IMPACTS ASSESSMENTS OF DAM DEVELOPMENT ON FLOW, SEDIMENT, AND SALINITY INTRUSION INTO VIETNAMESE MEKONG DELTA

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Flow and sediment budgetof the Mekong River (MR)is of typical importance for the sustainability and survivability of the Vietnamese Mekong Delta (VMD) in the context of sea level rise due to climatic change. The VMD is sinking and shrinking due to rapidly morphologicaldegradation caused byaltered flow regime and reduced sediment supply from the MR as the result of upstream hydropower dams' development.Dam-induced morphological degradation have further caused increasing salinity intrusion in the VMD. Within the framework of JASTIP project, Kyoto University research groups conducted several boat-based field surveys in 2017-2019 along main rivers and distributaries of the VMD to measure flow and sediment behaviors, river bathymetry, and salinity concentrations. We estimated that the riverbed of the target region near the Cu Lao Tay island in the Tien River was incised by -1.46 m (or -0.49 m/yr) over the period 2014-2017, which was nearly double that during the period 1998-2008, when the riverbed was incised by a rate of -0.25 m/yr. We revealed that rapid riverbed incision in the VMD was consistent with significant decrease of the sediment budget of the MR, which was decreased from 166.7 Mt/yr in the predam period (pre-1992) to 43.1 Mt/yr in thepostdam period (2012-2015), when 64 hydropower dams have been completed in the MR basin. Moreover, reduced high-flow discharges from the MR due to upstream hydropower dam operations - resulting in the reduction of the flow power necessary to transport the sediment - is more likely one of the drivers of the riverbed incision in the VMD. Due to riverbedincision and upstream dam developments, salinity intrusion in the VMDhas been significantly increased.Therefore, collaboratively integrated management of the MR among riparian countries is important for the sustainability and survivability of the VMD.

Keywords: Riverbed incision, Vietnamese Mekong Delta (VMD), Mekong River (MR), sediment budget, hydropower dams, salinity intrusion.

1. INTRODUCTION

Storage reservoirs provide important functions such as disaster prevention, flood mitigation, energy production, and water supply, all of which are vital for humankind (Kantoush and Sumi, 2016). However, their downside are also inevitable, as dams induce strong modifications in flow discontinuity in sediment and declining river ecosystem health.(Kantoush and Sumi, 2019). In the Mekong River (MR) basin, under the pressure of the population expansion and economic growth, more than 130 hydropower infrastructures have been planned and built since 1950s (Fig. 1), of which sixty-four large dams (> 15 m) were completed by 2015 (Kondolf et al., 2014). The total storage capacity of the sixty-four existing dams is over 80 km^3, accounting for 96.8% of the annual discharges at the Chiang Saen station, of which six mega mainstream hydropower dams in China (known as Lancang cascade) constitute more than 51%. The total capacity of the Lancang cascade dams is more than 50% of the dry-season mean inflow volume. This is the main reason that the Vietnam Mekong Delta (VMD) always faces water shortage throughout the low flow years.

Dam related issues have become more daring, with raising concerns about flow and sediment regimes alterations, environment and increase of sedimentation issues in reservoirs (Kantoush et al., 2018). One of the clearest downstream impacts of dam construction is cutting the flood peak (Kantoush et al. 2017), which reduces the amplitude of annual flood pulses, disrupting the connectivity between rivers and floodplains. Although hydropower dams generally increase the low-flow discharges, which may reduce salinity intrusion, dam operations have caused prolonged and earlier salinity intrusion in the Vietnamese Mekong Delta (VMD) by 1-1.5 months compared to the past (Mai et al., 2018), which is likely because of riverbed degradation caused by upstream dam development (Binh et al., 2018a).

