Journal of Japan Society of Civil Engineers, Ser.
B1 (Hydraulic Engineering), Vol. 74, No. 5, I_871-I_876, 2018.

WATER LEVEL CHANGES UNDER INCREASED REGULATED FLOWS AND DEGRADED RIVER IN VIETNAMESE MEKONG DELTA

Doan Van BINH[1], Sameh KANTOUSH[2], Nguyen Phuong MAI[3] and Tetsuya SUMI[4]

[1] Member of JSCE, Doctoral Student, Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University (Goka-sho, Uji-shi, 611-0011, Japan)
E-mail: binhdv@tlu.edu.vn
[2] Member of JSCE, Dr. of Eng., Associate Professor, Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University (Goka-sho, Uji-shi, 611-0011, Japan)
E-mail: kantoush.samehahmed.2n@kyoto-u.ac.jp
[3]Member of JSCE, Faculty of Civil Engineering, Thuyloi University-Southern Campus
No.2 TruongSa street, Ward 17, BinhThanh District, HoChiMinh City, VietNam
E-mail: maiswru@tlu.edu.vn
[4]Member of JSCE, Dr. of Eng., Professor, Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University (Goka-sho, Uji-shi, 611-0011, Japan)
E-mail: sumi.tetsuya.2s@kyoto-u.ac.jp

Maintaining stable water levels during dry seasons is crucial for the irrigation of rice crops in the Vietnamese Mekong Delta (VMD) as agriculture, i.e. rice crops, is the main economic sector in the delta. Dry season water levels in the VMD are impacted by regulated flow discharges and river bathymetry. Hydropower dams, especially six mega mainstream dams in the upper Mekong River have caused tremendous reduction in the sediment budget of the VMD which, in turn, cause severe river bed degradation. Using in-situ bathymetric measurements and 2-D hydrodynamic modelling, this study investigates the alterations of water levels in the upper reach of the VMD as a combined impact of modified flow discharges and river bed degradation scenarios. Three thresholds of increased discharges associated with different degrees of river bed degradations were distinguished. Under low river bed degradation (< 1.5 m), water levels of dry seasons can be improved when the low-flow discharges increase by 10%. Under moderate degradation (1.5 m ≤ degradation ≤ 3 m), an increase of 20% of the low-flow discharge would help conserve the initial water levels. However, under high degradation scale (3 m < degradation ≤ 6 m), an increase of 50% of the low-flow discharge from upstream dams is expected.

Key Words : *Vietnamese Mekong Delta (VMD), river bed degradation, river bathymetry, TELEMAC-2D, hydropower dams*

1. INTRODUCTION

Stretching along the last 200 km of the Mekong River (MR), which flows through six countries from China to Vietnam, the Vietnamese Mekong Delta (VMD) (**Fig.1**) is one of the most productive agro-aquaculture in the world. The delta has been formed from an abundant sediment supply from the upstream of the MR of about 160 Mt/year[1)]. Agriculture (i.e. rice crops) is the main economics of the delta. Two or three rice crops are cultivated annually.

Tien and Hau Rivers (**Fig.1**) are two main waterways in the delta which empty into the East Sea of Vietnam through eight river mouths. Tien River transports the flow about four times larger than Hau River. The main discharges of Tien and Hau Rivers are 9,900 and 2,500 m^3/s. The flow hydrograph is distinguished by flood and dry seasons. The former is from July to December and the later is from January to June of the next year. Rice crops are mainly cultivated in the dry season, beginning from the end of the flood season. The flood inundates the delta but the dry causes disadvantages for the irrigation.

Constructions of hydropower dams in the upstream of the MR has been expected to reduce floodings and increase dry season flows in the VMD[2)]. However, Binh et al.[3)] reported that in the dry season, the average flow discharge increases while

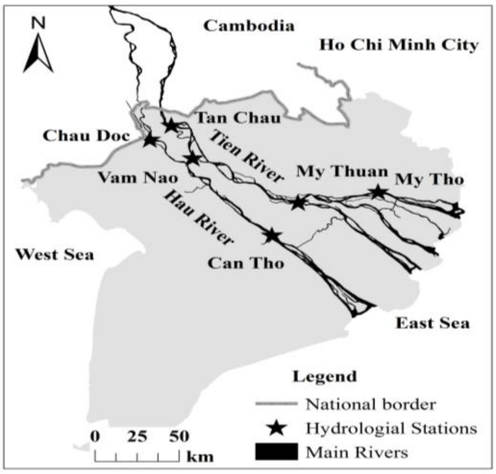

Fig.1 Map of Vietnamese Mekong Delta.

