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PERSPECTIVE

The worst 2020 saline water intrusion disaster of the past century in the Mekong Delta: Impacts, causes, and management implications

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Abstract Vietnam Mekong Delta (VMD), the country's most important food basket, is constantly threatened by drought-infused salinity intrusion (SI). The SI disaster of 2020 is recognized as the worst in recent decades, hence inspiring this perspective article. The authors' viewpoints on the disaster's impacts and causes are presented. The arguments presented are mainly drawn from (i) up-to-date publications that report on the recent SI intensification in the VMD and (ii) the power spectral analysis results using water level data. We verified the intensifying SI in the VMD both in its frequency and magnitude and remarked on four of the key SI drivers: (i) upstream hydropower dams, (ii) land subsidence, (iii) the relative sea-level rise, and (iv) riverbed sand mining. Also, a non-exhaustive yet list of recommendable management implications to mitigate the negative effects of the SI is contributed. The mitigation measures must be realized at multiple scales, ranging from pursuing transboundary water diplomacy efforts to managing internal pressures via developing early warnings, restricting illegal sand mining activities, alleviating pressures on groundwater resources, and diversifying agriculture.

Keywords Mekong delta · Riverbed incision · Salinity intrusion · Sea-level rise · Upstream dams

INTRODUCTION

Originating from the Chinese Tibetan-Qinghai Plateau, the Mekong River (MR) runs across six countries, feeding the four million-hectare Vietnamese Mekong Delta (VMD), which is often referred to as the country's most important food basket. Not only does VMD play the key role in safeguarding national food security, but it also contributes approximately 15% of the country's GDP in terms of agricultural product exports (Dung et al. 2019; Piesse 2019). Similar to many large rivers' deltas, the VMD has a long history of Anthropocene footprints (Nguyen et al. 2016; Arias et al. 2019; Minderhoud et al. 2020, among others), thus constantly being threatened by several pressures, e.g., land subsidence (LS) (Erban et al. 2014), floods, (Tri et al. 2013; Triet et al. 2017), droughts and salinity intrusion (SI) (Eslami et al. 2019), and riverbed mining (Brunier et al. 2014; Park et al. 2020). The intrusion of saline water is usually overlooked due to its relatively slower impacts compared to the other environmental pressures. However, approximately two million hectares of agricultural land of the VMD are prone to the SI risks annually, incurring millions USD in economic loss every year (Toan 2014; Smajgl et al. 2015).

The Mekong River splits into two main tributaries, namely the Mekong and Bassac Rivers near Phnom Penh, Cambodia. When entering the VMD, these two tributaries are locally known as the Tien and Hau rivers before discharging into the East Sea (also known as the South China Sea) via eight sub-branches (from North to South are Tieu, Dai, Ba Lai, Ham Luong, Co Chien, Cung Hau, Dinh An, and Tran De) as illustrated in Fig. 1a. Carew-Reid 2007 observed that, for a standard hydrological year, saline water can be detected up to 60 km upstream from the estuaries of the VMD along the Ham Luong branch, and is associated with the surface water measurement. Carew-Reid's report also remarks that the SI length in other branches (i.e., Co Chien, Cung Hau, and Dinh An) reaches up to 40 km from the river mouths. Such a relatively higher SI length in the Ham Luong branch than other branches is substantially in line with the results from our study, as shown in Fig. 1a. However, in 2016, reinforced by the severe drought, the saline water had penetrated up to 93 km

