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ASSESSING AND ADAPTING THE IMPACTS OF DAMS OPERATION AND SEA LEVEL RISING ON SALTWATER INTRUSIONS INTO THE VIETNAMESE MEKONG DELTA

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Various studies for salinity intrusion in the Vietnamese Mekong Delta (VMD) have been conducted mostly focusing on the lower river mouth without considering the upstream dam impacts. The present paper investigates both the lower and the middle river mouths. Historically, the latter was safer grace to sufficient fresh water from Mekong river basin, which is significantly reduced due to upstream dams' operations. In addition, climate change as sea level rise also increases the salinity effect on the river mouths of VMD. Therefore, this paper focuses on assessing the combined effects of the upstream dam developments and sea level rise to sustain the safe freshwater condition in both lower and middle river mouths. This study can serve as a basis for the consideration of how to mitigate salinity intrusion impacts and discuss the boundary condition of Chinese Dams' operations. The results indicated that the salinity control at the VMD is sensitive to the upstream dams' operations as the modified dam operation scenarios. By increasing the peak discharges during high salinity concentrations from February, the average of maximum salinity concentrations (S_{max}) and intrusion length (L_{sal}) in the VMD would reduce by 15.0% and 10.0%, respectively. The combined scenario of flow reduction and sea level rise in the dry season indicated that the average salinity concentration and average intrusion length increased by 45.0 % and 30.0 %, respectively.

Key Words: *salinity intrusion, upstream hydropower dams, Vietnamese Mekong Delta (VMD), drought*

1. INTRODUCTION

The Mekong River (MR) has a basin area of 795,000 km^2 and a mainstream length of about 4,800 km from the Tibetan Plateau. The Vietnamese Mekong Delta (VMD) is located at the lowermost of MR with total area of 39,000 km^2 from Vietnam-Cambodia border to the East Sea[1)] (**Fig. 1**). The MR is divided into two branches flowing into TienRiver and Hau River in Vietnamese territory. After MyThuan and CanTho, Tien and Hau Rivers flow into the East Sea of Vietnam through 8 estuaries. By 2016, 56 hydropower dams had been completed[2)] along the mainstream and tributaries among 133 proposed dams[1)], in which six mega dams (known as Langcang cascade) are in the mainstream. The total and active storage capacities of these six dams are approximately 41.2 km^3 and 23.1 km^3, respectively (**Table 1**)[3)], accounting for 48.9% and 27.4%, respectively, of the annual mean discharge at

Table 1 Key indicators of the six commissioned Langcang cascade dams of uptream Mekong River

Dam	Catchment area (km^2)	Annual inflow (m^3/s)	Normal storage water level (m)	Dam hight (m)	Total Storage (km^3)	Active storage (km^3)	Installed capacity (MWh)	Guaranteed capacity (MW)	Annual generation (10^{4}MWh)	Reservoir filling
Manwan	114,500	1,230	994	132	1.06	0.26	1,500	807	781	Mar.1993
Daochaoshan	121,000	1,340	899	121	0.88	0.37	1,350	712	670	Nov.2001
Xiaowan	113,300	1,220	1,240	292	15.13	9.90	4,200	1,854	1,889	Dec.2008
Jinghong	149,100	1,840	602	107	1.23	0.25	1,500	833	806	Apr.2008
Gongguoqiao	97,300	985	1,319	130	0.51	0.12	750	390	406	Sep.2011
Nuozhadu	144,700	1,750	812	260	22.37	12.20	5,500	2,403	2,378	Nov.2011
Total					41.18	23.10	14,800	6,999	6,930	

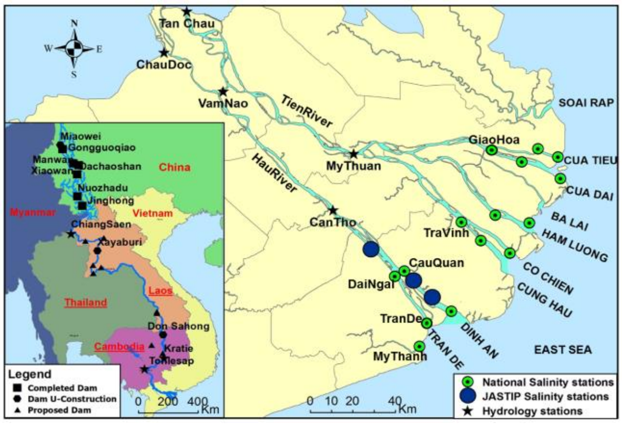

Fig. 1 Location map of upstream dams and monitoring stations.