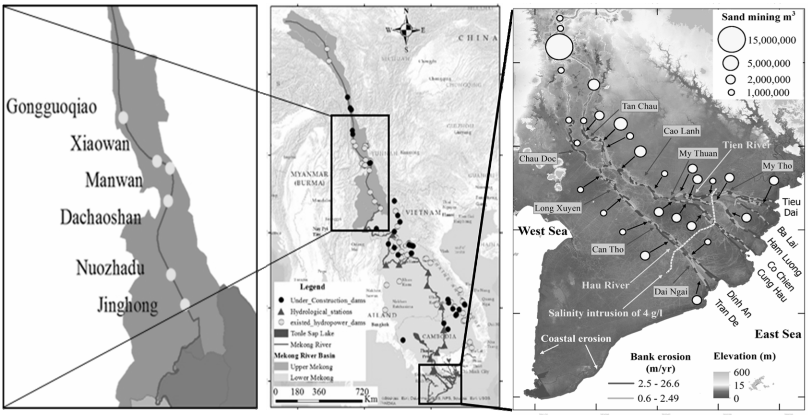


Fig. 1. *Hydropower dams in the MR basin and general characteristics of the VMD*

However, the annual sediment load at the Chiang Saen station (just downstream of the Lancang cascade) (Fig. 1), has been reduced by over 50% due to the completion of only the Manwan dam (Binh et al., 2017).

Salinity intrusion is becoming a more serious phenomenon in the Vietnam Mekong Delta (VMD) under the impact of upstream dams' development and the significant change of sediment budget (Mai et al., 2019). In the severe droughts of 2016, VMDrecorded the lowest water level over the last 90 years since 1926 (Kantoush et al., 2017) in the Tan Chau station and highest salinity value in February and March. Therefore, China implemented three emergency water release from Jinghong reservoir starts from 10th March 2016 until the end of May 2016. These urgent interventions were rapidly reduce the salinity concentration on April and May in the VMD.

Although some prior studies have figured out the impacts of hydropower dams in the MR basin on the flow and sediment downstream, the understanding of the cumulative impacts of upstream dam development on the long-term alterations of the flow, sediment, morphology, and salinity intrusion in the VMD remains largely unknown (Binh et al, 2018b). The focus of this research is to bridge these knowledge gaps by (i) quantifying dam impacts on long-term alterations of the flow and sediment budget of the MR, (ii) estimating morphological changes of the VMD due to reduced sediment supply from the MR, and (iii) ascertaining the impacts of hydropower dam operations on changes in salinity intrusion in the VMD.

2. DATA AND METHOD

As part of assessing the temporal and spatial morphological changes in the Vietnamese Mekong Delta under Kyoto University project, three field survey campaignsalong the Tien River and four times in the Hau River were successfully monitored on the summer of 2014 and 2017. For the field survey campaign on August-September 2017 was along Tien, Hau, and Vam Nao Rivers, were conducted to measure the flow velocity, discharge, turbidity, river bathymetry, and salinity concentrations. Moreover, under JASTIP research project at Kyoto University, we have installed five permanent stationsto monitor suspended sediment and salinity concentrations. The installed turbidity meter are located at Tan Chau, Vam Nao, and ThoiThuan commune. The installed location of the salinity meter are located at BacTrang and Din Anh. Long-term data of water levels, discharges, precipitation, sediment concentrations, and salinity concentrations (from 1950s to 2018) were collected from the Mekong River Commission and the Vietnamese National Center for Hydro-meteorological Data.

Different analytical methods were applied to quantify changes of the long-term flow and sediment budget of the MR, and salinity intrusion in the VMD, then linked with upstream hydropower dam impacts. Based on analytical results, a 2D numerical model by coupling Telemac-2D and Sisyphe models was developed to estimate riverbed incision and associated impacts of low-flow water level reduction in the VMD induced by sediment supply reduction from the MR due to hydropower dams (Binh et al., 2018b). Moreover, we analyzed the impacts of upstream dam operations on salinity intrusion by using MIKE 11 model. Various simulation scenarios have been produced to study the alterations of the flow and salinity intrusion in three hypothesis by hydrodynamic module and advection-dispersion module (Mai et al., 2018).