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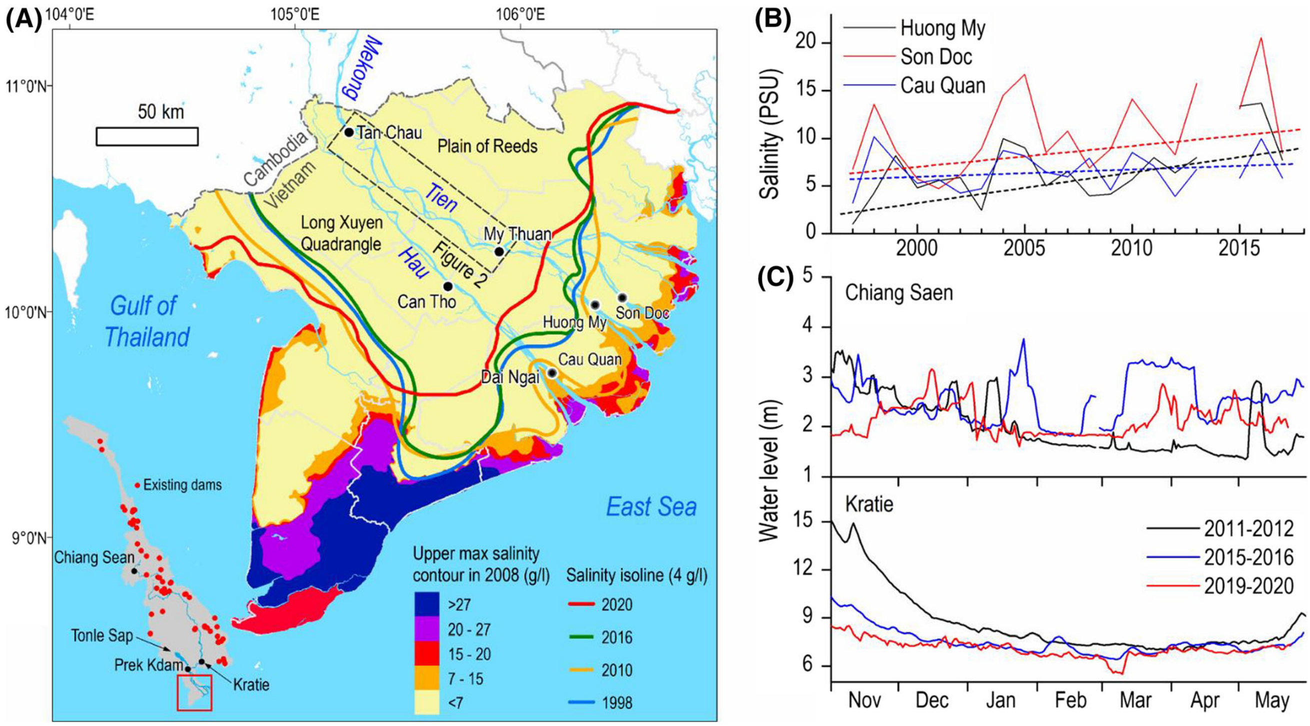

Fig. 1 **a** Areas affected by SI in different years. Salinity isolines of four drought years: 1998, 2010, 2016, and 2020 (data from the Southern Institute of Water Resources Research). Some part of the map has been reproduced from Fig. 1 in Loc et al. (2021a). **b** The increasing trend of SI (mean annual series calculated from 2-hourly series) between the same period detected from three stations: Cau Quan (Hau river), Son Doc, and Huong My (Tien river). The survey data were collected by Eslami et al. (2019). **c** The water levels of Chiang Saen and Kratie in Cambodia, upstream of the VMD (data were obtained from the Mekong River Commission (MRC))

in land, making it, by then, the worst-ever intrusion of seawater ever recorded (Kantoush et al. 2017; Toan 2017). Hydrological year, or water year is a term commonly used in hydrology to describe the surface water resources supply within a period of 12 months. In the VMD contexts, hydrological years are usually from April 1st for any given year through March 30th of the following year.

In the dry season of 2019–2020, the VMD witnessed a drought so severe, that substantially surpasses the one in 2016 in all hydrological accounts (Fig. 1a, b). The saline water intruded up to 110 km in land, approximately 10 km deeper than the historical average and in many locations surpassing the highest levels reported in 2015–2016 at the same time of the year. For instance, the SI was 71 km on the Ham Luong River in February 2019, exceeding the respective record in 2016 by 11 km. Typically the SI emerges from December and lasts until May of the following year, during the dry season. During the 2019–2020 disaster, the seawater was detected in the VMD from November 2019, which was 2.5—3.5 months earlier than the annual average (10–20 days earlier than 2015–2016) while lasting approximately 30 days longer. As of early February, it was reported that nearly 40,000 households suffered from the shortage of fresh water, mostly in the coastal provinces (United Nations 2020). Concerning agricultural production, the disaster has potentially damaged 30,000 hectares of paddy rice in Ca Mau, and about 20,000 hectares of fruit trees and 6500 hectares of vegetables in Ben Tre. These numbers are likely to increase when the associated official statistics become available in the coming months. SI is an annual phenomenon in the VMD because of the inter-intra-annual interactions between the fluvial upstream flows the tidal regimes (Pritchard 1952; Savenije 2012). However, SI has increasingly intensified (Loc et al. 2021a) caused by tidal amplification, riverbed incision, upstream dam operations, and land subsidence (Mai et al. 2018; Minderhoud et al. 2018; Eslami et al. 2019; Binh et al. 2021). Notably, SI is even more severe in drought years e.g., in droughts 2015–2016 and 2019–2020 than in standard hydrological years (without an extreme event) as some comparable values indicated above.

