in the VMD from pre-to-post-dam period can be seen at AnThuan station in HamLuong branch of Tien River (Fig. 16). In pre-dam period (1990-1992, because salinity concentration data before 1990 are not available), salinity concentration is the much lower than those in post-dam periods. While the annual maximum salinity concentration in pre-dam period is about 22.5 g/l, such concentrations in 2009-2011 and 2012-2015 periods are 27 g/l and 25.5 g/l, respectively. It is stressed that all six Lancang cascade dams completed in 2009-2001 period and become stably operated since 2012. That implies that Lancang dams have caused more saltwater intrusion in the VMD. It is of important concern because the owners of these dams have always emphasized that the appearance of these dams helps increase the dry season flow in downstream areas.

Another impact of Lancang cascade on salinity regime in the VMD is in changing the timing of saltwater intrusion (Fig. 16). If salinity concentration at AnThuan station started rising from March in pre-dam period, the timings of increasing salinity concentration in post-dam periods are shifted occurring in February which is about 1 month earlier than pre-dam period. It is understandable because this time is at the beginning of the dry season when upstream reservoirs stop releasing water downstream to save for the electricity generation during the coming dry season. Such shifting is harmful to agriculture, especially ricer fields because this time is in Winter-Spring rice crop which is the most productive and important in the VMD.

It is worth noting that the salinity concentrations in the latest period do not include those in the driest drought year 2016 because of the lack of available data. However, one can imagine that salinity concentrations of 2012-2015 period will be much more increased if salinity concentration data in 2016 are compiled with. Inter-annual variations in salinity concentrations of 2012-2015 period are then analyzed in conjunction with those in the drought year 2016 at stations where data are available to have a deeper understanding on how all six Lancang dams impact on salinity concentration change annually in the VMD. Annually maximum salinity concentrations at different stations in the VMD are used for this analysis (Fig. 17). The figure also contains the position of each station from the river mouth. As can be seen that salinity concentrations increase year-by-year since 2012. This is the consequence of Lancang dams. As a limited known information on the water utilization in the UMB in China of which this country strictly limits access to monitored data to international researchers, especially during and after the development of the Lancang cascade (apart from Lancang cascade is hydropower scheme), the authors suspect that there may have a water diversion from Mekong River to other river basins in Chinese parts. However, this suspension must be further investigated by other researchers who are able to put a hand on Chinese data sets.

Obviously, salinity concentrations in 2016 are much higher than average values in 2012-2014, maximum difference can reach 10-15 g/l in some

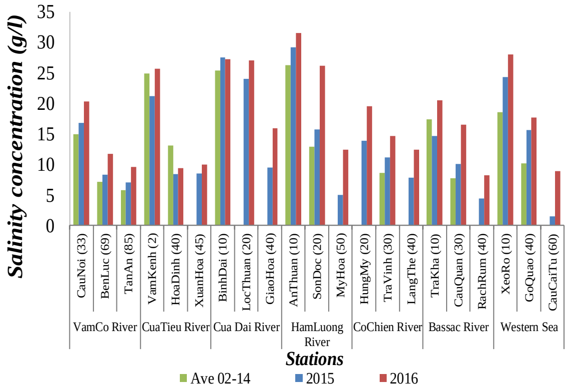

Fig. 17 Annually maximum salinity concentrations in the VMD

stations. The impacts of upstream hydropower dams' regulation on salinity dynamics in the VMD, especially in the extreme dry event is the gap in our knowledge and it is out scope of our research. Filling this gap is welcomed for other researchers.

6. Prediction on the impacts of eleven proposed mainstream hydropower dams in the LMB on the VMD under climate change

The prediction of hydrology changes in the VMD under the development of 11 dams in Laos, Thailand, and Cambodia along with sea level rise were investigated by (Kantoush et al., 2017). This part we attempt to summarize their work. The prediction of the impacts were preformed using Mike 11 hydrodynamic model developed by DHI (DHI, 2009). The model solves the 1-D Saint Venant equations using an implicit finite difference scheme. Details of the model setup and results will be introduced in the following sub-sections.