3. RESULTS AND DISCUSSIONS

3.1 Dam impacts on flow regime of the VMD

Annual minimum discharge of the VMD decreased in the predam period (pre-1992) but significantly increased in post-dam periods (Fig. 2a and b). Similarly, annual maximum discharge also decreased in the predam period (Fig. 2a). However, their trends varied in postdam periods due to some exceptional high floods, i.e., in years 2011, 2013, and 2014. The decreasing tendency of discharges in the predam period was directly related to a reduction of the flow at upstream stations in the MR's mainstream, such as Chiang Saen and Pakse (Lu and Siew, 2006). These decreasing trends may be due to the reduction in the annual rainfall in the MR basin because river discharges are mainly driven by the rainfall when hydraulic structures (i.e., hydropower dams) have not appeared in pre-dam period. Nevertheless, changes in the maximum and minimum discharges in postdam periods were associated with the appearance of upstream hydropower dams, especially after the completion of all six mega dams in the Lancang cascade.

Due to small reservoir capacities of hydropower dams before 2009 compared to the MR's flow, the impacts of dams on the low-flow in the VMD was not obvious (Fig. 2b). However, low-flow discharge significantly increased but water levels decreased after 2009 when three largest dams were in operation. Moreover, discharges and water levelsafter 2009were significantly reduced in January-February while increased in March-June compared to those in the predam period. These findings clearly show that dry season flows were shifted to begin earlier in postdam periods. That may cause difficulty in irrigating the winter-spring crop, which is the most productive and important among three crops in the VMD.

Similarly, changes in high-flow discharges and water levels in the VMD between pre and postdam periods, up to the year 2009, were not clear (Fig. 2c), indicating that the impacts of upstream dam by this year was not significant. This is because of small reservoir capacity of hydropower dams completed before 2009. However, both high-flow discharges and water levels in 2012-2015, when all six mega dams in the Lancang cascade completed, significantly decreased compared to those of the predam period (Fig. 2c). Median and maximum discharges decreased by-13.5% and –4.6%, respectively. Similarly, median and maximum water levels decreased by -19.6% and -20.2%, respectively. Such reductions weredue to the fact that reservoirs in the Lancang cascade stored flood water for electricity generation in the next dry season.

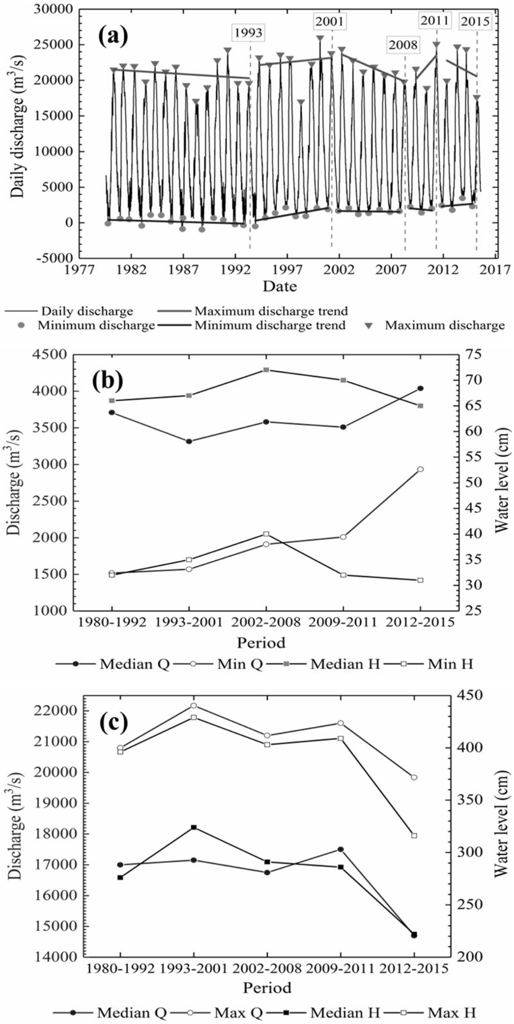


Fig. 2. *Tan Chau station: (a) long-term daily discharges, (b) discharges and water levels in the low-flow season, and (c) discharges and water levels in the high-flow season*

Additionally, we found that changes in tropical cyclones and the construction of upstream dams controlled flow regimes in the low-dam development period (1993-2008), while hydropower dams in the Mekong River basin cumulatively caused flow regime alterations in the high-dam development (2009-2015). Mainstream hydropower dams manipulated the annual maximum and high-flow discharges, while tributary dams drove the annual minimum and low-flow discharges.