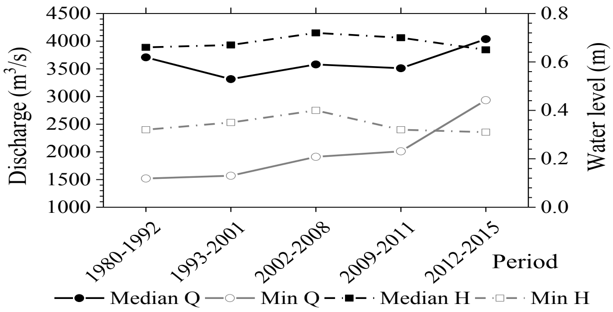

Fig. 2 Discharges and water levels in dry season at TanChau.

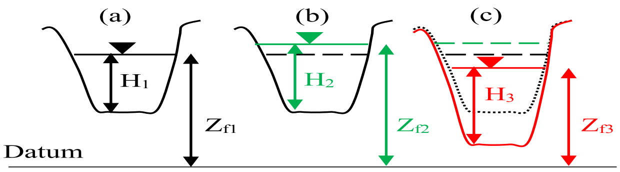

Fig.3 Conceptual effects of increased flow discharge and degraded river bed on water depth (H) and water level (Z_f): (a) initial condition, (b) increased flow discharge, (c) increased flow discharge with degraded river bed. $H_1<H_2<H_3$ but $Z_{f3}<Z_{f1}<Z_{f2}$.

the water level decreases (**Fig.2**). The study compared discharges and water levels during five periods linked with constructions of six mega mainstream hydropower dams in the upper MR: Manwan (1993), Dachaoshan (2001), Jinghong (2008), Xiaowan (2008), Gongguoqiao (2011), and Nuozhadu (2011)[4]. Binh et al.[3] concluded that the altered water levels in the VMD is due to a reduced sediment supply from the upstream of the MR because reservoirs trap sediment[5] that may leads to river bed degradation[3]. Therefore, the present paper formulates two hypothetical scenarios to account for the influences of increased flow discharges and lowered bed elevation based on the conceptual **Figure 3**. Specifically, a large variation of water levels are mainly due to the increased discharges in the dry season and the rate of river bed degradation which is higher than the rate of water level changes. Consequently, the reduction in water levels specially during dry seasons leads to difficulty to irrigate the crops. **Figure 2** shows that in the dry season, median discharge increases by 10% but median water level reduces by 2% by comparing the two periods 1980-1992 (pre-dam) and 2012-2015 (six dams in operation). These two periods are compared because we would understand the cumulative impacts of all main stream dams, of which Nuozhadu (completed in 2011) is the largest, having a total storage capacity of 22.37 km^3, on future flows of the VMD based on the historical changes bewteen post-dam and pre-dam flows.

Large scale hydrodynamics modelling of a complex river network and floodplains such as the VMD requires detailed bathymetric, water level and discharge data. The available topography and cross sectional profiles for the whole main rivers and floodplains of the VMD are limited. Therefore, we conducted a detailed bathymetric survey along 200 km of the main rivers in the VMD from TanChau and ChauDoc until river mouths. This paper presents the developed 2-dimensional (2-D) hydrodynamic model for the VMD and the bathymetric surveys for such a complex river network. The objective of 2-D model is to investigate the impacts of the regulated flow discharges and eroded river bed on water level variations during the dry season.

The model is built on a river bathymetry measured in August 2017 for the main rivers of the VMD using Acoustic Doppler Current Profiler (ADCP).

2. BATHYMETRY MEASUREMENT

Prior studies based on numerical simulations have used combined rivers' bathymetric data that were measured in different fragments of the delta in different years. Moreover, the bathymetry measured during 2000s has been still used by some researchers. Such considerations may have limitations in the interpretation on the flow directions and quantities.

To overcome such limitations, we conducted a challenging bathymetric survey in Tien and Hau Rivers and VamNao channel, in August 2017 (**Fig.1**). Two-hundred cross-sections were measured, starting from TanChau, ChauDoc to the river mouths. The distance between two adjacent cross-sections ranged from 1 to 5 km. A 4-beam ADCP coupled with GPS (global positioning system) were employed. Bathymetric data were collected in a combination of cross sections and longitudinal profiles in the area accessible by boat. Water-depth measurements were treated with WinRiver ADCP software and imported for further processing. At the same time, cross-sectional flow velocities and discharges were also measured by using ADCP.