This paper seeks to report some viewpoints on a recent disastrous saline water intrusion disaster in the Mekong Delta in terms of impacts and causes. The discussions later expand to some recommendable management implications for the delta. The arguments presented in this paper are firstly fueled by some key findings recently published in the relevant topics, i.e., SI and drought of the VMD in the last decade. Given that this paper, in all regards, should not be considered as an exhaustive review of literature, it strived to identify, analyze and report some notable peer-reviewed published results based on the authors' knowledge within the scope of the topic matters. The literature-based discussions are further backed by our own analysis of gauged water level data of two major riverine systems of the VMD. More specifically, we hypothesized that a compound effect of riverbed incision and sea-level rise might have created considerable shifts in the tidal signals, such that the in-land tidal signals have grown stronger leading to the intensification of SI over the years. To clarify, we employed the Fast Fourier Transform (FFT) to the hourly water level series to reveal the spectral peaks at different temporal oscillations by changing the original time-domain series to frequency-domain data. In doing so, periodicities of each temporal domain (as inverse frequency) have been quantitatively estimated. Despite potentially opinionated to some extent, our synthesis of previously published findings combined with the primary analysis of gauged data could serve as a meaningful communication of not only the specific SI disaster in 2020 but also relevant implications on one of the most critical recurrent human-induced adverse phenomena of the VMD. The paper, as such, can essentially stimulate full-scale research and investigations in the future.

DATA AND METHODS

We structure this work as a *Perspective* article to quickly disseminate our preliminary findings to the scientific community. Our arguments are inferred from two sources of evidence: (i) up-to-date reports of relevant findings in the topic matters, i.e., recent intensification of SI in the VMD, and (ii) power spectral analysis water level data.

Brief review of the literature

In this paper, we strived to gather the results from some of the relevant scientific findings investigating the SI in the VMD, the majority of which are peer-reviewed journal articles or book chapters. We subsequently classify the collected literatures based on their conclusions of the roles of different environmental pressures on the ever-intensifying SI of the VMD: upstream dams, riverbed mining, land subsidence, and sea-level rise. This paper is not a review paper; hence our collection might have been non-exhaustive and potentially opinionated. We nevertheless remark that the quick communication of these information is critical for any recent natural disasters such as the historical drought reported herewith. We strongly believe that our work could have inspired more investigations and discussions so that deeper insights can be created by the scientific community.

Power spectral analysis of the water level data

We performed a rapid investigation of the water level time series data for two representative riverine stations of the VMD to contribute a novel perspective into understanding how SI has intensified over the years. In this paper, we employed the Fast Fourier Transform (FFT) to the hourly water level series to reveal the spectral peaks at different temporal oscillations by changing the original time-domain series to frequency-domain data (Welch 1967; Torrence and Compo 1998). FFT is a widely used technique to assess time series hydrological variables containing non-stationarities that decompose different frequencies and provide a time-scale localization of a signal (e.g., Lima et al. 2003; Restrepo et al. 2016; Loc et al. 2021a). Since the hourly water level series at river stations close to the coast contains multiple frequencies from the river (e.g., basin-scale hydrological seasonality), sea (e.g., tidal effect) and regional climate (e.g., ENSO), FFT is used to estimate the periodicities of each domain (as inverse frequency), intra-annual and inter-annual variability patterns in terms of power spectral density (in dB as square of FFT magnitude). The chosen stations are My Thuan and Dai Ngai representing the in-land and coastal conditions, respectively. FFT is applied to two different time periods (before and after 2000) to investigate how the power spectral density of each cyclic effect has changed recently.

RESULTS

Under pristine conditions, salinity is the outcome of the tug of war between upstream fluvial discharges and downstream tidal mixing forces (Pritchard 1952; Savenije 2012). In the VMD, salinity is determined by the water level dynamics between river and sea. Relative lowering of the riverbed (and thus the water level) is caused mainly by the upstream dams, riverbed mining and land subsidence, while increased sea level in the coastal area has been amplifying tidal signals in the VMD over the past two decades. Among them, the first one has been considered the most important (Eslami et al. 2019). In tracing the root causes of the 2019–2020 disaster, this section sought to re-evaluate the relative importance of these drivers.