3.2 Morphological degradation of the VMD due to reduced sediment supply from the MR induced by hydropower dams

We developed SSC-Q rating curves (SSC: suspended sediment concentration; Q: discharge) for Tan Chau and Chau Doc stations in 1980-1992 by compiling all available data in this period. Based on these rating curves, we estimated the mean annual sediment budget of the VMD during the predam period of 166.7±33.3 Mt/yr, which is in good agreement with the estimated value of 160 Mt/yr by Kondolf et al.(2014). Figure 3ashowed that annual sediment budgets of the VMD have significantly decreased while the annual flow volumes were relatively stable in postdam periods. Reductions in the annual sediment of the VMD were in a similar manner with those at NongKhai station (Fig. 3b). Indeed, the sediment budget at downstream sites should be larger than that of the upstream sites because of the contributions of the sediment from tributaries. However, the postdam sediment budgets of the VMD were even smaller than the predam sediment budget at the NongKhai station (Fig. 3b). On the other hand, the annual sediment loads have been increased at the Jiuzhou station (upstream of the Lancang cascade dams) in between 1965 and 2003 (data after 2004 were not publicly available). All indicated that the sediment supply from the upper MR basin has been increased but the sediment budgets of the lower MR, i.e., at NongKhai and the VMD, have been decreased after the completion of the Lancang cascade dams. In other words, the Lancang cascade dams have caused significant reductions in the sediment budget of the VMD, which may explain for the reductions in the water levels at the Tan Chau station as assessed in Section 3.1.

Compared to the pre-dam sediment budget of 166.7 Mt/yr, the annual post-dam sediment budgets of the VMDhave been significantly decreased due to upstream dam constructions. Sediment reductions initiated rapidly in 1993-2001, then gradually reduced as the number of the dam in the cascade increased (Fig. 3c). Compared to the predam sediment load, the sediment budget of the VMD in the 1993-2001 period has reduced by 59%, which would be the consequence of all dams in the basin. Moreover, all 64 existing dams have caused a reduction of 74% of the sediment budget in 2012-2015 compared to predam condition. Considering 65% of the sediment budget of the MR was contributed by the upper MR (Kummu et al., 2010), all six existing Lancang cascade dams have directly caused a reduction of over 48% of sediment budget in the VMD, of which 38% was due to the first two mainstream dams: Manwan and Dachaoshan.

Due to significant sediment reduction in the VMD induced by upstream hydropower dams, the riverbed and riverbank of the VMD's rivers have been severely incised and eroded, respectively. We estimated that the riverbed of the Tien River and Vam Nao channel around the Cu Lao Tayisland (Fig. 4) was incised by -46.6 Mm^3 during the period 2014-2017 with a mean incision depth of -1.46 m, equivalent to an annual incision volume of -15.6 Mm^3 with a mean incision depth rate of -0.49 m/yr. This incision rate wasnearly double the mean riverbed incision rate of -0.25 m/yr over the decade 1998-2008, which had an absolute mean incision of -2.47 m (Brunier et al., 2014).

