INFLUENCE OF RIVER DISCHARGE AND MORPHOLOGY ON SALTWATER INTRUSION INTO THE VIETNAMESE MEKONG DELTA

Nguyen Thi Phuong Mai[1], Sameh Ahmed Kantoush[2], Tetsuya Sumi[3], Tang Duc Thang[4]

Abstract: *In recent years, i.e., in 2016 and 2020, large-scale saltwater intrusion has been causing shortage of freshwater for domestic and agricultural uses in the Vietnamese Mekong Delta. Therefore, sufficient understanding of the impact factors on saltwater intrusion in the delta is important for water resources management. This paper examines the effects of reduced water flow by upstream dams' operation and river bed incision on saltwater intrusion in the Mekong Delta. In that regard, long-term water flow at two upstream hydrology stations from 1980 to 2020 and river bed incision from 2009 to 2017 were analyzed. Then, one-dimensional hydrodynamic and advection-dispersion model was used to compare salinity concentration and intrusion length between three scenarios. The results indicated that the influence of river flow on saltwater intrusion is more significant than that of river bed incision. When river flow at Kratie reduced by 14,4%, the highest salinity concentration (S) and intrusion length (L) increased by 17.4% and 10.5%, respectively. While, river bed incised by 0.88m for the next four years, S and L increased by 2.8% and 1.67%, respectively.*

Keywords: Saltwater intrusion, upstream dams, drought, riverbed incision, numerical modelling.

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 the MR with total area of 39,000 km^2 from the Vietnam-Cambodia border to the East Sea (see figure 1). The MR is divided into two branches flowing into Tien and Hau Rivers in the 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 along the mainstream and tributaries among 133 proposed dams (Allison, 2017), in which six mega dams (known as the Langcang cascade) are in the mainstream.

Dams are known to have significant influences on the flow hydrology: changes in the timing, magnitude and frequency of the flow in both dry and flood seasons. Many studies assessed the impact of upstream dams on the VMD. These research results all showed that the total dry flow (from Dec. to May) increases while the total rain flow decreases. Rasenen (2017) concluded that the river discharges in March to May in 2014 have significantly increased by 121%-187% and 41% -74% at ChaingSaen and Kartie respectively while total flow in July -August 2014 reduced by 32-46% at Chiang Saen compared to average discharges of 1960-1990. Also, Lauri (2012) reported that the operations of all planned dams may lead to increases in the dry season discharges of 41.0-108.0% at Chiang Saen and 25.0-160.0% at Kratie, upon comparing the 1982-1992 period and the 2030-2040 period. However, the Mekong River

[1] *Thuyloi University-Southern Campus (No.2 TruongSa street, HoChiMinh City, Vietnam)*
[2] *Associate Professor, DPRI, Kyoto University (Goka-sho, Uji-shi, 611-0011, Japan)*
[3] *Professor, DPRI, Kyoto University (Goka-sho, Uji-shi, 611-0011, Japan)*
[4] *Professor, Vice President of VietNam Academy for Water Resource*

Commission (MRC, 2016) reported that the flow increasing is about 12.0% at Kratie for the same periods. In the recent study of Mai (2018) referred to an increase in the dry season flow of 7.2-11.9%. The dry flow fluctuation in the post-dam period is much larger than that in the pre-dam period due to the operations of the reservoirs. However, the dry flow increasing was not evenly distributed for all six months in the dry season, the total dry flow increases but this is occurring at the end of the dry season while decreasing significantly at the beginning of the dry season. For instance, the flow at Kratie has reduced by 8.0-3.0% from November to January in the period of 1990-2016 with a higher reduction rate during the 2010-2016 period of 14.0-4.0% (Mai et al, 2018). That accounts for earlier saltwater intrusion with higher magnitudes in recent years.