(1) Model setup and scenarios

The model was set up for the whole VMD, including 2,551 branches with 13,429 points as in Fig. 18. In the model, hourly discharges at TanChau and ChauDoc stations are used as upstream boundaries whereas hourly water levels at seven stations along the coast, including MyThanh, BenTrai, VamKenh, GanhHao, SongDoc, BinhDai, and RachGia are prescribed as downstream boundary conditions. One hundred and fourty-five (145) cross sections describing the geometry of Tien river from TanChau to MyThuan (see Fig. 1b) are updated to 2014 whereas cross sections measured in 2010 are applied elsewhere.

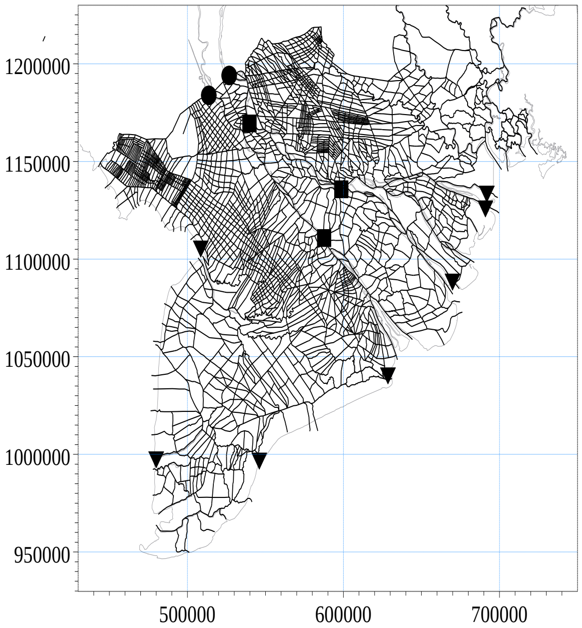

Fig. 18 1-D hydrodynamic model setup

Three scenarios are used to simulate changes of hydrology in the VMD (Table 1). The baseline (Sc0) refers to discharges and water levels of the drought year 2015. Scenario 1 (Sc1) considers the impact of 11 dams. In scenario 1, discharges at Tan Chau and Chau Doc are reduced by 1.9% and 2.5% (DHI-HDR, 2015), respectively, in between January and May and by 0.5% in June (DHI-HDR, 2015) compared to the baseline (Table 1), but water levels remain unchanged. Scenario 2 (Sc2) is similar to Sc1 but sea level rise is considered at the downstream ends.

According to (Doyle et al., 2010), sea level increases by 5.5 mm/year under high emission scenario. Therefore, water levels of scenario 2 are those of 2015 increased by 47 cm as the total increase in water level up to the year 2100.

Table 1 Simulation scenarios

Scenarios	Description of boundary condition	Remark
Baseline (Sc0)	-Upstream: discharge hydrograph of 2015 -Downstream: water level stage of 2015	*Without dam and without sea level rise*
Scenario 1 (Sc1)	-Upstream: discharge hydrograph of 2015, considering 11 proposed dams -Downstream: water level stage of 2015	*With dam and without sea level rise* - Jan. – May: -1.9% at TanChau and -2.5% at ChauDoc - Jun. : -0.5% at both TanChau and ChauDoc
Scenario 2 (Sc2)	-Upstream: discharge hydrograph of 2015, considering 11 proposed dams -Downstream: water level stage of 2015, considering sea level rise 47 cm	*With dam and with sea level rise* -Jan. – May: -1.9% at TanChau and -2.5% at ChauDoc - Jun. : -0.5% at both TanChau and ChauDoc -Water level of 2015 + 47cm (high emission scenario - A1FI – increasing 5.5mm/year (Doyle et al., 2010))