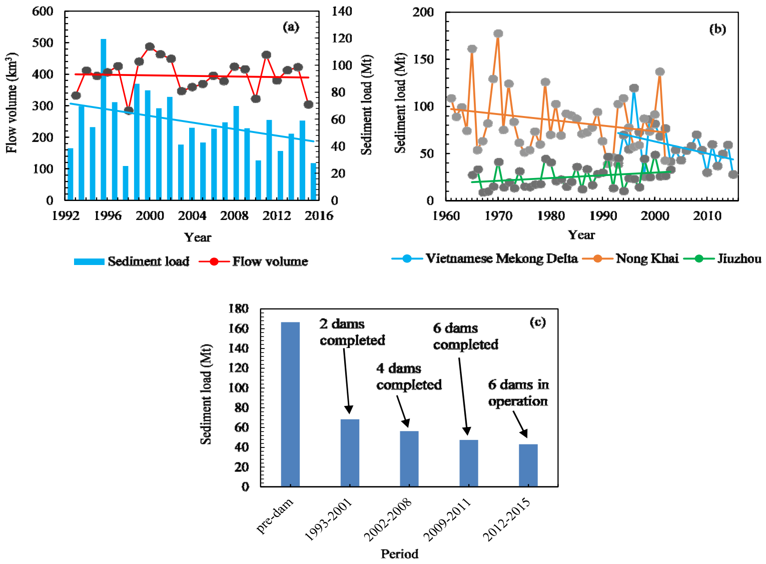


Fig. 3. *(a) Annual sediment loads and flow volumes in the VMD, (b) annual sediment loads along the MR, and (c) mean annual sediment loads in pre and postdam periods in the VMD under appearance of Lancang cascade dams*

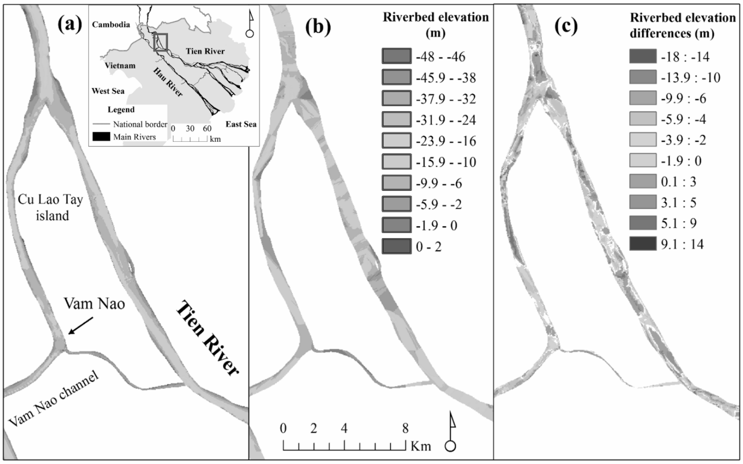


Fig. 4. *Morphological changes of the Cu Lao Tay island sector. (a) morphology in 2014; (b) morphology in 2017; (c) morphological evolution between the 2014 and 2017 datasets*

To quantify the effects of sediment supply reduction from the MR on riverbed incision and reduced low-flow water levels (as shown in Section 3.1) in the VMD, a 2D numerical model coupling Telemac-2D and Sisyphe-2D. The model was established using the input water level, discharge, sediment load, and river bathymetric data of 2014 and was simulated until 2017 for model calibration. After calibrating the model, we established three simulation scenarios for a period 2017-2026 by decreasing the inflow sediment budget entering the VMD as a result of upstream dam impacts and remaining inflow discharges and outflow water levels unchanged. Scenario A (ScA) considered unchanged sediment budget entering the VMD over 2017-2026. In scenario B (ScB), we gradually reduced the sediment budget entering the VMD based on long-term analysis of sediment data; as a result, the sediment budget in 2026 was -17.5% smaller than that in 2017. In scenario C (ScC), the sediment budget of the VMD was remained unchanged during 2017-2019, then reduced by -84.8% in 2020 (based on the results of Kondolf et al., 2014) from which the sediment budget was kept unchanged until 2026.

Fig. 5 shows riverbed incision in the VMD under effects of reduced sediment supply from the MR due to upstream hydropower dams. Particularly, the mean riverbed of the VMD in 2026 was net incised by -1.27m, -1.48m, and -2.04m in ScA, ScB, and ScC, respectively, compared to the riverbed in 2017. The riverbed incision is more severe in the Tien River than the Hau River, and is more severe in the upper part (the boundaries are at Cao Lanh in the Tien River and Long Xuyen in the Hau River) than the lower part. Responding to incised riverbed, the low-flow water levels in April 2026in the Tien River decreased by a maximum value of -47cm, -54cm, and -68cm in ScA, ScB, and ScC, respectively, compared to water levels in April 2017. The corresponding values in the Hau River were -35cm, -40cm, and -49cm in ScA, ScB, and ScC, respectively. Such predicted reduced low-flow water levels may cause increasing salinity intrusion in the delta in the future.