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

Another transboundary effect of upstream dams is a reduction in the riverine suspended sediment load. By 2015, the sediment load in the VMD has reduced by 74.1% due to reservoir sediment trapping in the MR basin, of which 40.2% has been caused by six mega dams in the Langcang cascade (Binh et al., 2020). If all 133 planned dams are completed, only 4% of the MR sediment load will be reach the Mekong Delta (Kuenzer, 2013), which may lead to severe river bed incision. Dry flow fluctuation and reduced sediment load may lead to various impacts on the VMD such as freshwater shortage, channel bed incision, lateral channel expansion, morphological changes which may increase saltwater intrusion. All these changes would cause damages to agriculture and aquaculture and thus negatively impact people's livelihoods in the VMD.

Therefore, this paper aims to emphasize the causes of the extreme drought and saltwater intrusion in 2020 in the VMD. Then, to assess the influence of riverine water level reduction and river bed incision on salinity intrusion into the VMD by field observations and a numerical model.

2. FIELD SURVEY - DATA COLLECTION

Field survey: an Acoustic Dropple Current Profile (ADCP) and a Trimble GPS were used to measure 200 cross-sections along over 550km of the Hau and Tien Rivers and the VamNao channel on August 2017. The distance between two adjacent cross-sections ranged from 1 to 5 km. Over 500 cross-sections in 2009 were collected from ThuyLoi University, Vietnam.

Daily water levels (WL) and discharges at the Chiang Saen, Kratie, TanChau, ChauDoc, CanTho and MyThuan hydrological stations were collected from the MRC. Hourly WL and salinity concentration (S) data at 13 stations along the Tien and Hau Rivers and along the coasts were also collected from the Southern Regional Hydro-meteorological Center, Ho Chi Minh City.

3. THE STATUS OF DROUGHT AND SALTWATER INTRUSION IN VMD

3.1 The status of saltwater intrusion in the VMD

The year 2016 broke the record of severe droughts and saltwater intrusion in the VMD over the last 90 years. The highest salinity occurred 1.0 to 1.5 months earlier than that in previous years. The maximum salinity (S_{max}) and intrusion length (L) in 2016 were 3 to 6 psu higher and 7 to 8 km longer than those recorded in 1998 (a historical drought year)[9]. The repeating cycle of extreme drought year was 5 to 6 years (occurred in 1998, 2005, 2010 and 2016) (Mai et al., 2018).

Notably, drought and saltwater intrusion in 2020 exceeded the record levels in 2016. For instance, saltwater intrusion in 2020 appeared 1 month earlier than that in 2016 (from Nov. 2019) (see figure 2) and over two months earlier than previous years. The intrusion length of 4 psu (critical S for fruit trees) was 4 km to 8 km deeper inland than those in 2016 in all Mekong estuaries.

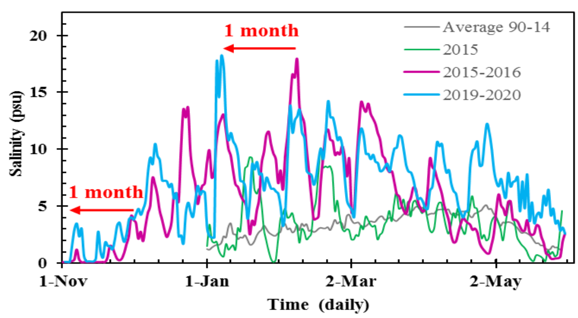


Fig 2. Daily highest salinity concentrations at BacTrang station

Consequently, 10 out of 13 provinces in the VMD were affected by saltwater intrusion while 5 provinces had declared a state of emergency by water shortage and significant damages to crops, threatening agriculture production, livelihoods and water uses. For instance, more than 332,000 ha winter-spring rice crop (22% of the total area) and 136,000 ha orchard (39.1%) have been affected by saltwater intrusion and approximately 200,000 households lacked safe water for domestic uses (Mai et al., 2018).

