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IMPACT OF LANCANG CASCADE DAMS ON FLOW REGIMES OF VIETNAMESE MEKONG DELTA

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Hydropower dams have been rapidly developed in the upstream Mekong River Basin without considering the downstream related issues. This research aims at investigating possible impacts of six hydropower dams of the Lancang cascade in the main Mekong River on flow regimes, including the magnitude, timing, and inter-and-intra variations, of the Vietnamese Mekong Delta (VMD) based on time series of historical flow data at TanChau station as a protocol. The results show that the impacts of the first four dams in the Lancang cascade on flow regimes in the VMD are not obvious. However, flow regimes in the VMD have been significantly altered when all six dams in the Lancang cascade were completed. In flood season, median discharge and maximum water level decrease by 13.5% and 20.2% respectively. High and low stage durations decrease by 55% and 66% when six dams existed. Flows from November to February are significantly reduced, causing difficulty for irrigation in the VMD. In dry seasons, discharges generally increase while water levels decrease due to river bed incision and reduction in sediment supply from the upstream, causing an increase in tidal influence accompanied by saltwater.

Key Words: *Dam impacts, Mekong Delta, Mekong River, Lancang cascade, Flow regime, Hydropower dams*

1. INTRODUCTION

The Mekong River Basin (MRB) has been formed from the 4,880 km long Mekong River (MR), covering an area of 795,000 km^2 partly from China, Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam (**Fig. 1a**). The MRB consists of the Upper Mekong Basin (UMB) and the Lower Mekong Basin (LMB). The UMB contributes about 18% out of 475 km^3 annual flow[1)] and 50% out of 160 million tons of annual suspended sediment[2)] to the MR. At about the last 200 km, the MR has formed the Vietnamese Mekong Delta (VMD) through its eight branches before emptying to the East Sea of Vietnam (**Fig. 1c**). The inflow enters the VMD through Tien and Hau Rivers (names of Mekong and Bassac Rivers in Vietnamese). Flow regimes at TanChau and ChauDoc stations (**Fig. 1c**) are important to understand the combined effects from upstream cascade dams and the tide.

The average elevation of the VMD is 0.7-1.2 m, ranging from 2.0-4.0 m close to the Vietnam-Cambodia border to 0.3-0.7 m in the coastal regions. The VMD has a dense channel network with the total length of about 87,500 km[3)]. According to the daily data from 1980-2015 used in this study, mean daily discharges at TanChau and ChauDoc stations are 9,944 and 2,489 m^3/s, respectively. Similarly, mean daily water levels at TanChau and ChauDoc stations are 1.75 and 1.52 m, respectively. These values divide the hydrograph of the VMD into: (1) flood season from June/July to November/December and (2) dry season from December/January to May/June of the following year. Moreover, the flows in the VMD can be divided into the rising stage (April–September) and falling stage (October–March).

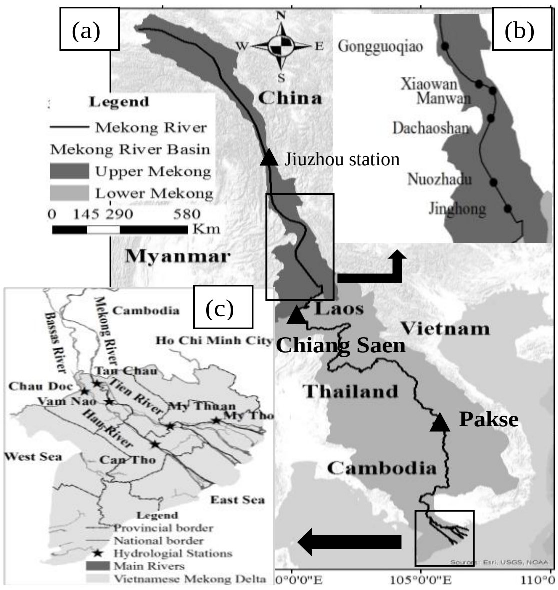

Fig. 1 Maps of: (a) Mekong River Basin, (b) Lancang cascade dams, and (c) Vietnamese Mekong Delta