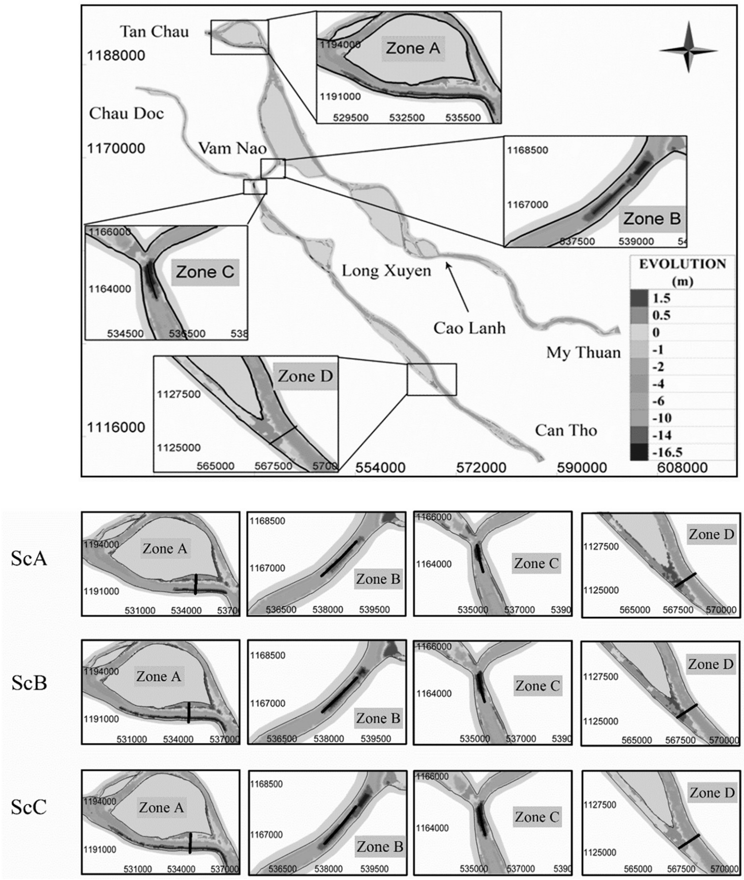


***Fig. 5.** Predicted riverbed incision in the VMD in 2026 under different degrees of sediment supply reduction from the MR from the baseline 2017*

3.3. Increasing salinity intrusion in the Vietnamese Mekong Delta associated with hydropower dams

Many previous researchers concluded that upstream dams operation also alter the flow regime in VMD, i.e. total flow increases in the dry season and decreases in the wet season, the dry flow discharge are significantly increasing from 41% to 108% at ChiangSaen and 25.0 to 160.0% at Kratie(Lauri at al., 2012). However, in the Mekong River Commission (MRC) reports the percentage of total dry flow increasing is about 12.0%.

The total monthly flow in November to January reduces from 8% to 3% respectively, especially a periods 2010 to 2016, total monthly dry flow decreases from 14% to 4%. That is a cause of prolonged and earlier salinity intrusion in the VMD by 1-1.5 months compared to the past (Mai et al., 2018). Figure 6 shows that the maximum salinity in January 2016 almost equals the peak of historical highest salinity years. Moreover, maximum salinity in 2016 appeared in the mid Februarywhile usually occurred on April and March.