3.2. Changes in flow regime

Two key upstream factors that control water resources and saltwater intrusion in the 2019-2020 dry season in the VMD are the flows from the Tonle Sap Lake (30-35%) and from the main MR at Kratie (figure 1). Because the flow at Chiang Saen represents 40% of the total runoff at Kratie in the dry season (Kuenzer et al., 2013), any abnormal flow regulations from dams in the upper Mekong basin (i.e., the Lancang cascade), especially during the dry season, may worsen saltwater intrusion in the VMD. In 2019, the onset of the rainy season in the Mekong basin started late and its duration was short compared to other years. Therefore, the total annual flow of the MR was lower than the long-term annual average. Therefore, the Tonle Sap Lake was not filled up, leading to limited reversal water back to the VMD from January to March compared to normal years (Zoe Osborne, 2020). Similarly, the flow at Kratie decreased rapidly from the beginning of the 2020 dry season and became the lowest in this century (see figure 3). The water level in the beginning of dry season 2020 is lowest and lower than that in 2016 by 1.84m and 1.69m at Chiang Saen and Kratie respectively. We estimated that the flow 2016 at Kratie reduce about from 18.82% to -5.4% with an average value of 14.4%. It was partly caused by a reduction of the corresponding flow at Chiang Saen by up to 40.7%.

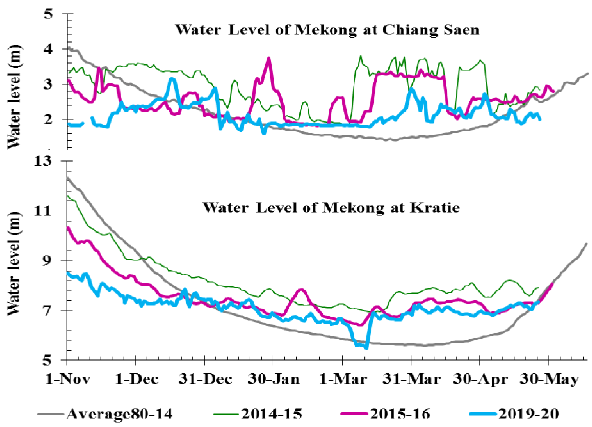


Fig 3. Daily water levels in Chiang Sean and Kratie, showing extremely low values in 2019-2020 drought year

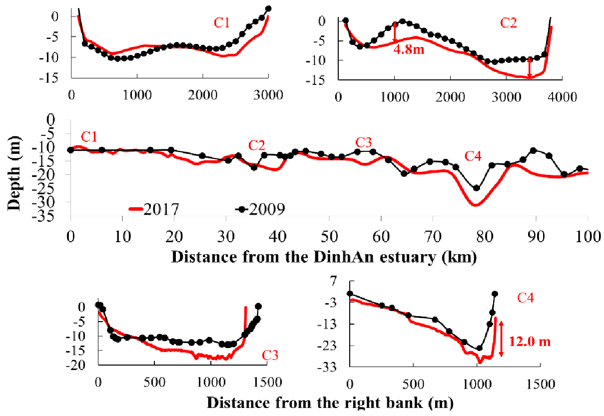


Fig 4. Comparisons of longitudinal profiles and cross-sections of the Hau River in 2009 and 2017

This is a cause of the 2019-2020 drought started earlier than that in 2016. The water level at Chiang Saen and Kratie are higher than the long-term annual average from Jan but salinity concentrations in 2020 remained high value until the end of May. This may be due to many river diversion projects in the Mekong River and the increase in water demand of the downstream countries due to increased agricultural land area. For example, Laos and Cambodia will increase by 27.98% and 53% of irrigated area by 2030 (Quang 2016).

Table 1. The scenarios of numerical simulations

Scenarios	Description of Boundary condition	Remark
Baseline	Real conditions of the 2016 dry season + DEM 2017	Measured during our field survey in August 2017
Scenario 1 (Sce1)	Upstream boundary at Kratie: discharge 2020 (reduced by 14.4%) + DEM 2017	The influence of flow reduction
Scenario 2 (Sce2)	Riverbed incision from 2017 to 2020: 0.22m/yr x 4 = 0.88m	The influence of river bed incision
Scenario 3 (Sce3)	Sce 2 + Sce 3	The influence of flow reduction and river bed incision