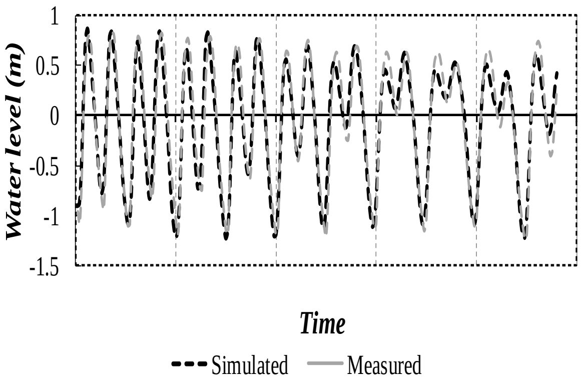

Fig. 19 Predicted and measured water levels at CanTho station

Table 2 Values of two performance indicators at three stations.

Station	VamNao	MyThuan	CanTho
Calibration (2015)			
R^2	0.913	0.936	0.978
E_f	0.807	0.862	0.913
Validation (1998)			
R^2	0.877	0.97	0.95
E_f	0.727	0.912	0.890

(2) Model validation and results

Water levels at VamNao and MyThuan stations in Tien River and CanTho station in Hau River (see Fig. 1b) of the year 2015 are used to calibrate the model. The model is validated using water levels measured at the same stations during the drought year 1998. Computed versus measured water levels at CanTho station are plotted in Fig. 19. The accuracy of the numerical results is evaluated using correlation coefficient (R^2) and Nash-sutcliffe coefficient (E_f) (Table 2). Based on these performance indicators, one can see that a satisfactory model-data agreement is obtained.

Hydrological parameters of the VMD are directly affected by changes in the upstream discharges at TanChau and ChauDoc and downstream water levels along the coast. Table 3 shows the reduction in average simulated discharges and the increase in average simulated water levels within the studied period (Jan. – Jun.) under different scenarios. Moreover, Fig. 20 shows a comparison between the difference in Sc1 and Sc2. The difference between scenarios is calculated as follow the equations 1 and 2:

$$(Scx - Sc0) = \frac{\sum_{i=1}^{N}(A_{Scx\_i} - A_{Sc0\_i})}{N} \tag{1}$$

$$P(\%) = \frac{\sum_{i=1}^{N}[(A_{Scx\_i} - A_{Sc0\_i})/A_{Sc0\_i}.100]}{N} \tag{2}$$

where: (*Scx-Sc0*): the difference of discharges or water levels in absolute values between scenario *x* (*x=1: scenario 1 and x=2: scenario 2*) and the baseline (*Sc0*); A_{Scx_i}, A_{Sc0_i}: discharge or water level of scenario x and

Table 3 Average discharge reduction and water level increase within the simulated period (Jan. – Jun.) in VMD under different simulation scenarios at eight measurement stations

Station	**TanChau**	**VamNao**	**MyThuan**	**MyTho**	**ChauDoc**	**LongXuyen**	**CanTho**	**DaiNgai**
Discharge reduction (m^3/s)								
(Sc1-Sc0)	-63.8	-31.6	-27.0	-9.6	-13.8	-50.6	-50.0	-17.1
P (%)	-1.7	-2.2	-1.2	-0.5	-2.1	-2.8	-2.9	-3.6
(Sc2-Sc0)	-63.8	-24.1	-34.8	-16.3	-13.8	-213.8	-260.2	-22.2
P (%)	-1.7	-1.0	-2.8	-2.7	-2.1	-11.6	-14.9	-4.6
Water level increase (cm)								
(Sc2-Sc0)	0.423	0.436	0.456	0.467	0.436	0.452	0.458	0.467
P (%)	94.6	127.1	75.5	221.2	139.2	172.6	162	25.7