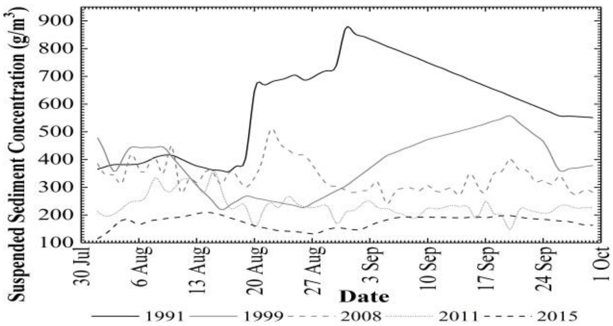

Fig. 2 Suspended sediment concentrations at TanChau station

The flow regimes in the VMD (and in the LMB in general) have been already altered due to dam development in the MRB, especially in the UMB[4]. Dams may affect the water quantity, quality, and intra-and-inter variation of river flows[5], resulting in a degradation of aquatic and terrestrial ecosystems[6]. In general, hydropower dams significantly reduce flood season flows and moderately increase dry season flows. For instance, annual flood peak in the VMD has been reduced due to Lancang cascade dams (LCDs) in the UMB[7]. In addition, reduction in the rising and high stages in the flood season in the VMD has been detected[8]. Besides, reservoirs in front of dams may trap almost all bedload and a large proportion of suspended sediment[2], leading to a degradation of river morphology in the downstream reaches. **Figure 2** shows that suspended sediment concentrations at TanChau station have been much reduced from the year 1991 (under natural condition) to the year 2015 (six dams in the Lancang cascade (LC) were in operation).

Previous researches mainly focused on evaluating impacts of the LCDs on flow alterations in the LMB limited from Chiang Saen station in Thailand to Kratie station in Cambodia while there is no study investigating possible impacts of the LCDs on flow regimes in the VMD. To fill this gap, the aim of this study is (1) to investigate possible impacts of the LCDs on the alteration of flood and dry season flows in the VMD and (2) to quantify such impacts using the alteration index of the hydrological regime.

2. DAMS IN THE MEKONG RIVER BASIN

To date, six out of eight planned hydropower dams (known as Lancang cascade) have been built in the mainstream of the MR in Chinese territory (**Fig. 1b**). Other eleven hydropower dams have been planned and under construction in the main MR in Thailand, Lao PDR, and Cambodia[7]. The total storage capacity of the six existing dams in the LC is over 41 billion m^3 (occupying 8.7% of the flow budget in the MRB), in which Nuozhadu is the biggest with 22.37 billion m^3 and Gongguoquiao is the smallest with 510 million m^3 (**Table 1**). Among these dams, Manwan is the first of the LC started building in 1986 and operating in 1993[9]. Since then, the remaining five dams have been consecutively built and operated in 2011 (**Table 1**).

Based on the total storage capacity, Auel et al.[10] classified reservoirs into transparent, sorting, and black hole. Transparent reservoirs (e.g. run-of-river dams, having reservoir volume, V, $< 10^6$ m^3) neither trap floods nor sediment as their sizes are small. Sorting reservoirs ($V \cong 10^6$-10^9 m^3) do not trap large floods but trap the incoming sediment. In contrast, both floods and sediment are trapped by black hole reservoirs ($V > 10^9$ m^3) due to their large size. Based on this classification, four out of six existing LCDs are classified as black hole while the remaining two are sorting (**Table 1**).

3. DATA AND METHOD

Impacts of the LCDs on flow regimes in the VMD is evaluated using hydrological data of TanChau station (**Fig. 1c**) as a protocol. TanChau station is important as 80% of the MR inflow runs through Tien River and the remaining 20% flows through ChauDoc in Hau River. Provided by the National Hydro-meteorological Data Centre in Hanoi, historical daily water levels have been analyzed for the period between1980 and 2015. Time series regression for the continuously measured daily discharges from 1996-2015 and the scattered in 1980-1995. Therefore, rating curves were established in the rising and falling stages separately to fill missing discharges. Then the whole data are divided into five periods: pre-dam period (1980-1992) and four post-dam periods: 1993-2001 (1 dam), 2002-2008 (3 dams), 2009-2011 (4 dams), and 2012-2015 (6 dams). Then, median discharges and

Table 1 Configurations of six existing dams in the Lancang cascade

Name	Catchment area (km^2)	Annual inflow (m^3/s)	Dam height (m)	Active storage (km^3)	Total storage (km^3)	Started year	Reservoir filling year	Reservoir classification
Nuozhadu	144,700	1,750	260	12.2	22.37	2005	Nov. 2011	Black hole
Xiaowan	113,300	1,220	292	9.9	15.13	2002	Dec. 2008	Black hole
Jinghong	149,100	1,840	107	0.25	1.23	2003	Apr. 2008	Black hole
Manwan	114,500	1,230	132	0.26	1.06	1986	Mar. 1993	Black hole
Daochaoshan	121,000	1,340	120.5	0.37	0.88	1997	Nov. 2001	Sorting
Gongguoqiao	97,300	985	130	0.12	0.51	2008	Sep. 2011	Sorting
Total				23.1	**41.18**			