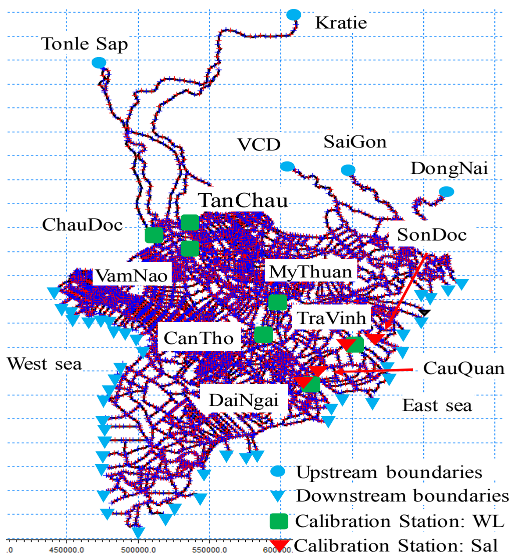


Fig 5. 1-D Hydrodynamic model setup.

3.3. Morphology changes

Figure 4 shows evidence of critical riverbed incision in the VMD from 2009 to 2017 in the Hau River. Longitudinally, the river bed of along Hau River from CanTho to the estuary (100 km) drops down from 0.02 to 12 m with an average value of 1.76 m, equivalent to a mean reducing rate of 0.22 m/yr. It is approximately 1.6 times greater than the bed erosion rate of 0.14 m/yr in the period of 1998-2008 (Alison, 2017). Increasing river bed erosion in recent years is attributed to the reduced sediment load of the MR caused by upstream dams and sand mining. Binh et al (2020) concluded that the suspended sediment load of the VMD has decreased by 74.1% from the pre-dam (166.7 ±33.3 Mt/yr) to the 2012-2015 (43.1 Mt/yr) periods, in which 40.2% was caused by six mega-dams in the Lancang cascade. Also, sand mining was responsible for a maximum of 14.8% of annual river bed incision in the VMD (Bravard et al., 2013 and Binh et al., 2020). River bed incision could be a cause of saltwater intrudes deeper inland and more prolonged into VMD.

4. 1-D MODEL SETUP AND SCENARIOS

4.1. 1-D Model setup

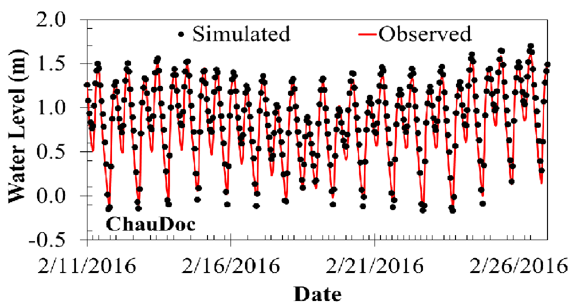
MIKE 11 model developed by Danish Hydraulic Institute was used to simulate the flow by the hydrodynamic module (HD) and saltwater intrusion in the river and channel network by the advection-dispersion (AD) module. The computational scheme consists of five discharge (Q) boundaries in the upstream and 59 downstream boundaries using hourly WL and hourly salinity (see figure 5).