Tien and Hau Rivers can ben divided into two parts:

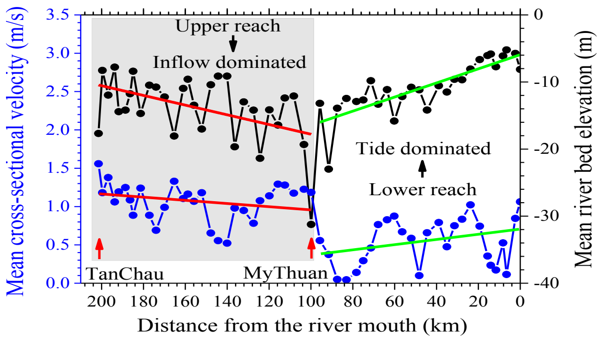

Fig.4 Mean river bed elevation and velocity along Tien River in August 2017.

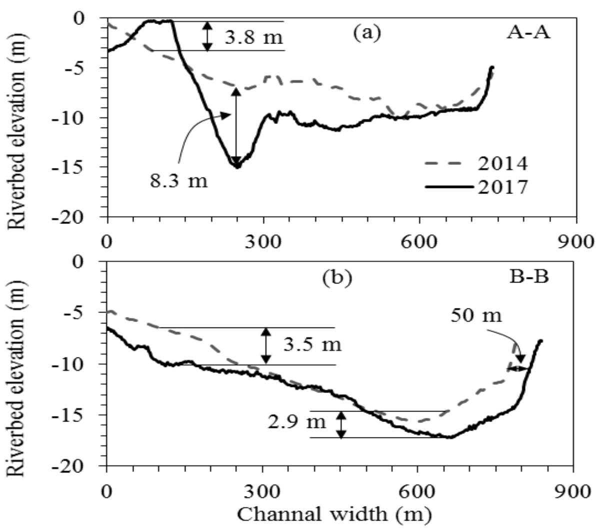

Fig.5 Typical river bed degradation in VMD.

the upper and lower reaches based on variations of mean river bed elevations and velocities along the rivers (**Fig.4**). These reaches are separated at MyThuan in Tien River and CanTho in Hau River (**Fig.1**). The upper reach is dominated by the inflow from the MR while the lower reach is dominated by the tide and wave. The river bed is deep in the upper reach, decreasing seaward (**Fig.4**). There are several scour holes deeper than 25 m in the upper reach with an exception of more than 40 m at a location 2 km upstream of MyThuan station. In the lower reach, the river bed becomes shallower as sediment tends to deposit near the estuaries due to river widening, tide and salinity effects. The shallowest areas are within 15 km from the river mouths. As a result, the flow velocity is high in the upper reach, reducing seaward while it is low in the lower reach, increasing seaward (**Fig.4**). Although these velocities were measured at different time during the field survey, they are a good indicator (together with river bed elevation) to distinguish between upper and lower reaches.

In the upper reach, the bed material of Tien River is constituted mainly by sand, decreasing seaward from medium sand in TanChau to fine sand in MyThuan. In the lower reach, fine sand and mud

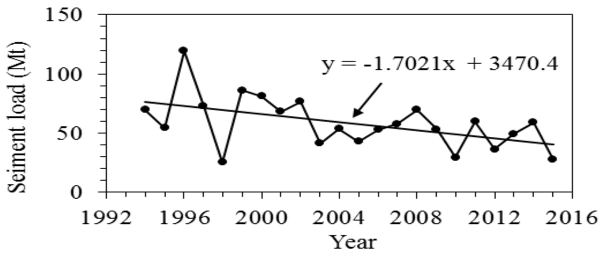

Fig.6 Reduction in annual sediment budget of VMD.