Although on 10th March 2016, Jinghong reservoir had released water but it took 17days to 19 days for moving from ChiangSaen to reach VMD (Mai et al. , 2017 and MRC report 2016). If Jinghong reservoir release 1 month earlier (scenario 1) and if upstream dams do not increase the discharge on 10th March (scenario 2), how doessalinity intrusion happen in VMD? The results give that when Jinghong reservoir releases water from 10th February, the maximum salinity (S_{max}) on 13th March will reduce 11.6% (at Daingai station) to 17.3% (at CauQuan station). The maximum intrusion length (L_{max}) also reduces from 4 km to 7km at each river branch. Vice verse, if the 1st emergency water supply in Jinghong reservoir do not occur, S_{max} and L_{max} will increase from 14% to 23.2% and from 4km to 8km in MK estuaries respectively. Furthermore, when combine scenario 2 with the spring tide at the same time (scenario 3), S_{max} will increase 34% to 50.8% and L_{max} of 4g/l salinity concentration will intrude longer than baseline 2016 scenario from 8km to 13km. Shortage fresh water from upstream combined with spring tide will be seriously impact on VMD.

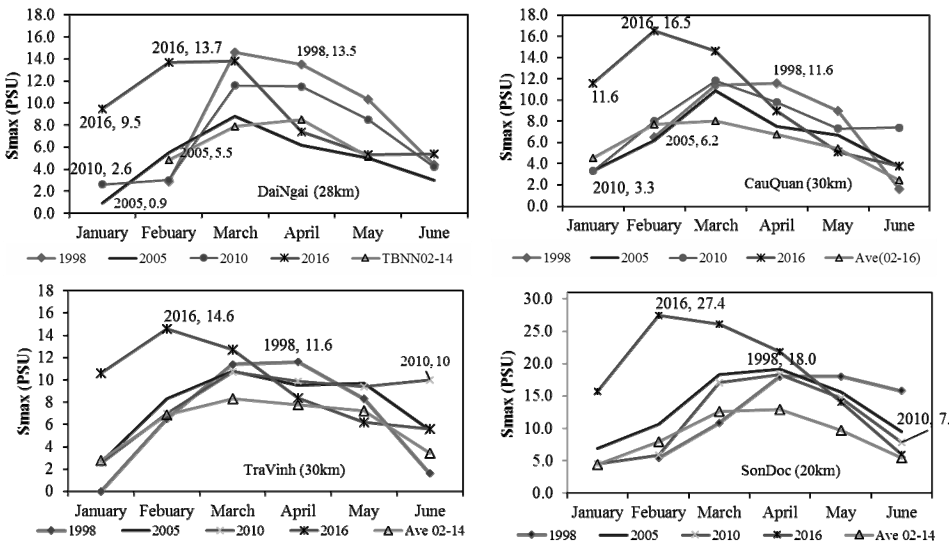
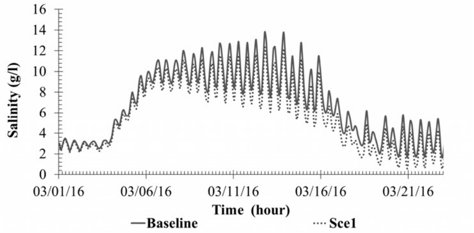


Fig. 6. Maximum monthly salinity concentration in four stations in four estuaries in MR



Hình 7a. *The result of scenario 1 at DaiNgai station, Jinghong reservoir releases water one month earlier*

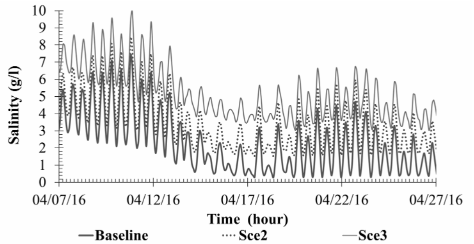


Figure 7b. *The result of Scenario 2 at DaiNgai station, Jinghong did not releasing for 1st emergency water supplements from 10th March to 12th April 2016*

Additional alternative, to reduce the salinity is to optimize the timing of freshwater occurrence during the dry season to open the sluice gates,have been investigated. The salinity distribution along the Hau River at high and low tide were measured (Figure 8). Vertical and longitudinal salinity distribution were conducted at one cross section during 12 hours. Figure 9 shows that the sluice gates can be opened at least 8 hours from 9am to 4pm for collection fresh water with less 1psu concentration during 4 hours at the ebb tide and 4 hours at the flood tide.