ChiangSaen, the nearest hydrological station downstream of the Chinese dams (**Fig. 1**). The operations of these dams have altered the flow regime of Mekong Delta, i.e. increase the dry season while decrease the wet season flows[4]. Rasenen et al.[5] concluded that the flow discharges in the dry season at ChiangSaen have significantly increased by 90.0%. Moreover, the operations of all planned dams may lead to increases of 25.0-160.0% and 41.0-108.0% of the dry season discharges at Kratie and ChiangSean, respectively, in comparison between 1982-1992 and 2030-2040 periods[6]. However, the Mekong River Commission (MRC) reports the percentage of increase is about 12.0%[7].

The VMD has two tidal regimes with a larger tidal magnitude from 2.5 m to 3.8 m in the East Sea of Vietnam[8]. The year 2016 broke the record of the severe drought and salinity intrusion in the VMD over the last 90 years since 1926[1), 2)]. Salinity intrusion was widespread over 22 thousand km^2 of the VMD with extremely high concentrations and intrusion length into the land, e.g. 4.0 g/l saline concentration on Tien River intrudes up to 65.0 km. Previous studies have not evaluated the combined impacts of flow change, tide and sea level rise (5.6 mm/year[8]) on the VMD during extreme drought years with a repeating cycle of 5 to 6 years (occurred in 1998, 2005, 2010 and 2016[2]).

Therefore, this paper aims to elucidate the sensitivity of salinity concentration and intrusion length into the VMD by taking into account the combined impacts of upstream dams' operations and sea level rise in extreme drought years similar to 2016, and based on that, measures are proposed for mitigation.

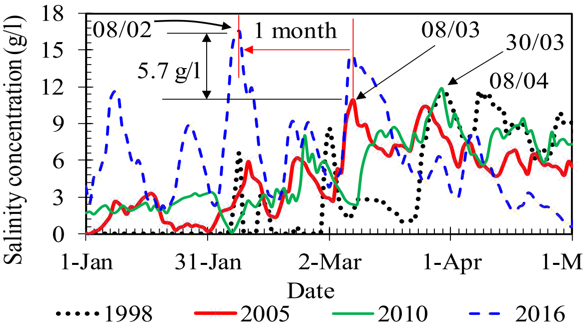

Fig. 2 Daily maximum salinity concentrations at CauQuan station.

2. THE STATUS OF DROUGHT AND SALINITY INTRUSION IN THE VMD

(1) The status of salinity intrusion in VMD

Figure 2 depicts daily maximum salinity concentrations (S_{max}) at CauQuan station in Hau River (**Fig.1**) of four highest salinity years historically. Throughout the VMD, the occurrence of S_{max} in 2016 is about 1.0-1.5 months earlier than that in previous years. At CauQuan station, for example, while S_{max} occurred in April 1998 and March 2005, it was shifted to take place in February 2016 (**Fig.2**). Moreover, the annual peak salinity concentrations in recent years are significantly higher than those in the past. For instance, the annual peak salinity concentration at CauQuan station on 8th February 2016 was recorded as high as 16.5 g/l which is about 1.4 times larger than that recorded on 8th April 1998 of 11.6 g/l (historical drought year). In addition, the intrusion length of 4.0 g/l concentration line in Hau River in 2016 is 60 km from the river mouth, which is about 7 km further than that in the same period of 1998. The drought event 2016 affected an area of 52.7% of the VMD with a total economic loss of about US$360 million[2]. CanTho province (**Fig. 1**), located at 80 km from the East Sea, was not affected by saltwater before but suffered from salinity intrusion with 2.0 g/l concentration in 2016.