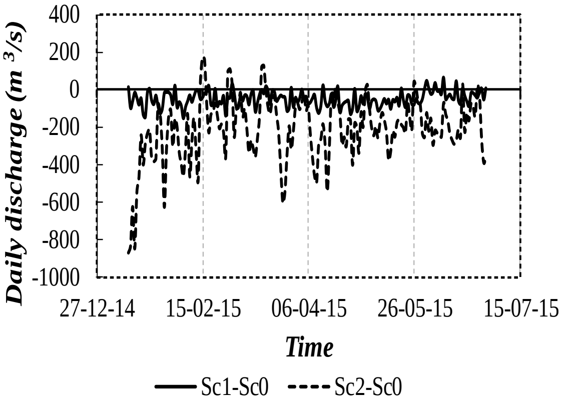

Fig. 20 Discharge reduction of scenario 1 and 2 compared to the baseline in solid and dash lines at LongXuyen station

the baseline, respectively, at day i^{th}; *P(%):* the difference of discharge or water level between scenarios and the baseline in percentage; *N*: number of days within Jan. – Jun. If (*Scx-Sc0*) (or *P(%)*) is possitive, discharge or water level will increase, vice versa they will decrease.

Under the reduction of discharges at TanChau and ChauDoc (*Sc1*), flow discharges at stations VamNao, MyThuan and MyTho in Tien River and at LongXuyen, CanTho, and DaiNgai in Hau River are reduced by 0.5 to 3.6% in average (Table 3). In Tien River, the maximum reduction of discharge is obtained at TanChau station with a mean value of 63.8 m^3/s, while in Hau River it is LongXuyen station that experiences the maximum reduction (50.6 m^3/s). More seriously, discharges in VMD are even more reduced in *Sc2* which further considers the influence of sea level rise. For example, mean discharge at CanTho station drops by 260 m^3/s, corresponding to 14.9% - the maximum reduction among stations (Table 3). In contrast, water levels at all stations in the VMD are increased, a clear example from MyTho station is shown in Fig. 21. Water levels in stations near the sea increase faster than those

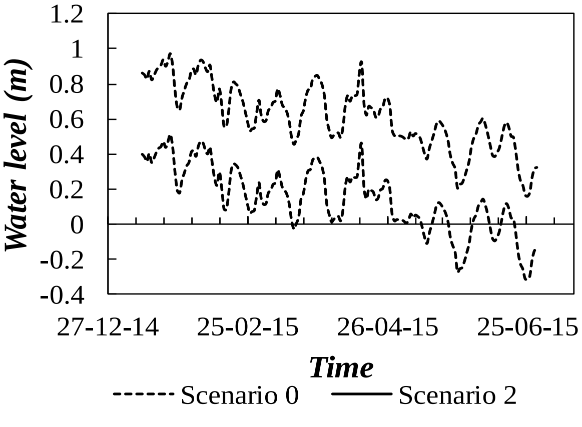

Fig. 21 Increase in water level of scenario 2 compared to the baseline at MyTho station