The hydropower dams

Between 1993 and 2008 when the total storage capacity of the hydropower dams in the upper MRB was still "small", Darby et al. (2016) observed that the flow regimes were mainly driven by climatic conditions, mainly a shift in tropical cyclones. In the following period, with six major dams on the main channel and more than 50 on the tributaries, discharges in the dry season had increased significantly (Binh et al. 2020b). It should be noted that the total capacity of these dam reservoirs has reached over 80 km^3, equivalent to 97% of the annual discharge at Chiang Saen. Therefore, even though the dry season precipitation decreased, the monthly discharges still increased by 39% (Chiang Saen), 62% (Kratie), 38% (Tan Chau), and 67% (Chau Doc), verifying the significant roles of the upstream dams in reshaping the hydrology of Lower Mekong Region. Thus, the upstream dams were considered to contribute to mitigating the SI during the dry periods, yet Binh et al. (2021) showed otherwise. Evidently in 2016 and 2020, even though the lower MRB discharges were still substantially higher than the long-term averages, the VMD still suffered from the two most severe droughts in history. This "hydrological paradox" is caused because although the higher discharge due to the dams, several key stations along with the Lower Mekong Region (e.g., Chiang Saen, Kratie and Prek Kdam) reported the record-low water levels in January 2020 (Fig. 1c), mainly due to the riverbed incision.

Riverbed incisions

As mentioned above, the increased discharges during the dry spells caused by the dams were expected to mitigate saline water intrusion in the VMD. However, these mega structures also have an opposite effect – sediment trapping that implicitly contributes to the riverbed incision, hence promoting the intrusion of saline water in the long term. Kummu and Varis, (2007) remarked that the major dams on the mainstream MR could have trapped up to 94% of the total volume generated in the upper MRB. As a result, the sediment loads at Chiang Saen, Nong Khai, and the VMD have, respectively, decreased by 90%, 81%, and 74% comparing the two periods: 2012–2015 and 1980–1992, during which the Jiuzhou hydropower dams in the upper MRB were constructed. Similarly, Binh et al. (2020a) found that 40% out of 74% of the sediment load reduction in the VMD is directly caused by these dams in the upper MRB. It is therefore commonly understood that the construction of these dams has effectively prevented the sediments from being deposited on the VMD. This has caused the gradual drops of the depositional rates on the riverbeds over time. The correlation between the reduction of sediment loads in the upstream and riverbed incision in the downstream, however, remains unquantified. Besides receiving substantially fewer sediment loads, the VMD rivers are aggressively dredged by the local mining activities, leading to accelerated bed incisions (Fig. 2). In fact, the excavation rates of the riverbed sands have increased from 7.75 Mm^3/year in 2012 (Bravard et al. 2013) to 29.3 Mm^3/year in 2018 (Jordan et al. 2018). Comparing the sand mining volume in the entire VMD with the riverbed incision volume in the Tien River (from Tan Chau to My Thuan) and the Vam Nao channel, it is speculated that the contribution of sand mining to riverbed incision has risen from approximately 15% in 2012 (Binh et al. 2020a) to 56% in 2018 in the VMD. This signifies the relative importance of the local mining compared to the upstream dams on the riverbed incisions, that may have substantially facilitated intrusion of saline water.

Relative sea-level rise

In this paper, relative SLR refers to the net impact resulting from interactions between the absolute changes of the ocean levels and delta-wide LS. While the former is a climate change-induced global phenomenon, the latter is the direct consequence of excessive groundwater extraction and natural soil compaction (Minderhoud et al. 2017). According to IPCC Fourth Assessment report, a 0.3 m SLR by 2050 is predicted along the coast of southern Vietnam, affecting nearly 1.8 million ha of the VMD, of which approximately 1.3 million ha is affected by saline water above 5 g/L (Carew-Reid 2007; Smajgl et al. 2015). As for the LS, Erban et al. (2014) remarked on the widespread declines of groundwater levels and concluded that the VMD has been sinking with an average rate of 1 to 4 cm every year. They also predicted that by 2020, the delta should have sunk by 0.88 m if the groundwater pumping rates remain unchanged. Likewise, Minderhoud et al. (2017)'s results revealed that since the 1990s, the VMD had sunk 18 cm in total, which translates to an average rate of 1.1 cm annually. They predicted that the relative SLR that the VMD will likely experience is approximately 1 m (0.42–1.54 m) in 30 years. The Mekong delta is now merely above sea level (mean elevation of $\sim$ 0.8 m). With estimated sinking rates faster than our expectation, the VMD is becoming more vulnerable to saline water intrusion.