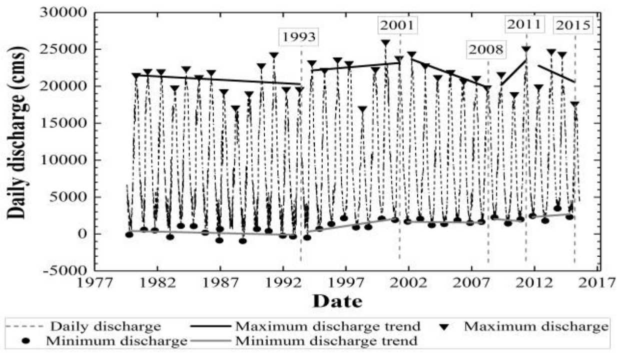

Fig. 3 Historical daily discharge at TanChau station

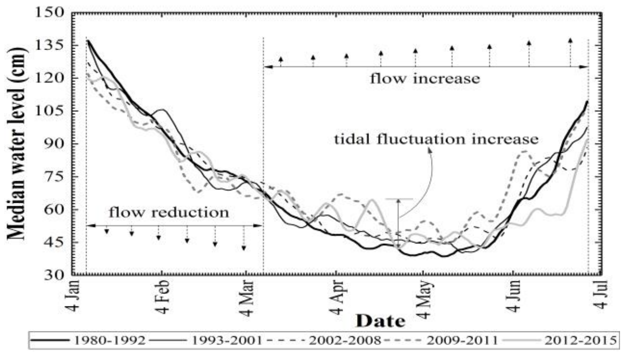

Fig. 4 Median water levels in dry season at TanChau

water levels in each period are used to investigate possible impacts of the LCDs on flow regime alterations in the VMD because the time scale in each period is not equal. The moving average values are used to illustrate the trend while absolute values are used to quantify the impacts in a direct and clear relationship.

4. CHANGES IN HISTORICALLY ANNUAL DISCHARGES UNDER DAM DEVELOMENT

Figure 3 shows historically daily discharges of 36 years from 1980 to 2015 at TanChau station. Maximum and minimum values are highlighted. The years of reservoirs' infilling are also included. The figure shows that annually minimum discharges reduce in pre-dam period but significantly increase in post-dam periods. **Figure 3** also shows that annual maximum discharges reduce in pre-dam period. However, their trends vary in post-dam periods due to some exceptional high flood peaks, i.e. in years 2011, 2013 and 2014.

The decreasing tendency of discharges in pre-dam period at TanChau are directly related to the reduction of flow to upstream stations in the MR's mainstream, such as Chiang Saen and Pakse[9] (Fig. 1). These decreasing trends may be due to the reduction in the annual rainfall in the MRB because rivers' discharges are mainly driven by the rainfall when hydraulic structures (i.e. hydropower dams) have not appeared in pre-dam period.

Obviously, changes in maximum and minimum discharges are different due to impacts of the LCDs. The following sections will discuss impacts of such dams on the flow regimes in the VMD in more detail.

5. IMPACTS OF LANCANG CASCADE DAMS ON DRY SEASON FLOWS

Discharges and water levels in post-dam periods, especially since 2009 when three largest dams were in operation, are significantly reduced in January-February while increased in March-June compared to those in pre-dam period (**Fig. 4**). These findings clearly show that dry season flows are shifted to begin earlier in post-dam periods. That may cause difficulty in irrigating the winter-spring crop, which is the most productive and important among three crops in the VMD[11].

Figure 5 demonstrates the similarity in the tidal patterns of VungTau (about 100 km Northward from the estuary of Tien River) and TanChau stations using mean water levels in 2012 and 2013. The river flows are more fluctuating in post-dam periods comparing to that of the pre-dam (**Fig. 4**). This fluctuation has the same pattern with the variation of the tide (**Fig. 5)**. Due to the LCDs, maximum tidal amplitude at Tan Chau increases from 0.19 m in pre-dam to 0.33 m in 2009-2011 (4 dams) and 0.44 m 2012-2015 (6 dams), corresponding to an increase of 1.7 and 2.3 times, respectively. This indicates that the tide carrying saltwater has gradually increased propagating upstream as the number of completed dams increase.