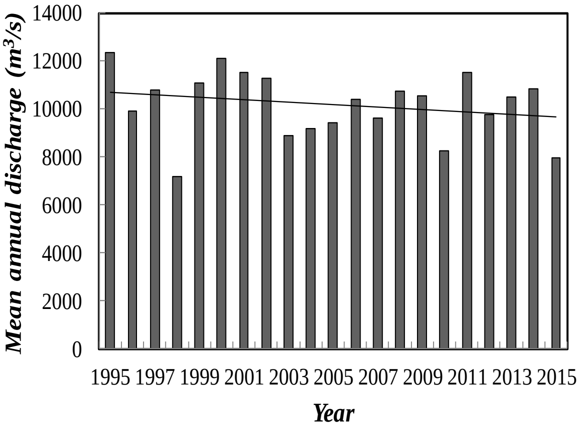

Fig. 22 Mean discharge at TanChau station

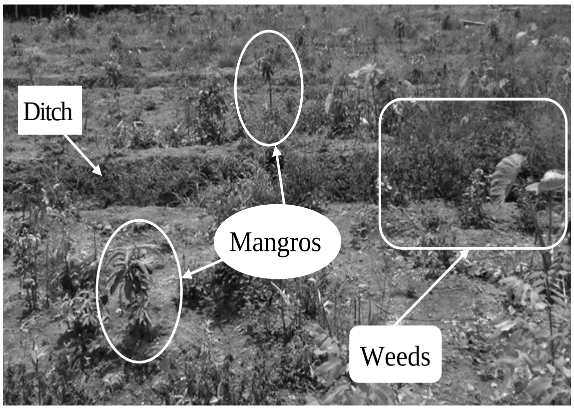

Fig. 23 Damaged fruit-garden in KeSach district-SocTrang province. Died mangosteen was replaced by new mango

in upstream sections (Table 3). Among these, water levels at MyTho station increase the most with over 220% (Table 3).

7. Discussion

Because of the geographical location, hydrology and salinity of the VMD is strongly dependent on activities of upstream countries such as dam construction and irrigation development. To date, China has completed six dams of the Lancang cascade in the UMB, in which Manwan was fully operated in 1996 and Nuozhadu in 2012 (Fan et al., 2015). Consequently, VMD has undergone a decreased trend in flow discharge (Fig. 22) which has caused saltwater more intruding upward. Obviously, Chinese dams must be the cause of water decrease in VMD. More seriously, two drought events happened just after the first and the last dams, in 1998 and 2015.

Recently, there are other eleven dams proposed by Thailand, Lao PDR, and Cambodia in the mainstream of MR. Results from scenario 1 show that these eleven dams will cause flow discharge declining in VMD from 0.5 to 3.6%. The Hau River experiences higher reduction than Tien River. Moreover, the further the areas from Vietnam-Cambodia border is, the more the reduction in flow discharges will be. Importantly, these proposed dams together with existed ones in China may lead to the disappearance of floods in the upper parts the VMD, which is extremely crucial to livelihoods of millions of people there.

Low discharge observed at the upper of the VMD during the drought event of 2015-2016 caused saltwater intruding deeply into lands, thereby resulting in detrimental impacts on agriculture and aquaculture. The drought of 2015-2016 has led to total damages of 31,198.94 ha (approximately 2.2 million US dollars) in only SocTrang province. Many regions, where paddy fields with 27,004.16 ha were affected, have reduced their agricultural productivity (Fig. 23).

As predicted by scenario 2, flow discharges are much reduced and water levels are increased in VMD (Table 3). Discharges at Can Tho station decrease the most with 14.9% while MyTho station faces an increase of more than 220% in water level. This causes saltwater significantly to intrude into the upper parts. It means that more areas, including regions having not been affected before, will be covered by saline water with higher concentration.

Sea level rise may also increase flooding in coastal regions of VMD (Hoa et al., 2007). Furthermore, because of decreasing discharges and increasing water levels, flow velocity will be reduced in the channels. Nutrient-rich sediment will deposit preferentially in rivers instead of conveying into floodplains that may lead to a reduction of agricultural productivity in a near future.

8. Conclusions

Hydropower dams upstream of MR are and will be leading to detrimental impacts to the VMD. Agricultural productivity has been reducing due to huge reduction of sediment supply from upper Mekong. In the other hand, increasing saltwater intrusion has been causing the shortage of fresh water for local people livelihoods. It also caused huge damage to agriculture, fisheries, wetlands, and ecosystem in the VMD, especially in the drought year 2015-2016. More seriously, in the future, if more dams are constructed as planned, the damages caused by similar drought event of 2015-2016 will indisputably magnify the severity to the VMD. Consequently, livelihoods of millions of people in the VMD will be severely affected.