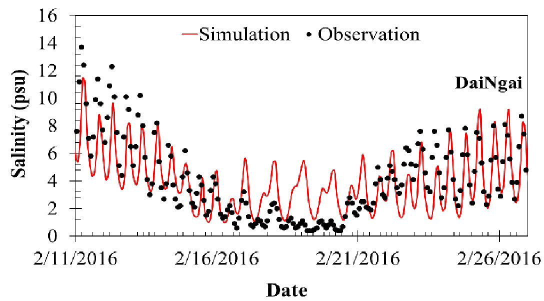
4.2. Simulation scenarios

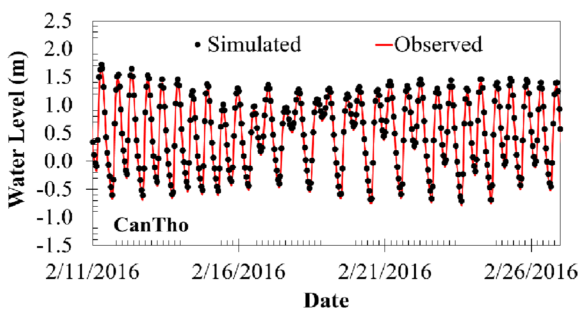
The baseline (Sc0) used Q, WL and S in the 2016 severe drought as boundaries. Historical data showed a recent repeating cycle of severe droughts of 4 years compared to 6 years in the past. Therefore, we considered the severity of saltwater intrusion in the next drought cycle when the discharge at Kratie reduces 14.4% combined with a bed erosion rate by 0.22 m/yr along 100km from the coastal zones to the upstream (see table 1).

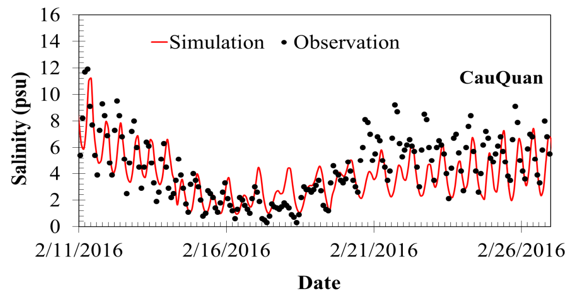
5. MODEL CALIBRATION

The model was calibrated using WL and S data of 2016 and verified using respective data of 2005. Firstly, the Manning coefficients and initial discharge and water level in rivers were adjusted to obtain the best fit between simulated and measured WL at ChauDoc, TanChau, MyThuan, CanTho, MyTho, TraVinh and DaiNgai. The accuracy of the numerical results was evaluated by using a coefficient of determination (R^2) and Nash-Sutcliffe coefficient (E_f) with R^2 and E_f being always higher than 0.84 (see table 2). Secondly, the calibration for advection-dispersion module was conducted by providing proper initial S and dispersion coefficient for the river reaches with observed data at DaiNgai, CauQuan, and TraVinh salinity stations which are approximately 30 km from the estuaries. The observed and simulated WL at CanTho (**see** figure 6) and S at DaiNgai (see figure 7) were matched well with R^2 being equal to 0.87 and 0.79, respectively.









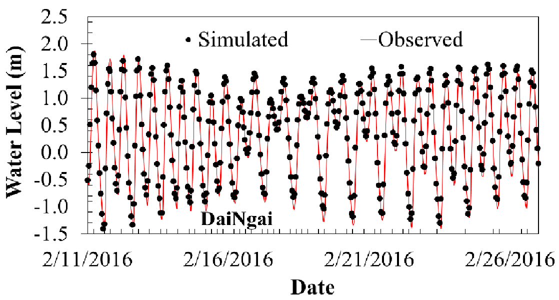


Fig 6. Simulated and observed water level at Chau Doc, Can Tho and Dai Ngai

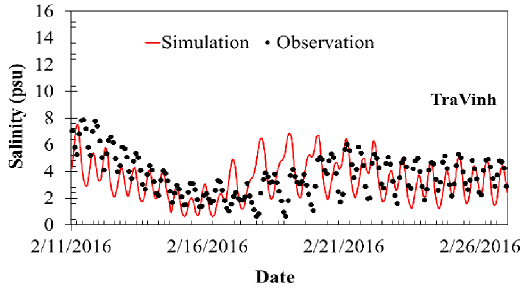


Fig 7. Simulated and observed salinity concentration at Dai Ngai, Cau Quan and Tra Vinh