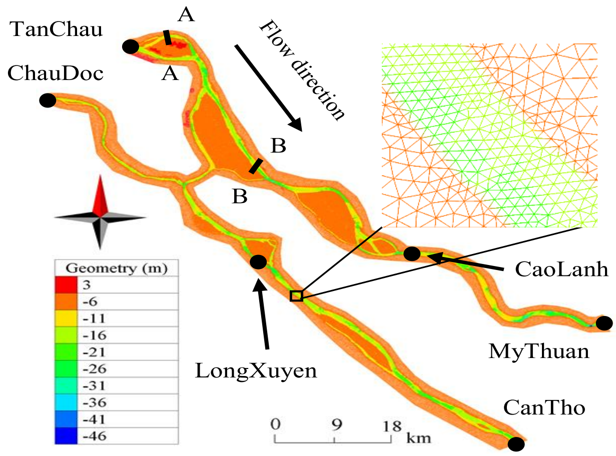

Fig.7 Geometry mesh of the study domain-upper reach.

content are dominant. Fine sand is almost unchanged throughout the lower reach.

The river beds of two main rivers in the VMD have been remarkably degraded. Although river bed aggradation has occurred in some areas, it is relatively small compared to river bed degradation in terms of both magnitude and domain. **Figure 5** compares typical river beds of 2014 and 2017 at cross sections A and B (see these cross sections in **Fig.7**). It can be seen that river bed degradation is dominant in each cross section. Maximum river bed degradation can reach 8.3 m at section A. On average, the river bed of Tien River from TanChau to a location of about 10 km downstream of VamNao station in 2017 is 1.5 m lower than that measured in 2014. Moreover, river banks have also been increasingly eroded. The erosion width can reach more than 100 m in some places, with medium value of about 50 m (**Fig.5b**). Such river bed degradation and river band erosion are expected due to a reduction in the sediment supply from the upstream of the MR where the sediment is mostly trapped by six mega mainstream hydropower dams. The annual sediment budget of the VMD has been reduced from 39 Mt/year in 1993 to 28 Mt/year in 2015 (**Fig.6**). Compared to the pre-dam (before 1992) sediment budget of 160 Mt/year[1)], the sediment budget of VMD in 2015 decreased by 83%. Study on the impacts of upstream dams on river bed evolution of the VMD is ongoing and out scope of this paper.

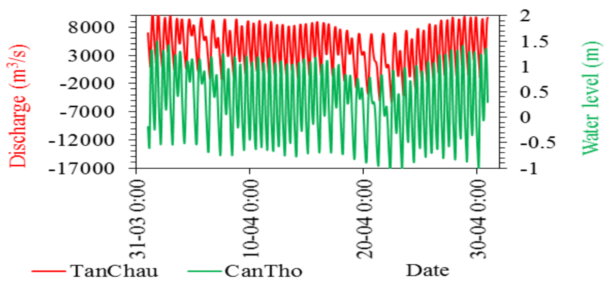

Fig.8 Boundary conditions: hydrograph of discharges at TanChau and water levels at CanTho in April 2017.

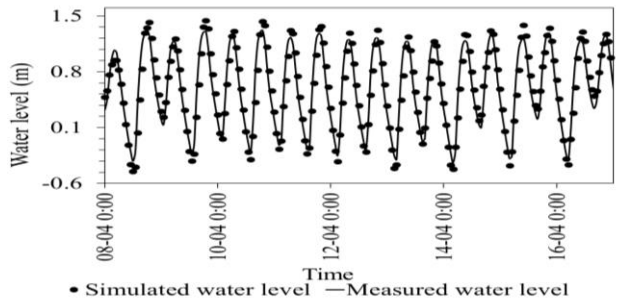

Fig.9 Measured versus simulated water levels at LongXuyen.

Table 1 Nineteen simulated scenarios by increasing inflow discharges and lowering river bed.

Bed elevation (Z_b)	Discharge (Q)				
	Q0	Q0+10%	Q0+20%	Q0+25%	Q0+50%
Z_b0	Sc0	Sc4	Sc9		Sc14
Z_b0-0.75m	Sc1	Sc5			Sc15
Z_b0-1.5m	Sc2	Sc6	Sc10	Sc13	Sc16
Z_b0-3m		Sc7	Sc11		Sc17
Z_b0-6m	Sc3	Sc8	Sc12		Sc18

Note: Q0 and Z_b0 are discharge and river bed of 2017

Considering the complexity of the lower reach due to the tide, wave, and salinity effects, we select the upper reach of VMD as our study domain (**Fig.7**). It includes part of Tien River from TanChau to MyThuan, part of Hau River from ChauDoc to CanTho and an entire VamNao channel (**Fig.1**). The bathymetry of these rivers measured in 2017 is used to create the geometry mesh for the 2-D numerical model. Because the distance between two adjacent cross-sections is relatively large, various interpolation methods are tested using geostatistical tool in ArcGIS. In our data, Universal Kriging method is the best.