The authors recommend the owners of six existed dams in the Lancang cascade in Chia sharing the operation schedules of their reservoirs at the beginning of every year with downstream countries (e.g. Vietnam) so that they can have their own plan regarding water resources management accordingly. To the investors of eleven proposed dams in Thailand, Laos, and Cambodia, an alternative design types as *run-of-the-river* hydropower plants are recommended. For new proposed dams in the mainstream as well as in the tributaries, the design should take into account their negative impacts on the downstream countries in order to have an integrated utilization of limited fresh water in the transboundary Mekong River. Furthermore, local governments in the impacted areas by salinity intrusion should temporarily change the purpose of land use from freshwater agriculture to saltwater aquaculture if it can improve livelihoods of local people. Finally, it is necessary to urgently develop an early warning system of drought and salinity intrusion to help people actively deal with such hazards.

The impacts of river-damming and climate change on water-related issues in VMD figured out in this research is the first-hand results based on simple data analysis and Mike 11 simulation. Two dimensional numerical simulations will be implemented to comprehensively understand the impacts of these drivers on both flow regime and sediment dynamics of VMD.

9. Acknowledgement

This research is funded by JASTIP. The authors thank Mr. Vinh (Department of Agriculture and Rural Development of SocTrang province) for his kindly help in site visits and data sharing.

References

Asch, F., Wopereis, M. S. C. (2000): Yield Responses of Irrigated Rice to Salinity Depend on Development Stage and Stress Level. The 3rd International Crop Science Congress, August 17-22, 2000, Hamburg, Germany.

Binh, D.V., Kantoush, S., Sumi, T., Mai, N.T.P., Ata, R., Abderrezzak, K.E., Trung, L.V. (2017): Flow regime changes in Vietnamese Mekong Delta due to river-damming, in: 10th Symposium on River, Coastal and Estuarine Morphodynamics.

CGIAR (2016): The drought and salinity intrusion in the Mekong River Delta of Vietnam: Assessment report, Hanoi, Vietnam.

DHI (2009): Mike 11: A Modelling System for Rivers and Channels: Reference Manual.

DHI-HDR (2015): Study on the Impacts of Mainstream Hydropower on the Mekong River. Impact Assessment Report. Volume 1-Models, Model Setup and Simulation, Ministry of Natural Resources and Environment.

Doyle, T.W., Day, R.H., Michot, T.C. (2010): Development of sea level rise scenarios for climate change assessments of the Mekong Delta, Vietnam, U.S. Geol. Surv.

Fan, H., He, D., Wang, H. (2015): Environmental consequences of damming the mainstream lancang-mekong river: A review. Earth-Science

Rev. 146, pp. 77–91.

Fu, K., He, D. (2007): Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the Lancang River. Chinese Sci. Bull. 52, pp. 134–140.

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

Grumbine, R.E., Dore, J., Xu, J. (2012): Mekong hydropower: Drivers of change and governance challenges. Front. Ecol. Environ. 10, pp. 91–98, doi:10.1890/110146.

GSO [General Statistical Office] (2013): Statistical Yearbook 2012. Statistical Publishing House, Hanoi, Vietnam.

Gupta, A., Liew, S.C. (2007): The Mekong from satellite imagery: A quick look at a large river. Geomorphology 85, pp. 259–274, doi:10.1016/j.geomorph.2006.03.036.

Hanington, P., Toan, T.Q., Tri, V.P.D., Ngoc, D., Vu, A. (2017): A hydrological model for interprovincial water resource planning and management : a case study in the Long Xuyen Quadrangle , Mekong Delta , Vietnam. J. Hydrol. 547, pp. 1–9, doi:10.1016/j.jhydrol.2017.01.030.

Hoa, L.T.V., Nhan, N.H., Wolanski, E., Cong, T.T., Haruyama, S. (2007): The combined impact on the flooding in Vietnam’s Mekong River delta of local man-made structures, sea level rise, and dams upstream in the river catchment. Estuar. Coast. Shelf Sci. 71, pp. 110–116, doi:10.1016/j.ecss.2006.08.021.

Hung, N.N., Delgado, J.M., Güntner, A., Merz, B., Bárdossy, A., Apel, H. (2013): Sedimentation in the floodplains of the Mekong Delta, Vietnam. Part I: Suspended sediment dynamics. Hydrol. Process. 28, pp. 3132–3144, doi:10.1002/hyp.9856.