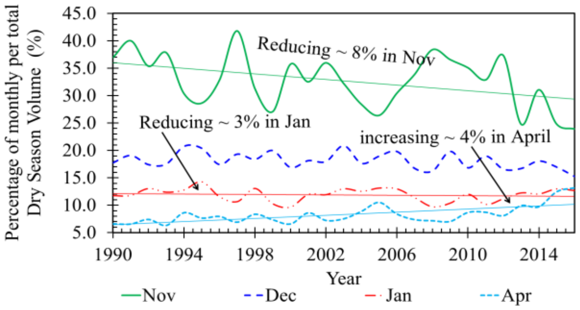

Fig. 3 Ratio of monthly flow and dry flow volumes at Kratie.

(2) The changing of flow regime and sea level rise

The flow discharge during the dry season into the VMD mainly passes through the Kratie hydrological station and a portion from the TonleSap Lake (**Fig. 1**). Meanwhile, the flow of ChiangSaen station represents 30% to 40% of the total runoff of Kratie station$^{4)}$. Therefore, the VMD is affected by the upstream dam operations, which shifts water from the wet season to the middle of the dry season$^{3)}$.

The rate of total dry flow volume (W_{dry} from Dec. to May) per total annual flow volume at Kratie has increased by 7.02-11.91% during 1990-2016 period, the maximum in 2013 reached to 16.78%$^{2)}$. Such increases are due to impacts of upstream dams. However, with a total active storage capacity of 22.2 billion m^3, accounting for 34.69% of annual mean flow volume at ChiangSaen (64x10^9 m^3)$^{3)}$; reservoirs of Xiaowan and Nuozhadu dams take very long time for water storage until the beginning of the dry season (November, December, and January). Consequently, over 26 years (1990-2016), monthly flows of November-January in the beginning of the dry season at Kratie have reduced by 8.0-3.0%, respectively, with a higher reduction rate during 2010-2016 period of 14.0-4.0%, respectively (**Fig. 3**). That accounts for earlier salinity intrusion with higher magnitudes in recent years. Particularly for the dry season in 2016, the flow in December and January at all stations was lower than those on 1998 and the average flow between 1980 and 2013, an example at Kratie in **Fig. 4**. Therefore, China took actions to implement three emergency water supplements to the MR by increasing the released discharge from Jinghong Reservoir$^{7)}$. During the first one, the flow monitoring at ChiangSaen started rising from 2.26 m (1,319 m^3/s) on 10th March to 3.25 m (2,230 m^3/s) on 14th March and remained stable at 3.25 m until 12th April. The second emergency supply was from 12th to 22nd April 2016 and the third was from 22nd April to 31st May (**Fig. 4**). The flow moving from ChiangSean to Kratie took about 15-17 days in dry season, depending on the discharges at ChiangSaen. This number was also reported by MRC$^{7)}$.

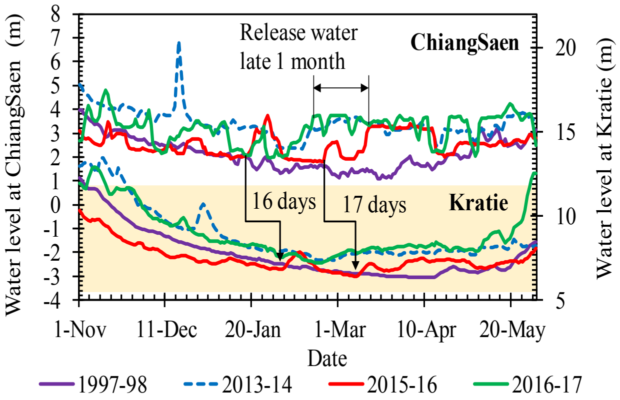

Fig. 4 Daily water level in ChiangSean and Kratie stations.