3. 2-D NUMERICAL SIMULATIONS

(1) Model setup

TELEMAC-2D is used in this study. It is an open source, solving depth-averaged free surface flow equations (Saint-Venant) developed by the National Hydraulics and Environment Laboratory of the Research and Development Directorate of the French Electricity Board (EDF-R&D). The simulated domain uses triangle mesh having a grid spacing of 80 m in the rivers and 150 m in the floodplains (**Fig.7**). The mesh is then incorporated with rivers' bathymetry and floodplain's DEM to produce a geometry mesh for the model. There are four open boundaries: two upstream at TanChau and ChauDoc using hourly discharges and two downstream at MyThuan and CanTho using hourly water levels (**Fig.7**). Typical time series of boundary conditions are shown in **Figure 8**. The study domain is inflow-dominated but influenced by the tide during dry season such as April.

(2) Simulation scenarios

The nineteen scenarios in **Table 1** are proposed to evaluate the impacts of water level changes under increased flow discharges and river bed degradation on the possibility of rice crops' irrigation. The worst conditions for changes of water levels are in April 2017, as the recorded water levels were the lowest during this year under different scenarios of discharges and bathymetry.

The baseline (Sc0) considers the discharges, water levels and bathymetry of April 2017. Four options of increased flow discharges by 10%, 20%, 25% and 50% at upstream boundaries (TanChau and ChauDoc) are considered. These scenarios are desgined based on the median discharge in the dry season at TanChau that increased by 10% in post-dam period (2012-2015) compared to pre-dam period (1980-1992) (**Fig.2**). **Figure 5** shows that river beds in the VMD are both degraded and aggraded. However, degradation is dominant throughout the study domain while aggradation occurred near banks in limited areas and magnitudes. Moreover, river bank erosion is also taken place in various locations in the delta. However, due to a lack of data, the effect of river bank erosion is not considered in this study. As a hypothesis, four degrees of river bed degradation of 0.75 m, 1.5 m, 3 m, and 6 m associated with 2017 bathymetry are simulated. The four scenarios are related to low (degradation < 1.5 m), moderate ($1.5 \text{ m} \leq$ degradation ≤ 3 m), and high ($3 \text{ m} <$ degradation ≤ 6 m) river bed degradation. These considerations are based on an average reduction in the river bed of 1.5 m in between 2017 and 2014 as mentioned above. Such an uniform degradation applied throughout the study domain is not really realistic but acceptable because we would investigate a general mechanism of water level changes responding to river bed degradation.

(3) Model calibration

The baseline scenario (Sc0) is calibrated by testing various friction coefficients (Manning law). The simulated water levels at CaoLanh and LongXuyen stations (**Fig.7**) are in good agreement with corresponding measured values with correlation coefficients of 0.91 for the former and 0.95 for the later.

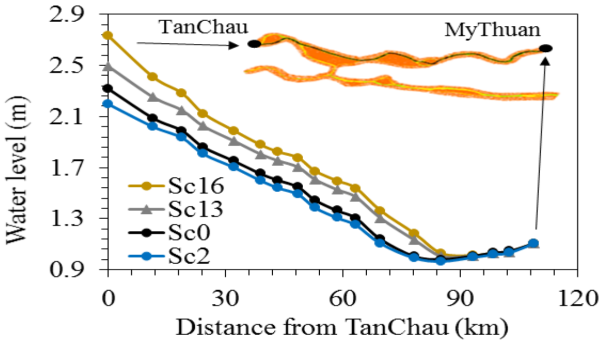

Fig.10 Mean daily maximum water levels along Tien River having the same river bathymetry with different discharges.

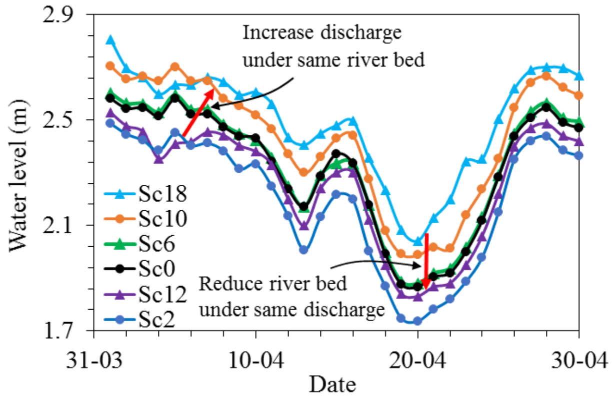

Fig.11 Mean daily maximum water levels at TanChau of various scenarios.