ICEM (2010): Strategic Environmental Assessment of Hydropower on the Mekong Mainstream: Summary of the Final Report, Mekong River Commission. Hanoi, Vietnam.

Kameyama, S., Shimazaki, H., Nohara, S., Sato, T., Fujii, Y., Kudo, K. (2013): Hydrological and sediment transport simulation to assess the impact of dam construction in the Mekong River main channel. Am. J. Environ. Sci. 9, pp. 247–258, doi:10.3844/ajessp.2013.247.258.

Kantoush, S., Binh, D.V., Sumi, T., Trung, L.V. (2017): IMPACT OF UPSTREAM HYDROPOWER DAMS AND CLIMATE CHANGE ON HYDRODYNAMICS OF VIETNAMESE MEKONG DELTA. J. Japan Soc. Civ. Eng. Ser. B1 (Hydraulic Eng. 73, pp. I_109-I_114).

Keskinen, M., Kummu, M., Käkönen, M., Varis, O. (2012): Mekong at the crossroads: Next steps for impact assessment of large dams. Ambio 41, pp. 319–324, doi:10.1007/s13280-012-0261-x.

Kondolf, G.. M., Annandale, G., Rubin, Z. (2015): Sediment starvation from dams in the Lower Mekong River Basin: magnitude of the effect and potential mitigation opportunities, in: E-Proceedings of the 36th IAHR World Congress. The Hague, Netherlands, pp. 1–7.

Kondolf, G.M., Rubin, Z.K., Minear, J.T. (2014): Dams on theMekong: Cumulative sediment starvation. Water Resour. Res. 50, pp. 5158–5169, doi:10.1002/2013WR014651.

Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V.Q., Dech, S. (2013): Understanding the impact of hydropower developments in the context of upstream-downstream relations in the Mekong river basin. Sustain. Sci. 8, pp. 565–584, doi:10.1007/s11625-012-0195-z.

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

Kummu, M., Sarkkula, J. (2008): Impact of the Mekong River flow alteration on the Tonle Sap flood pulse. Ambio 37, pp. 185–192, doi:10.1579/0044-7447(2008)37[185:IOTMRF]2.0.CO;2.

Kummu, M., Sarkkula, J., Koponen, J., Nikula, J. (2006): Ecosystem Management of the Tonle Sap Lake: An Integrated Modelling Approach. Int. J. Water Resour. Dev. 22, pp. 497–519, doi:10.1080/07900620500482915.

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

Lambert, D., Koponen, J. (2008): Flood Pulse Alterations and Productivity of the Tonle Sap Ecosystem: A Model for Impact Assessment. Ambio 37, pp. 178–184, doi:10.1579/0044-7447(2008)37.

Lauri, H., De Moel, H., Ward, P.J., Räsänen, T.A., Keskinen, M., Kummu, M. (2012): Future changes in Mekong River hydrology: Impact of climate change and reservoir operation on discharge. Hydrol. Earth Syst. Sci. 16, pp. 4603–4619, doi:10.5194/hess-16-4603-2012.

Li, J., Dong, S., Yang, Z., Peng, M., Liu, S., Li, X. (2012): Effects of cascade hydropower dams on the structure and distribution of riparian and upland vegetation along the middle-lower Lancang-Mekong River. For. Ecol. Manage. 284, pp. 251–259, doi:10.1016/j.foreco.2012.07.050.

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

Lu, X., Kummu, M., Oeurng, C. (2014): Reappraisal of sediment dynamics in the Lower Mekong River, Cambodia. Earth Surf. Process. Landforms 39, pp. 1855–1865, doi:10.1002/esp.3573.

Lu, X.X., Kummu, M., Oeurng, C. (2014): Reappraisal of sediment dynamics in the Lower Mekong River, Cambodia. Earth Surf. Process. Landforms 39, pp. 1855–1865, doi:10.1002/esp.3573.