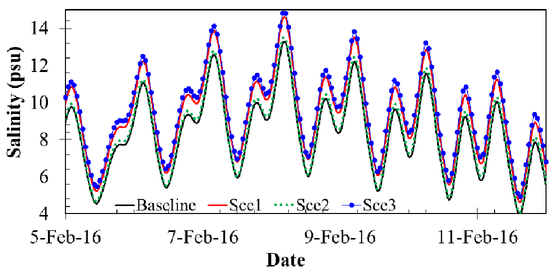


Fig 8. Hourly salinity concentrations at Cau Quan

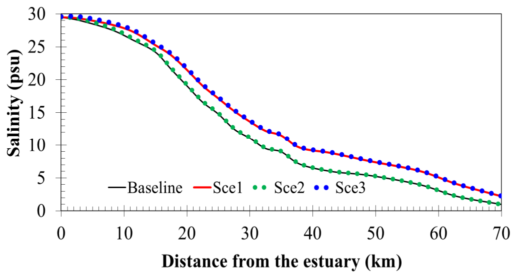


Fig 9. Intrusion length along the Hau River

Table 2. Model performance indicators at eight stations

Stations		Tan Chau	Chau Doc	My Thuan	Can Tho	My Tho	Dai Ngai	Cau Quan	TraVinh
Calibration 2016									
Water level	R^2	0.957	0.906	0.962	0.947	0.978	0.913		
	E_f	0.898	0.849	0.931	0.893	0.951	0.900		
Salinity	R^2						0.785	0.731	0.762
	E_f						0.753	0.702	0.748
Verification 2005									
Water level	R^2	0.985	0.891	0.949	0.89	0.947	0.970		
	E_f	0.946	0.840	0.970	0.926	0.962	0.960		
Salinity	R^2						0.830	0.657	0.795
	E_f						0.794	0.638	0.752

Table 3. Salinity concentrations and intrusion length of Mekong estuaries on 8th February 2016

No.	Scenario	Salinity concentration at about 30km from the estuaries.						Duration of 4 psu		Intrusion Length of 4 psu		
		DaiNgai Station		CauQuan Station		TraVinh Station		CauQuan	TraVinh	From TranDe estuary (km)	From Dinh An estuary (km)	From CoChien estuary (km)
		Salinity	(P%)	Salinity	(P%)	Salinity	(P%)	(days)	(days)			
1	Baseline on 8 Feb.	12.7		12.7		10.9		126	81	57	57	60
2	Sce 1	13.9	9.4	14.1	11.0	12.8	17.4	171	94	63	63	65
3	Sce 2	12.9	1.6	12.8	0.8	11.2	2.8	131	87	57.7	57.7	61
4	Sce 3	14.1	11.0	14.3	12.6	13.0	19.3	171	96	65	65	66

6. RESULTS AND DISCUSSION

Table 3 and **Figures.8-9** compare salinity concentrations in three simulated scenarios to the baseline in February. The percentage difference in the salinity concentration (S) between three scenarios and the baseline is defined as:

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

where: S_B: salinity concentrations of the baseline; S_i: salinity concentrations of scenario i^{th} ($i = 1, 2, 3$).

At stations 30 km from the estuaries, S and the L in the three scenarios increased by 0.8-19.3% and 0.7-8 km, respectively, compared to those in the baseline (Table 3 and Figure 8). The length of the 4 psu contour lines along four tributaries in the three scenarios ranged from 57 km to 66 km (**Fig.9**) while salinity control sluice gates were located from 50 km to 60 km along the main rivers from the estuaries of the Ham Luong, the Co Chien and the Hau Rivers toward upstream.

Moreover, the duration of saltwater intrusion in the three simulated scenarios increased substantially from the baseline (see table 3). Results showed that the reduced upstream flow had a great influence on saltwater intrusion in the VMD, which was the main driver of the severe events in 2016 and 2020.

Although the salinity peak between **Sce 1** and the baseline was small, of less than 2 psu, the duration difference was significant with a maximum increase by 1.35 months at Cau Quan (from 126 days in the observed data to 171 days in **Sce 1**).