Table 2 Changes of water levels (%) at TanChau comparing scenarios to the baseline (Sc0). "+": increase; "-": decrease.

Reduced river bed	Increased discharge				
	0	10%	20%	25%	50%
0	0	7	14		23
0.75m	-3	2			20
1.5m	-4	0	5	8	18
3m		-2	2		14
6m	-11	-6	-3		8

Note: changes (%) = (Sci-Sc0)/Sc0*100% with Sci: scenario ith.

Figure 9 shows a typical comparison of simulated and measured water levels at LongXuyen station.

4. RESULTS AND DISCUSSIONS

(1) Influence of flow discharge changes

In order to assess the influence of the increased flow discharges on the water level, a reduction of 1.5 m of the original measured bathymetry in 2017 is considered as a representative geometry. **Figure 10** depicts that water levels in April in the VMD increase by increasing the flow discharge under the same domain geometry. **Table 2** shows that, mean water levels in April at TanChau, on average, increase by 4%, 9%, 12% and 22% if flow discharges increase by 10%, 20%, 25% and 50%, respectively (Sc6, Sc10, Sc13, and Sc16 compared to Sc2). The amplitude of water level increase reduces longitudinally to downstream locations due to the effect of simulated constant water levels at the downstream boundaries. As a result, the influence of increased river discharge diminished with the increased distance from the upstream at 90 km (**Fig.10**).

(2) Influence of river bed changes

Under the same discharge, the cross-sectional area will increase if the river bed is degraded. This leads to a reduction in the water level accordingly. For example, mean water levels in April at TanChau, on average, decrease by 3%, 5%, 9%, and 15% under reductions of 0.75 m, 1.5 m, 3 m, and 6 m, respectively, of the river bed by comparing Sc15, Sc16, Sc17, and Sc18, respectively, to Sc14 (**Table 2**)

Figure 11 shows a typical pattern of water level reduction due to reduced river bed under the same discharge (Sc12 compared to Sc10).

(3) Combined impacts of flow discharge and river bed changes on water levels

Table 2 and **Figure 11** show that, compared to the baseline (Sc0), the mean water level in April at Tanchau reduces by 4% when the river bed degrades by 1.5 m (Sc2). It then gradually increases by 4% and 9% under the increases of 10% and 20% of the flow discharge, respectively (Sc6 and Sc10 compared to Sc2). Reversely, it reduces by 8% with a further degradations of 4.5 m of the river bed (Sc12 compared to Sc10). However, a further increase of 30% discharge helps increase water level by 11% (Sc18 compared to Sc12).

If the river bed degrades by 1.5 m, an increase of 10% in the flow discharge will help conserve the water level (Sc6 compared to Sc0) (**Table 2 and Fig.11**). **Table 2** also indicates that to maintain the water level unchanged when the river bed degrades by 4.5 m, the flow discharge should be increased by 25% (compared Sc18 to Sc13).

Another important result from **Table 2** is that when the river bed degrades by 6 m (Sc12), an increase of 20% of the flow discharge is not enough to conserve the water level as same as the baseline. However, an increase of 50% of the flow discharge is advantageous (Sc18).

(4) Discussions

Water levels in the VMD are sensitive to the changes of flow discharges and rivers' bathymetry. Six mega mainstream dams developed in the upper MR positively increase the dry season flow in the VMD[3]. However, they also trapped tremendous sediment supply from the upstream[6]. Compared to 160 Mt/year of the pre-dam[1], the sediment budget of the VMD in 2015 decreases by 83% (**Fig.6**). It may continue decreasing if more dams will be built in the future, especially eleven proposed mainstream dams in Thailand, Lao PDR, and Cambodia[7]. The reduced sediment supply will, in turn, cause significant river bed degradation and bank erosion.

Maintaining the water levels in VMD' rivers in the dry season that warranties for rice crop's irrigation is crucial, especially under a complicated impacts of upstream hydropower dams in the MR. It is found from our simulated results that increased flow discharge during the dry season by dams is helpful to the irrigation in the VMD, especially under the fact that river beds in delta has been severely degraded by reservoir trapping sediment. Under a low river bed degradation (< 1.5 m), an increase of 10% of the discharge helps improve water levels as high as initial values. Under moderate (1.5 m ≤ degradation ≤ 3 m) and high (3 m < degradation ≤ 6 m) degradation scenarios, 20% and 50% increases, respectively, of the dry season discharges by dams are recommended. While request for high levels of discharge release from upstream dams is not always warranted, river bed degradation in the VMD is foreseen to continue for longer time. Consequently, the dry season water levels in the VMD will be more and more decreased that will cause more and more difficulty for rice crops' irrigation.