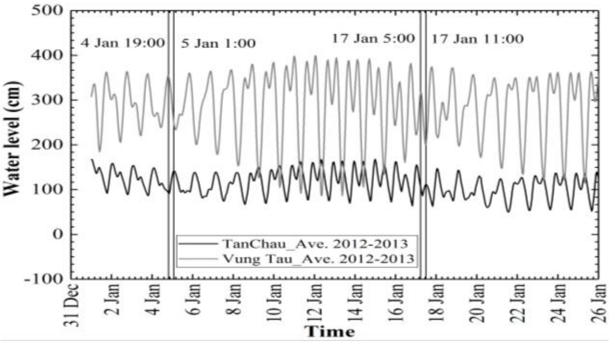

Fig. 5 Hourly water levels at VungTau and TanChau

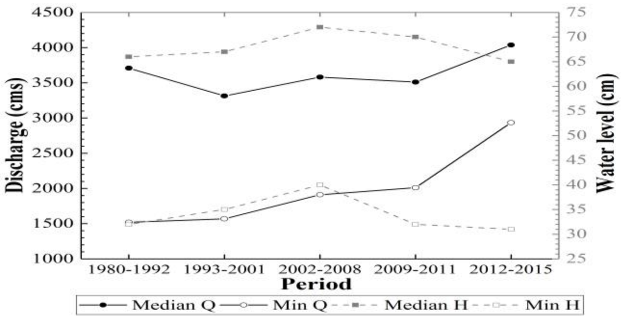

Fig. 6 Discharges and water levels in dry seasons at TanChau

As shown in **Fig. 6**, changed patterns of median discharges between post-dam periods up to 2009-2011 and pre-dam period are not clear. This is linked with no statistical trend in mean water levels in the dry season at the Jiuzhou station[12] (**Fig. 7**) which is upstream of the LCDs (**Fig. 1**). Water levels from 1980-2003 (not available since 2004) at Jiuzhou station are used for the comparison because discharge data are not publicly available upstream of the LCDs. It indicates that impacts of the LCDs on the dry season flow in the VMD by the year 2011 are not obvious, possible reason may be due to a relatively small reservoirs' capacity of the first for dams in the cascade compared to the MR's flow. However, median discharge of 2012-2015 period (4,037 m^3/s) when all six LCDs were in operation significantly increases compared to that of pre-dam period (3,708 m^3/s). **Figure 6** also reveals that minimum discharges significantly increase as the number of LCDs increases, from 1,519 m^3/s in pre-dam period to 2,935 m^3/s in 2012-2015 (+93.2%), equivalent to 1.9 times. This is commonsense because hydropower dams discharge water for electricity generation in the dry season. In contrast, median and minimum water levels generally reduce when the number of the LCDs increase.

Obviously, discharges and water levels at TanChau have opposite trends under the impacts of the LCDs. Discharges tend to increase while water levels tend to decrease (**Fig. 6**). When the inflow is high, the tide is kept far seaward, therefore water level is low and vice versa. This phenomenon can be explained through a reduction in sediment supply from the UMB due to the LCDs (**Fig. 2**). The figure shows that suspended sediment concentration in August and