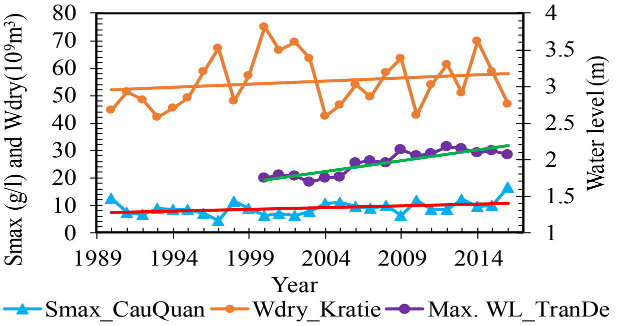

Fig. 5 Trend of W_{dry} measured at Kratie station, S_{max}, and water level in Hau River between 1990 – 2016.

Therefore, the flow at Kratie increased during 27th March to 17th June in the first emergency water supplement (**Fig. 4**). However, high saltwater concentrations in Hau River appeared two times, firstly, on 8th to 10th February and secondly from 8th to 15th March. If the first emergency water supplement had released water on February 2016, the VMD would have avoided maximum salinity on March 2016.

Climate change causes sea level rise about 5.6 mm/year and may rise to 100.0 cm in 2100$^{8)}$, where 38.9% of the VMD area would be inundated. **Fig. 5** shows that during 16 years (2000-2016) at TranDe station at Hau river mouth (**Fig. 1**), the water level rises from 175.0 cm in 1990 to 218.0 cm in 2016 with a rate of 26.87 mm/year. Sea level rise is one of the main causes that makes salinity intrusion more severe.

3. 1-D MODEL SETUP AND SCENARIOS

(1) 1-D Model setup

MIKE 11 model developed by Danish Hydraulic Institute$^{9)}$ was used to simulate the flow by hydrodynamic module (HD) and salinity intrusion in river and channel network by advection-dispersion (AD) module$^{9)}$. The computational scheme consists of five discharge boundaries in the upstream and 59 downstream boundaries using hourly water levels and odd hourly salinity concentrations **(Fig. 6)**.

Table 2 The scenarios of numerical simulations.

Scenarios	Description of boundary condition	Remark
Baseline (Sc0)	**Upstream**: Discharge hydrographs of 2016 **Downstream**: Water level and salinity of 2016	For calibration
Scenario 1 (Sce1)	Reducing flow discharge boundary by 364 m^3/s [= 0.4(2,230-1,319)] of Kratie from 27th March to 29th April.	**Dams impact**: No increasing of flow discharge in the first emergency water supplement (from 10th March to 12th April at ChiangSaen)
Scenario2 (Sce2)	Scenario 1 + Sea level rise by 3.36cm (= 5.6mm x 6 years)	Dams impact + Climate change
Scenario 3 (Sce3)	The first supplement1 month earlier: shifting the discharge from 27th March to 27th February at Kratie Discharge Boundary.	**For mitigation**: dam operation releases water 1 month earlier for the first emergency water supplement to avoid the peak salinity in Mar.
Scenario 4 (Sce4)	Scenario 3 + Sea level rise by 3.36cm	**For mitigation** + Climate Change

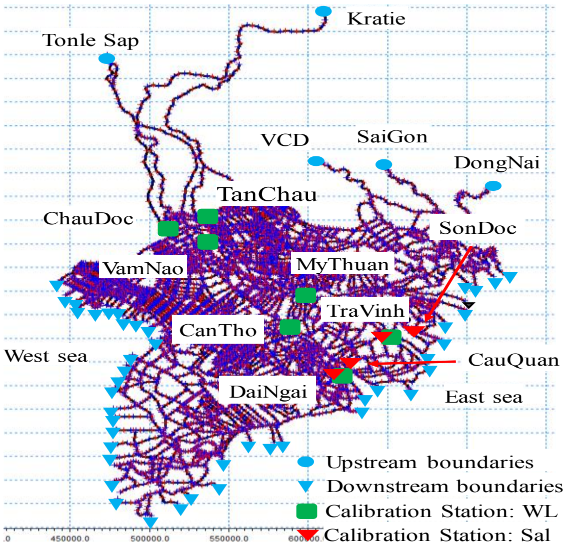

Fig.6 1-D Hydrodynamic model setup.