Sediment trapped by upstream reservoirs not only degrades the river bed but also erodes the river bank. Due to a lack of data, we do not consider the impact of river bank erosion on water level changes. However, it is expected to exacerbate the severity of the problem.

Sediment trapped by hydropower reservoirs not only causes negative impacts on downstream environment and ecosystem but also reduce the functioning of the dams themselves. We strongly recommend dams' owners to implement a strategic reservoir sediment management such as sediment routing (drawdown flushing, bypassing, sluicing) and advanced sediment management techniques (hydro-suction, dam asset management) which have been successfully applied in Japan.

5. CONCLUSIONS

Agriculture, i.e. rice crops, is crucial for the livelihood of millions of people in the VMD. Any reduction in the dry season water levels will cause difficulty on rice crops' irrigation which, in turn, may reduce the rice productivity and people's incomes. It is therefore important to maintain the dry season water levels in the VMD that warranty for the irrigation.

Water levels in the VMD are sensitive to changes of the regulated flow discharge and river bathymetry induced by upstream dams, especially six mega mainstream dams in the upper MR. By investigating various scenarios of increased low flow discharges and river bed degradation in the upper reach of the VMD using TELEMAC 2-D, some main findings are:

(1) Water levels in the VMD increase under increased flow discharges. In contrast, river bed degradation has opposite effect.

(2) Under a low river bed degradation (< 1.5 m), water levels in the VMD can be improved when the dry season discharge increases by 10%.

(3) Under moderate (1.5 m ≤ degradation ≤ 3 m) and high (3 m < degradation ≤ 6 m) river bed degradation scenarios, increases of 20% and 50%, respectively, of the dry season discharges by dam operations are expected to improve the irrigation.

This study assumes a constant degradation of the river bed, stemming from the fact that degradation is dominant compared to aggradation due to reservoir trapping sediment. Our upcoming studies will focus on numerically investigating the long-term morphological evolution and river bank erosion of the VMD under decreased upstream sediment supply.

ACKNOWLEDGMENT: This research is funded by Japan-ASEAN Science, Technology and Innovation Platform (JASTIP) and the Supporting Program for Interaction-Based Initiative Team Studies SPIRITS 2016 of Kyoto University. We acknowledge Dr. Riadh ATA for his valuable contribution on numerical simulations. Dr. La Vinh Trung is acknowledged for his help in the field survey.

REFERENCES

1) Milliman, J. D and Syvitski, J. P. M. : Geomorphic/Tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers, *J. Geol.*, Vol. 100, No. 5, pp. 525-544, 1992.
2) Lauri, H., Moel, D., Ward, P. J., Räsänen, T. A., Keskinen, M. and Kummu, M. : Future changes in Mekong River hydrology: impacts of climate change and reservoir operation on discharge, *Hydrol. Earth Syst. Sci.*, Vol. 16, No. 12, pp. 4603-4619, 2012.
3) Binh, D. V., Kantoush, S., Sumi, T. and Mai, N. P. : Impacts of Lancang cascade dams on flow regimes of Vietnamese Mekong Delta, *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol. 74, No. 4, pp. I_487-I_492, 2018.
4) Fan, H., He, D. and Wang, H. : Environmental consequences of damming the mainstream Lancang-Mekong river: A riview, *Earth-Science Rev.*, Vol. 146, No. 2, pp. 77-91, 2015.
5) Kummu, M., Lu, X. X., Wang, J. J. and Varis, O. : Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, *Geomorphology*, Vol. 119, No. 3-4, pp. 181-197, 2010
6) Kondolf, G. M., Rubin, Z. K. and Minear, J. T. : Dams on the Mekong: Cumulative sediment starvation, *Water Resour. Res.*, Vol. 50, pp. 5158-5169, 2014.
7) DHI and HDR : Study on the impacts of mainstream hydropower on the Mekong river: final report, *Ministry of Natural Resources and Environment*, Vietnam, 107 pp., 2015.

(Received May 31, 2018)