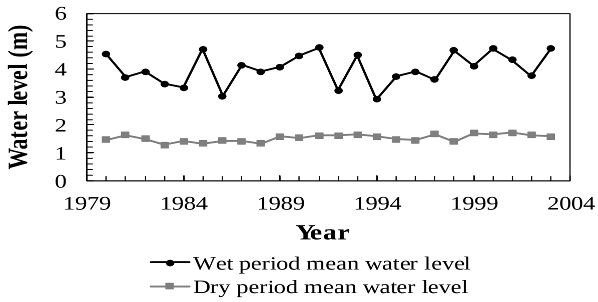

Fig. 7 Mean water levels in wet and dry seasons at Jiuzhou

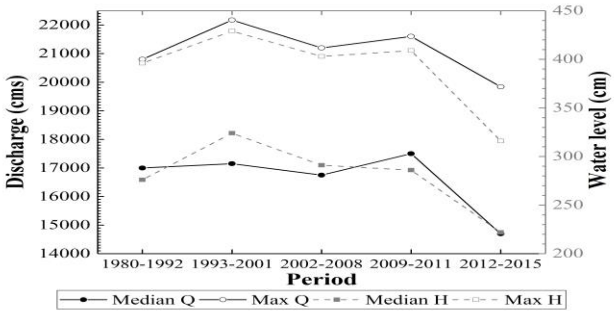

Fig. 8 Discharges and water levels in flood seasons at TanChau

September at TanChau is gradually reduced as the number of dams increases, from about 600 g/m^3 in 1991 (pre-dam) to about 175 g/m^3 in 2015 when six dams in the LC completed (about 340% reduction). Moreover, Kondolf et al.[2] revealed that dams in the UMB trap about 83% of sediment generated in this region, equivalent to about 40% of the total sediment generated in the MRB. Such huge reduction may result in an increase in river bed incision, causing an increase in the influence of the tide. More seriously, such increased tidal influence may lead to more salinity intrusion to the VMD, damaging agriculture, aquaculture, ecosystem, and livelihood of local citizens[7].

6. IMPACTS OF LANCANG CASCADE DAMS ON FLOOD SEASON FLOWS

Although there are some fluctuations, mean water levels in the wet season at Jiuzhou station from 1980-2003 do not statistically follow any trend (**Fig. 7**). Consequently, trends in median and maximum discharges and water levels at TanChau station in the flood season between pre-and-post-dam periods, up to the year 2011, are not clear (**Fig. 8**). Thus, the impacts of the LCDs on flood flows at TanChau station by the year 2011 are not obvious. This is because reservoirs' capacity of the first four dams is still relatively small compared to the total flow budget of the MR.

However, both discharges and water levels in 2012-2015 period (six LCDs completed) significantly decrease compared to those of pre-dam period (**Fig.8**). Median and maximum discharges reduce by

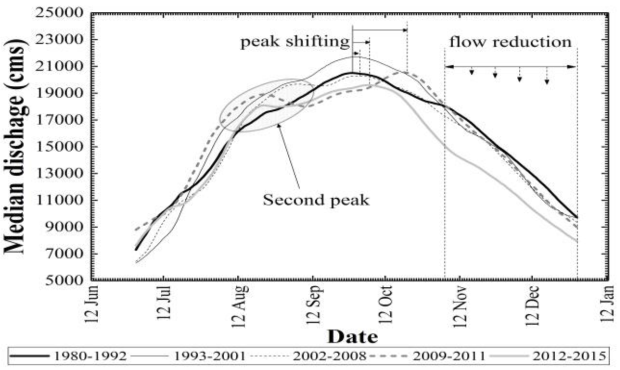

Fig. 9 Median discharges in flood seasons at TanChau

Table 2 Alteration indexes of post-dam periods

FQ	1993-2001	2002-2008	2009-2011	2012-2015
FQ^F	0.43	0.45	0.41	0.55
FQ^D	0.48	0.52	0.52	0.66

-13.5% and –4.6%, respectively. Similarly, median and maximum water levels decrease by -19.6% and -20.2%, respectively. Such reductions are due to the fact that reservoirs in the LCDs store flood water for electricity generation in the next dry season.

Flow reductions in flood seasons due to LCDs are somehow helpful for the VMD by reducing losses caused by floods, i.e. from infrastructure, human lives. However, unexpected huge reductions in flood flows become significantly negative because the VMD needs floods for its development. Floods provide fisheries and rich natural fertilizers, remove contaminants, and maintain biodiversity and ecosystem. The best water levels at TanChau are 0.35-0.45 m[1]. At these levels, damages caused by floods are acceptable while benefits are advantageous. Maximum water levels of 0.32 m in 2012-2015 period (0.8 m smaller than that in pre-dam period) is lower than these limits; therefore, LCDs may have negative impacts on flood flows in the VMD.

LCDs not only change the magnitudes but also shift the peaks and patterns of the flood flows in the VMD (**Fig. 9**). The figure shows that the timing of the flood peak is shifted to happen lately due to of reservoir regulation. For instance, the flood peak occurred on October 11 in 2009-2011 compared to September 20 in pre-dam period. Seriously, the hydrograph appears a second peak in August in post-dam periods instead of one peak in September in pre-dam. This second peak may additionally inundate and damage the second rice crop (April/May-July/August) in some areas not protected by dyke systems because local people used to be familiar with single-peak floods in pre-dam. Meanwhile, flows from November to December in post-dam periods significantly reduce due to reservoirs' regulations, causing difficulty in irrigating the winter-spring rice crop.