(2) Simulation scenarios

The baseline (Sc0) considers daily discharges at upstream boundaries and hourly water levels at downstream boundaries (**Fig. 6**) of the most severe drought year 2016 (**Table 2**). Moreover, historical data show that a severe drought event in the VMD has a return period of 6 years. Therefore, we would investigate the severity of salinity intrusion of the next cycle when a cumulative sea level rise of 3.36 cm combined with regulated inflow discharges at Kratie due to dams' operations are taken into account (**Table 2**).

4. MODEL CALIBRATION AND RESULTS

The model calibration was carried out with the hydrological and salinity concentration data of 2016 by two steps and verification by data of 2005. Firstly, the Manning coefficients and initial water level in rivers were adjusted to obtain the best fit between simulated and measured water level at ChauDoc, TanChau, MyThuan, CanTho, MyTho, TraVinh and DaiNgai stations. The accuracy of the numerical results are evaluated by using coefficient of determination (R^2) and Nash-Sutcliffe coefficient (E_f) with R^2 and E_f always higher than 0.85. Secondly, calibration for advection-dispersion module was conducted by initial salinity concentrations and dispersion coefficients for the river reaches with observed data at DaiNgai, CauQuan, and TraVinh salinity stations about 30.0 km from estuary. The observed and simulated water levels at CanTho station (**Fig. 7**) and saltwater in DaiNgai station (**Fig. 8**) are well matched with R^2 of 0.97 and 0.81, respectively.

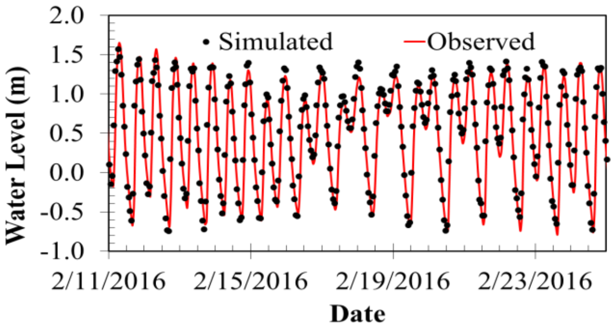

Fig. 7 Simulated and observed water level at CanTho.

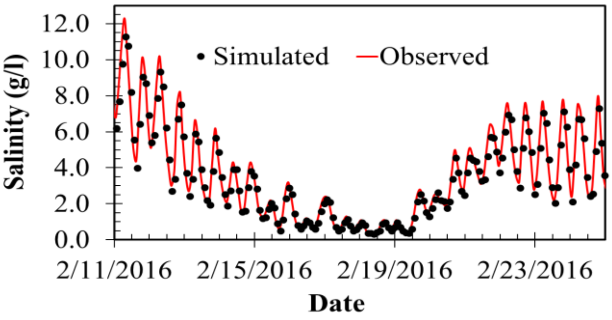

Fig. 8 Simulated and observed Salinity at DaiNgai.

Table 3 and **Fig.9**, **Fig.10** compare simulated salinity concentrations of four scenarios to the baseline in April and March. The difference in percentage ($P\%$) between simulated salinity concentrations of four scenarios to the baseline is defined as

Table 3 Salinity concentrations and intrusion length of Mekong estuaries on 13 Mar. and 10 Apr.