Amplified tidal signals

Eslami et al. (2019) noted that annually, while offshore tidal amplitude increases by 1.2–2 mm due to sea-level rise (SLR), the respective change within the delta is around 20 mm, thus increasing the salinity in the channels by 0.2–0.5 PSU. Our result shows similar results, in which the 12-h frequency semi-diurnal amplitude (i.e., tidal effect from the sea) at My Thuan had increased by 66% (− 9.6 to − 3.3 dB), substantially higher than the 20% increase (− 7.46 to − 6 dB) at Dai Ngai (Fig. 3). Even though tidal

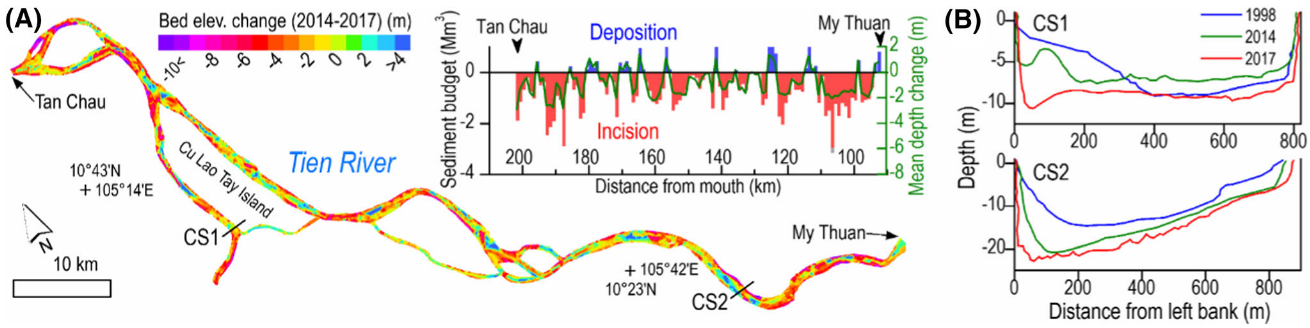

Fig. 2 **a** Bed elevation change (along the reach in between Tan Chau and My Thuan) between 2014 and 2017 from bathymetry surveys using single beam echosound showing the bed lowering (incision). Sediment budget of the surveyed reach and longitudinal mean depth changes calculated from the bathymetric data are also shown. **b** River cross-section (CS) survey results over three years (1998, 2014 and 2017) showing dramatic incision of the riverbed in Tien River. The bathymetry (adapted from Binh et al. (2020a)) and cross-section data shown here are the authors' field survey results