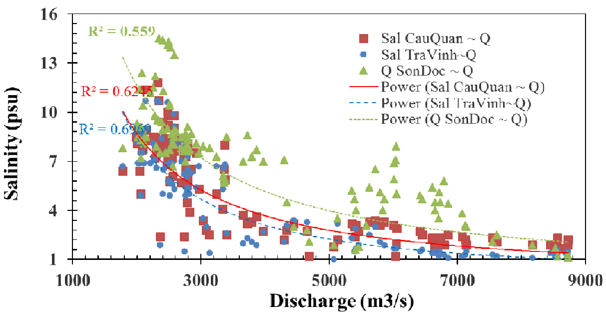


Fig 10. Relationship between average daily Q_{TC+CD} and average maximum daily S at 3 stations: CauQuan, TraVinh and SonDoc stations

Saltwater intrusion began earlier and remained longer than that in 2016, due to low WL from the beginning (mid-Nov.) to the end of the dry season (mid-May) (see figure 3**).** The results of **Sce 1** showed that the timing, magnitude, and duration of the released discharges from upstream dams greatly control the duration, S, and L of saltwater intrusion in the delta.

Fig.10 shows the relationship between the daily average discharge at TanChau and ChauDoc (Q_{TC_CD}) with the average maximum daily salinity at SonDoc, TraVinh, and CauQuan (20 to 30 km from the river mouths) in 1990-2016. S at the three stations was less than 4psu and 1psu when Q_{TC_CD} was higher than 3000 m^3/s and 9000 m^3/s respectively. This result can be used to predict S in short-time about 17-20 days because the duration of the flow moving from Chiang Saen to TanChau and ChauDoc is about 17-20 days (Mai, 2018 and MRC report 2016) in the dry season.

When the river bed level reduces by 0.88 m in the next 4 years from the baseline (**Sce 2**), S and L will increase 0.3 psu and 1km compared to the baseline. Eslami et at (2019) calculated that river bed of CoChien river dropped down by 2 m, leading to L and S increased 5km and 1.5 psu respectively. Thus, in a short period, the influence of river bed incision on saltwater intrusion is not significant and the increasing rate of L and S is different between each branch.

The worst case is the combination of the reduced upstream discharge and river bed incision (**Sce 3**) which was predicted to increase S by up to 19.3% and L by up to 8 km (see table 3).

The saltwater intrusion may be more serious when all 133 planned upstream dams are completed so some soft and hard measures should be implemented to mitigate the impact of saltwater intrusion in the future. For instance: changing of the seasonal calendar and land use pattern, raising awareness and building capacity of local people and increasing of storing fresh water during the rainy season. Furthermore, appropriate operations of sluice gates along estuaries through setting up early warning systems and supervisory control and data acquisition (SCADA) system are also promising alternatives.

7. CONCLUSION

The reduced upstream flow had a great influence on saltwater intrusion in the VMD, which was the main driver of the severe event in 2020 in the VMD. Saltwater intrusion in 2020 started 1.0 to over 2 months earlier and was 1.3-2 months more prolonged than that in 2016 and the long-term average respectively.

The flow at Kratie plays an important role in controlling saltwater intrusion in the VMD. Reducing the discharge at Kratie by 14.4% was predicted to increase S and the L by up to 17.4% and 10.5% respectively. Because the flow at ChaingSaen contributes 40% of the total dry season flow at Kratie, it can be stated that upstream dams may have a significant impact on saltwater intrusion in the VMD.

The influence of river bed incision on a saltwater intrusion is not significant in a short time. Therefore, river bed incision should be considered for a longer-term assessment to examine its impact on salinity mechanism.

Hence integrated water management through the cooperation on sharing water among countries in the MR plays an important role in the sustainable development of the MR basin. 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.

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REFERENCES

Allison, M.A., Weatherr, H.D., and Meselhe, E. A. (2017), *Bottom morphology in Song Hau distributary channel Mekong River Delta*, Vietnam, Continental Shelf Research, pp.1-11.

Binh, D.V., Kantoush, S., and Sumi, T. (2020), *Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams*, Geomorphology, pp. 1-14.

Bravard, J. P. and Marc Goichot et S. G. (2013) *Geography of Sand and Gravel mining in the lower MR,* EchoGeo 26, pp.1-20.

DHI and HDR report (2015), *Study on the impacts of mainstream hydropower on the Mekong river*, Ministry of Natural Resources and Environment, pp. 1-93, 2015.