		Salinity concentration at about 30km from the estuaries.								Intrusion Length of 4g/l			
No.	Scenario	DaiNgai Station (g/l)		CauQuan Station (g/l)		TraVinh Station (g/l)		Giao Hoa Station (g/l)		From TranDe estuary (km)	From DinhAn estuary (km)	From CoChien estuary (km)	From CuaDai estuary (km)
		Salinity	(P%)	Salinity	(P%)	Salinity	(P%)	Salinity	(P%)				
1	Baseline on 13 March	13.8		11.8		8.2		8.4		57	57	47	62
2	Sce 1	13.8		11.8		8.2		8.4		57	57	47	62
3	Sce 2	17.2	24.7	15.4	30.5	12.5	52.4	13.8	64.3	81	81	63	75
4	Sce 3	12.2	-11.6	9.8	-17.3	6.9	-15.9	7.1	-15.5	51	51	43	55
5	Sce 4	15.3	10.6	13.2	12.1	9.1	11.0	11.2	33.3	72	72	55	70
1	Baseline on 10 April	7.4		5.4		4.9		7.3		41	41	35	55
2	Sce 1	8.4	14.0	6.4	19.2	6.0	23.2	8.9	21.9	45	45	40	63
3	Sce 2	10.0	34.9	7.9	46.3	7.4	50.8	10.9	49.3	49	49	47	68
4	Sce 3	6.9	-6.8	5.1	-5.5	4.6	-6.0	7.1	-2.7	39	41	35	53
5	Sce 4	9.4	27.0	7.5	38.9	7.3	49.0	10.7	46.6	49	49	45	68

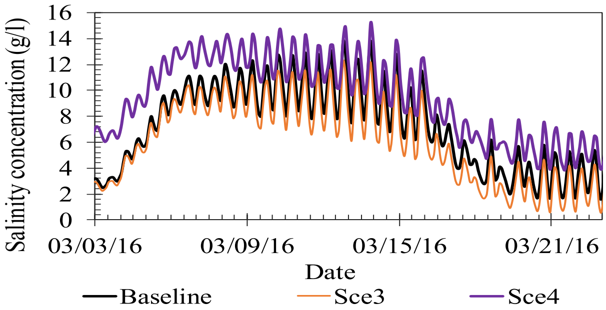

Fig. 9 Hourly salinity concentrations in April at DaiNgai.

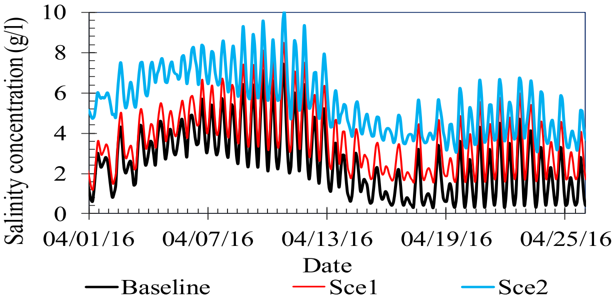

Fig. 10 Hourly salinity concentrations in March at DaiNgai.

$$P\% = 100*(S_i - S_B)/S_B \qquad (1)$$

where: S_B: salinity concentrations of the baseline; S_i: salinity concentrations of scenario i ($i = 1 \div 4$).

When discharges at Kratie (upstream boundary) reduce by 364 m^3/s from 27th March to 27th April (***Sce1***), the salinity at each estuary in the VMD starts to increase from 1st April. On 10th April, the maximum salinity concentrations of ***Sce1*** at stations located 30 km from the sea increase by 14.0%÷23.2% compared to those of baseline (**Table 3**) because discharge at these stations increase by 2.21% (from -5108.8 m^3/s to -5222 m^3/s) to 2.71% (from -6723 m^3/s to -6905 m^3/s). Under the flow reduction with 3.36 cm sea level rise in ***Sce2*** **(Table 2)**, the salinity concentrations at DaiNgai and TraVinh stations increase by 34.9% and 50.8%, respectively (**Table 3**) as a result of discharge changing of 4.9% and 5.9%, respectively. Moreover, the length of the salinity intrusion was shifted inward by 16.0-24.0 km in main streams due to the lack of freshwater to push saltwater back to the sea. Specially, the 4.0 g/l of saline water intruded over CanTho city where has never been in such situation in the past. The people in this region therefore are necessary to learn strategies to control or adapt to the saltwater.