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

Manh, N.V., Dung, N.V., Hung, N.N., Kummu, M., Merz, B., Apel, H. (2015): Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. Glob. Planet. Change 127, pp. 22–33, doi:10.1016/j.gloplacha.2015.01.001.

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

MARD [Ministry of Agriculture and Rural Development] (2011), http://www.mard.gov.vn/en/Pages/Lawdocument.aspx.

Milliman, J.D., Syvitski, J.P.M. (1992): Geomorphic/Tectonic Control of Sediment Discharge to the Ocean: The Importance of Small Mountainous Rivers. J. Geol. 100, pp. 525–544, doi:10.1086/629606.

MONRE (2009): Climate change, sea level rise scenarios for Vietnam.

Rubin, Z.K., Kondolf, G.M., Carling, P.A. (2014): Anticipated geomorphic impacts from Mekong basin dam construction. Int. J. River Basin Manag. 13, pp. 105–121, doi:10.1080/15715124.2014.981193.

Smajgl, A., Toan, T.Q., Nhan, D.K., Ward, J., Trung, N.H., Tri, L.Q., Tri, V.P.D., Vu, P.T. (2015): Responding to rising sea levels in the Mekong Delta. Nat. Clim. Chang. 5, pp. 167–174, doi:10.1038/nclimate2469.

Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Tanabe, S., Saito, Y. (2002): Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. Quat. Sci. Rev. 21, pp. 1807–1819, doi:10.1016/S0277-3791(02)00007-0.

Thu, H.N., Wehn, U. (2016): Data sharing in international transboundary contexts: The Vietnamese perspective on data sharing in the Lower Mekong Basin. J. Hydrol. 536, pp. 351–364. doi:10.1016/j.jhydrol.2016.02.035.

Toan, T.Q. (2014): Climate Change and Sea Level Rise in the Mekong Delta: Flood, Tidal Inundation, Salinity Intrusion, and Irrigation Adaptation Methods. In: Coastal Disasters and Climate Change in Vietnam, Elsevier. Elsevier Inc. doi:10.1016/B978-0-12-800007-6.00009-5

Tri, V.P.D., Trung, N.H., Thanh, V.Q. (2013): Vulnerability to Flood in the Vietnamese Mekong Delta : Mapping and Uncertainty Assessment. J. Environ. Sci. Eng. B 2 2, pp. 229–237.

Trung, N.H., Tri, V.P.D. (2014): Possible Impacts of Seawater Intrusion and Strategies for Water Management in Coastal Areas in the Vietnamese Mekong Delta in the Context of Climate Change. In: Coastal Disasters and Climate Change in Vietnam, Elsevier. Elsevier Inc. doi:10.1016/B978-0-12-800007-6.00010-1.

Walling, D.., (2008): The changing sediment load of the mekong river. Ambio 37, pp. 150–157. doi:10.1579/0044-7447(2008)37.

Wang, J.J., Lu, X.X., Kummu, M. (2011): SEDIMENT LOAD ESTIMATES AND VARIATIONS IN THE LOWER MEKONG RIVER. River Res. Appl. 27, pp. 33–46. doi:10.1002/rra.1337.

Wolanski, E., Huan, N.N., Dao, L.T., Nhan, N.H., Thuy, N.N. (1996): Fine-sediment dynamics in the Mekong River Estuary, Viet Nam. Estuar. Coast. Shelf Sci. 43, pp. 565–582, doi:10.1006/ecss.1996.0088.

Xuan, V.-T., (1975): Rice Cultivation in the Mekong Delta. South East Asian Stud. 13, pp. 88–111.

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., Levin, S.A. (2012): Trading-offfish biodiversity, food security, and hydropower in the Mekong River Basin, in: Proceeding of the National Academy of Science of the United States of America. pp. 5609–5614, doi:10.1073/pnas.1201423109.

(Received June 13, 2017)