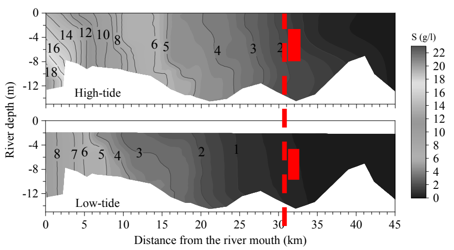


Figure 8. *Longitudinal salinity distribution at DinhAn branch*

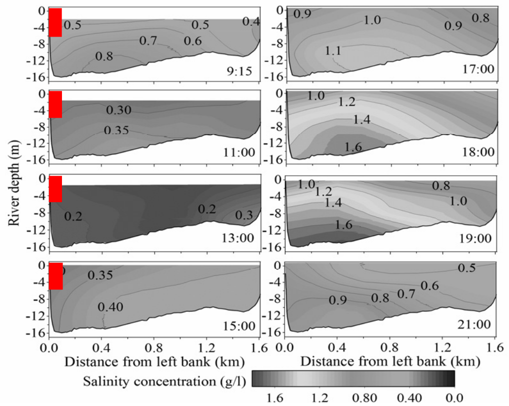


Figure 9. *Longitudinal and vertical salinity distribution at one cross-section during 12 hours*

4. CONCLUSIONS

We investigated the impacts of hydropower dams in the MR basin on long-term changes of the flow and sediment budget along the lower MR, and morphology and salinity intrusion in the VMD by means of analytical analysis, field surveys, and numerical simulations. The main conclusions are:

(1) changes in tropical cyclones and the construction of upstream dams controlled flow regimes in the low-dam development period (1993-2008), while hydropower dams in the Mekong River basin cumulatively caused flow regime alterations in the high-dam development (2009-2015). Mainstream hydropower dams manipulated the annual maximum and high-flow discharges, while tributary dams drove the annual minimum and low-flow discharges.

(2) Climate conditions controlled the sediment budget of the MR during the pre-dam period. Sediment reductions in 1993-2001 in the VMDwere caused by combined impacts of climate condition variations and hydropower dams. However, the 64 hydropower dams that were completed by 2015 were the main driver of sediment reductions in the entire MR during the period 2012-2015.

(3) The sediment budget of the VMD in 2012-2015 decreased by 74% compared to the pre-dam condition, among thatall six existing Lancang cascade dams have directly caused a reduction of over 48%, of which 38% was due to the first two mainstream dams: Manwan and Dachaoshan.

(4) Due to reduced sediment supply from the MR, the riverbed in the VMD rapidly incised, by a rate of -0.5 m/yr during the period 2014-2017, which is double the incision rate in 1998-2008. The predicted mean riverbed incision in the VMD in 2026 compared to that in 2017 is -1.27 m, -1.48 m, and -2.04 m under scenarios of unchanged, -17.5% reduction, and -84.5% reduction, respectively, of the sediment budget of the VMD.

(5) Total dry flow volume increase during the pre-dam period, but total monthly from November to February reduced from 8% to 3% so this is a cause of prolonged and earlier salinity intrusion in the VMD by 1-1.5 months compared to the past.

(6) The timing of water release from upstream dams is very important in drought prevention and salinity control in the VMD. Comparison with baseline scenario, lack fresh water combine with spring tide (Scenario 3) S_{max}will increase from 34% to 50.8% and L_{max} will intrude longer than from 8km to 13km.

(7) Installing the auto salinity monitoring in the main river just at the upstream of sluice gates canal to select the optimal timing to open the gates and withdraw fresh water during the dry season.

ACKNOWLEDGEMENTS

This work was funded by the Japan-ASEAN Science, Technology and Innovation Platform (JASTIP) and the Supporting Program for Interaction-Based Initiative Team Studies SPIRITS 2016 of Kyoto University.

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