7. QUANTIFYING DAMS IMPACTS

Not only the timing and amplitude, but also do the frequency and duration of flows have important implications on ecosystems, biology and agriculture practices. Changes in the frequency and duration of flood and dry season flows are evaluated through the high and low stage discharges, respectively, using the method of alteration index of the hydrological regime (FQ)[13]. High stage discharges (Q^H) are those larger than or equal to 75 percentile of daily discharges from 1980 to 2015. Low stage discharges (Q^L) are those smaller than or equal to 25 percentile of daily discharges of the same period. At TanChau, high and low stage discharges are 16,500 and 3,660 m^3/s respectively. FQ of high and low stage flows are calculated as follow,

$$FQ^F = \frac{NQ^H_{post\_i}}{NQ^H_{pre}} - 1 \quad (1)$$

$$FQ^D = \frac{NQ^L_{post\_i}}{NQ^L_{pre}} - 1 \quad (2)$$

where FQ^F and FQ^D are indexes of frequency alteration of flood and dry season flows, represented by high and low stage discharges, respectively; NQ^H_{pre} and $NQ^H_{post\_i}$ are number of days having discharges larger than high stage discharge in pre-dam and post-dam periods, respectively; NQ^L_{pre} and $NQ^L_{post\_i}$ are numbers of days having discharges lower than the low stage discharge, respectively.

Using Eqs. 1 and 2, FQ^F and FQ^D are then determined (**Table 2**). The table shows that flood durations in post-dam period significantly reduce compared to those of pre-dam period. High stage duration firstly reduces by about 43% in 1993-2001 period (after the first Manwan dam constructed), then increases by 45% in 2002-2008 (3 dams completed) and by 55% in 2012-2015 (6 dams in operation). It should be mentioned that floods are important for the development of the VMD. The delta needs to avoid large floods, e.g. floods in 2000, 2011, to mitigate damages. However, medium floods can bring sediment and freshwater for agriculture and provide benefits from fisheries for the local people[14]. A reduction in the total area of floodplains due to lower wet season flow and higher dry season flow may have negative impacts on fish feeding, spawning and nursery grounds[15]. In that sense, a reduction of 55% in high stage discharges in 2012-2015 may cause adverse impacts on various sectors in the VMD. Severe damages caused by extremely low flow in drought event 2015-2016 were introduced by Kantoush et al.[7].

Similarly, durations of dry season flows gradually reduce with the increase in the number of dams. Low stage duration decreases by about 48% in 1993-2001, then increases to 52% in 2009-2011 and 66% in 2012-2015 (**Table 2**). A decrease in durations of low stage discharges in post-dam periods indicates that dry season flows are shortened due to upstream dams, implying that such dams have positive effects on minimizing dry season span. In a wider consideration, however, shortening low stage flows may have negative impacts on ecosystem, particularly on some species whose living conditions are in low stage environment. Consequently, it may cause negative effects of other species in the ecosystem because each specie has its own role in the food chain of the river environment.

8. CONCLUSION

Possible impacts of the LCDs on flow regimes of the VMD are evaluated by analyzing time series discharges and water levels from 1980-2015 at TanChau station as a protocol. The time series data were divided into five periods depending on the time of filling reservoirs in the LC: pre-dam (1980-1992) and four post-dam periods, being 1993-2001 (1 dam), 2002-2008 (3 dams), 2009-2011 (4 dams), and 2012-2015 (6 dams). Some conclusions are:

(1) Impacts of the LCDs up to the year 2011 (4 dams completed) on river flows at TanChau are not obvious. However, such impacts are significantly when all six dams in the LC were in operation.

(2) Impacted by all six dams, minimum discharges have increased by 1.9 times, equivalent to +93.2% and duration of low stage flow reduces by 55%. However, water levels in dry season generally reduce under dams' impacts because of river bed incision as a result of reduction in sediment supply, leading to an increase in tidal influence in the VMD (maximum increase is 2.3 times in 2012-2015 period).

(3) Six dams in the LC have caused a reduction in both discharges and water levels in flood years in the VMD. The median discharge and the maximum water level are reduced by -13.5% and -20.2% respectively. Duration of high stage flow decreases by 66%. These reductions, on the one hand, are helpful in mitigating losses caused by floods but, on the other hand, may have unexpectedly negative impacts on the VMD because normal floods provide important natural resources for the VMD' development.

(4) Flood peak has shifted to happen more lately due to the LCDs. Furthermore, these dams have created a second flood peak in August which is unusual and disadvantageous to the livelihood in the VMD.

(5) Dams' owners are strongly recommended to share the regulation rules of reservoirs to downstream countries to help them become active in their integrated water resources management strategies.

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