Eslami,S., Piet, H., Nam, N.T., Sameh, A.K., Binh, D.V., Dung, D.D., Tho, T.Q. and Maarten, V.D.V (2019), *Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation*, Scientific report.

Kondolf, G.M., Rubin, Z.K., Minear, J.T. (2014), *Dams on the Mekong: cumulative sediment starvation*. Water Resour. Research, pp.5158–5169.

Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V.Q., and Dech, S.(2013), *Understanding the impact of hydropower development in the context of upstream-downstream relations in Mekong river basin*, Sustainability Science, Vol.8, pp.565-584.

Lauri, H., Moel, H., Ward, P.J., Rasanen, T.A., Keskinen, M. and Kummu, M. (2012), *Future changes in Mekong River hydrology: Impact of climate change and reservoir operation on discharge*, Hydrology and Earth system sciences, Vol. 16, pp. 4603–4619.

Mekong River Commission (2016), *Joint observation and evaluation of the emergency water supplement from China to the Mekong river,* MRC technical report, pp. 1-74.

Mai, N.T.P, Kantoush, S., Sumi, T., Thang,T.D., Trung, L.V. and Binh, D.V.*(2018), Assessing and adapting the impacts ò dám operation and sea level rising of saltwater intrusion into the Vietnamese Mekong Delta*, Journal of Japan Society of Civil Engineering, Ser. B1 (Hydraulic Eng.) Vol. 74, pp. 373-378.

Quang, N., N.(2016), *Water Diversion in Lower Mekong River and the impact on Vietnamese Mekong Delta*, PanNature centre.

Rasenen, T.A, Someth, P., Lauri, H., Koponen, J., Sarkkula, J., and Kummu, M, (2017), *Observed river discharge changes due to hydropower operations in the Upper Mekong Basin*, Journal of Hydrology 545, pp. 28-41.

Zoe Osborne (2020), *The great salt drought desiccating Vietnam's Mekong Delta*, Journal of environment, April.

Tóm tắt:

ẢNH HƯỞNG CỦA LƯU LƯỢNG THƯỢNG LƯU VÀ HÌNH THÁI SÔNG LÊN XÂM NHẬP MẶN Ở ĐỒNG BẰNG SÔNG CỬU LONG

Trong những năm gần đây, đặc biệt là năm 2016 và 2020, xâm nhập mặn trên diện rộng là nguyên nhân chính của thiếu nước ngọt cho sinh hoạt và nông nghiệp ở Đồng Bằng Sông Cửu Long. Do đó, sự hiểu biết đầy đủ và chính xác những yếu tố tác động đến xâm nhập mặn trên đồng bằng là thực sự rất quan trọng cho các nhà quản lý tài nguyên nước. Bài báo phân tích những ảnh hưởng do sự suy giảm lưu lượng thượng lưu từ vận hành của các hồ chứa thượng nguồn và sự hạ thấp đáy sông lên xâm nhập mặn ở ĐBSCL. Thông qua phân tích chuỗi số liệu mực nước và lưu lượng các trạm thượng nguồn từ năm 1980 đến 2020 và số liệu địa hình đáy sông năm 2009 và 2017. Sau đó sử dụng mô hình MIKE11- HD-AD để so sánh nồng độ mặn và chiều dài xâm nhập mặn giữa các kịch bản. Các kết quả thể hiện rằng nồng độ mặn bị ảnh hưởng bởi lưu lượng thượng nguồn nhiều hơn là địa hình đáy sông. Khi lưu lượng tại trạm Kratie giảm 14,4% nồng độ mặn lớn nhất (S) và chiều dài xâm nhập (L) tăng 17,4% và 10,5% tương ứng. Trong khi địa hình đáy sông bị hạ thấp 0.88m cho kịch bản 4 năm tới thì S và L tăng có 2.8% và 1.67% tương ứng.

Từ khóa: Xâm nhập mặn, đập thượng lưu, hạn hán, xói đáy sông, mô hình MIKE11.

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