In ***Sce3*** (**Table 2**), grace to the modified dam operations under emergency water releases of about one month earlier than the usual (shifting the discharge time series at Kratie from 27th March in the baseline to 27th February in ***Sce3***), salinity concentrations in the VMD, therefore, gradually reduce during March; particularly reduce by 11.6% and 15.9% on 13th March because of discharge increasing by 5.1% (from +2337.6 m^3/s to +2456.1 m^3/s) and 6.9% (from +5226 m^3/s to +5470 m^3/s) at DaiNgai and TraVinh stations, respectively. The intrusion length would also decrease by about 7.0-10.0 km (**Table 3**). Hence, the timing of water release from upstream dams is very important in drought prevention and salinity control in the VMD.

Sea level rise is a natural phenomenon caused by climate change. In the context of sea level rise of 3.36 cm in the next six years (***Sce4***), saline water will quickly extend 8.0-10.0 km further inland into the VMD and salinity concentrations increase by over 2.0 g/l compared to the baseline but salinity concentrations in ***Sce4*** are 2.0 g/l less than those of ***Sce2*** (**Table 3**).

Table 3 reveals that the most critical salinity intrusion in the VMD is the combination of decreased inflow discharge due to dams' operations and sea level rise due to climate change in ***Sce2***. Average salinity concentrations ($S_{average}$) and the intrusion length (L_{sal}) of four stations (DaiNgai, CauQuan, TraVinh and GiaoHoa stations) in ***Sce2*** increase by 45.0% and 30.0%, respectively, compared to the baseline. In contrast, emergency water release by dams in ***Sce3*** has positive impacts in terms of drought mitigation as the $S_{average}$ of those stations and L_{sal} in the VMD reduce by 15.0% and 10.0%, respectively.

5. DISCUSSION

By taking into consideration both dam operation and sea level rise, the salinity intrusion level is clarified quantitatively. Such outcomes are crucial and can be used as a base for proposing the effective mitigation strategies to deal with salinity intrusion in the VMD. The simulated results demonstrate that appropriate timing and discharge release from dams upstream are likely to provide effective results for sustainable water management in the VMD. When upstream dams release high discharges during a long time in February, the VMD could have avoided the history salinity intrusion in 2016, resulting in the salinity concentration reducing at least 11.0% and intrusion length of 4.0 g/l being within saltwater control gates.

Some other soft and hard measures should be conducted to mitigate the impact of sea level rise and changes of the MR flow in the dry season. One of them is to change the seasonal calendar and land use pattern to reduce the water use and increase flood inundation area to reserve more fresh water for the dry season. Raising awareness and building capacity of local people in response to sea level rise and upstream development is also necessary.

Taking more active control in the operation of the sluice gates along estuaries through early warning systems and setting up supervisory control and data acquisition (SCADA) system are also good choices.

6. CONCLUSION

With the six mega dams upstream of the MR operating since 2012, the flows at ChiangSaen and Kratie have quickly reduced during November÷January, causing maximum salinity concentration occurring 1.0-1.5 months earlier and lasting longer than what happened in the past. The maximum salinity concentration in 2016 reached the highest maximum salinity during the last 90 years as historical drought[1), 2)]. That caused a huge impact on the VMD's human activities such as timing of sowing and harvesting, crop and aquiculture productions.

The flow at Kratie plays an important role in salinity control of the VMD. Reducing the discharge at Kratie combined with sea level rise **(*Sce2*)** provides evidences that they make more significant impact to the VMD, 4.0 g/l salinity intrusion length reach over 81.0 km along the VMD estuaries such as CanTho. It is therefore required more saline control infrastructure to be built along the middle of river mouths.

In contrast, by releasing water 30 days earlier than the normal dam operation (***Sce3***), salinity concentrations reduce by about 2.0 g/l and the intrusion length reduces by 7.0-10.0 km at all estuaries. Hence the cooperation on sharing water among countries in the MR plays an important role for integrated water management. Dams' owners are strongly recommended to share the regulation rules of reservoirs to downstream countries to help them become active in integrated water resources management strategies.

The impacts on VMD would be more severe if eleven proposed dams in the main-stream of the MR in Thailand, Lao PDR and Cambodia come into operation. Further research should be carried out to elucidate the possible impacts and propose mitigating measures accordingly.

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