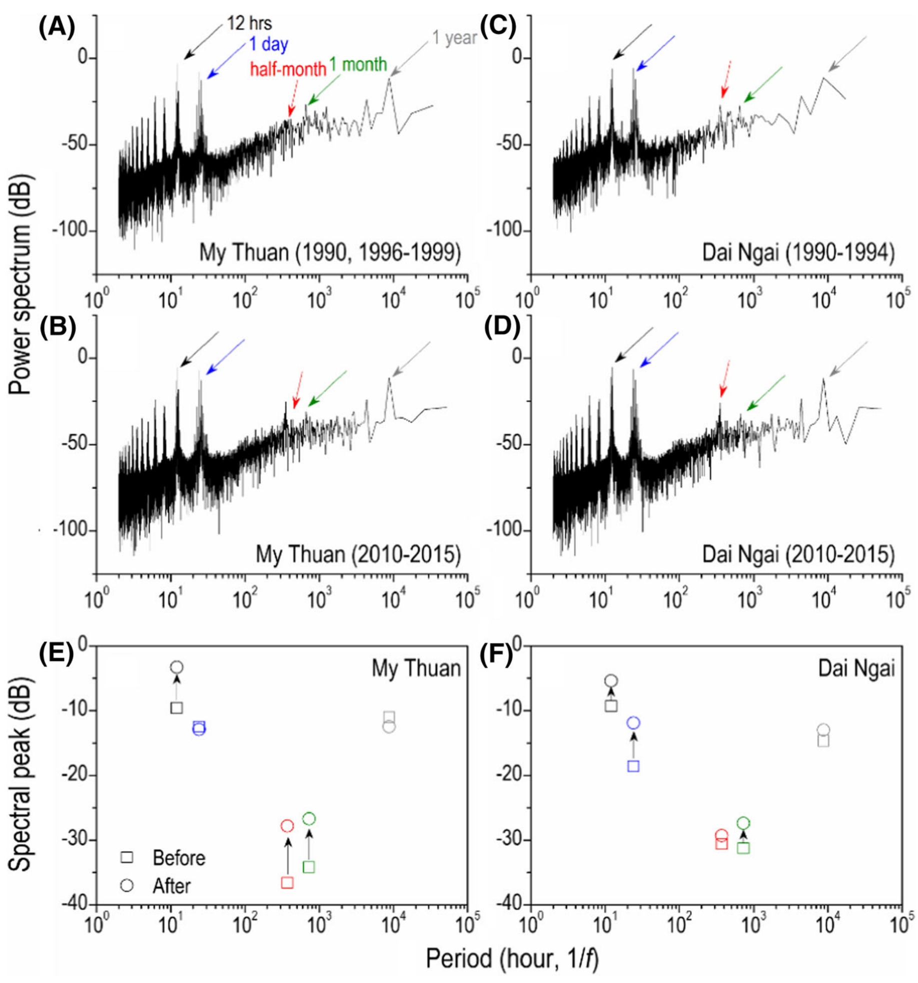

Fig. 3 Tidal Power spectrum analysis for the two representative stations along Tien and Hau Rivers close to the coastal areas of the Mekong: My Thuan and Dai Ngai. **a** and **c** power spectrum of the pre-2000 period. **b** and **d** power spectrum of the post-2000 period. **e**, **f** The summarized shifts of different temporal cycles (periodicity). Some part of the graph has been adapted from Loc et al. (2021a)

signals' land-ward amplification is a known geomorphological and hydrological phenomenon as tide transmits through the narrower upstream channels, the imbalanced shifts of tidal amplification between the two analyzes stations could have been further exacerbated by the riverbed incision and the relative sea-level rise. In essence, the tidal effect in the water level recorded at My Thuan has more significant increase from 1990 to 2010 than Dai Ngai, which could have been related to the larger drop in water levels since the 1990s (Eslami et al. 2019; Binh et al. 2020a), leading to a stronger backwater effect, intensified tidal amplitude, and thus extended saline water intrusion in VMD.

RECOMMENDABLE MANAGEMENT OUTLOOKS

The historical record indicates that the interval between the drought events has decreased by at least two years (the recent drought years reported 1992, 1998, 2005, 2010, 2016, and 2020). At present, the VMD is expected to experience at least one drought event every four years with intensifying severity; the difference in magnitude between the drought of 2020 and 2016 serves as a grave example. It is therefore remarkable that the drought-reinforced SI has become a recurrent natural disaster in the VMD (Binh et al. 2021; Loc et al. 2021a). As a response, we shared the view of notable scholars, including Apel et al. 2020 or Smajgl et al. (2015) in that reliable forecast models of SI are of critical necessity to mitigate the saline water's negative effects on agricultural production and people's livelihoods. The dissemination of forecasts and early warnings as such can contribute practical guidelines for timely adaptation and mitigation planning (Smajgl et al. 2015; Apel et al. 2020). Although a simple statistical seasonal forecast model to forecast a short to medium term of SI has been reported with positive implications (Apel et al. 2020), we expect that more advanced techniques, such as machine learning can support in producing longer-term forecasting of not only SI but also multiple environmental pressures, especially with respect to timing and severity to facilitate better mitigation measures (Le et al. 2019; Loc et al. 2020a, b).

Within the scope of this paper, four key drivers of the ever-intensifying intrusion of saline water within the VMD are reported, including (i) upstream hydropower dams, (ii) land subsidence, (iii) the relative sea-level rise, and (iv) riverbed sand mining. However, it should be noted that our list is far from exhaustion. For instance, there are multiple global-scale factors such as Climate change, climatic extremes, and ENSO events that play a significant role towards in intensifying various disasters across the VMD, including SI and droughts, however, are not discussed within the scope of this perspective paper. The El Niño, for example, even though does not contribute directly to SI; an extreme El Niño event could significantly reduce the rainfall volume and trigger the drought, and ultimately stimulating salinity intrusion. (CGIAR 2016). Therefore, it would be meaningful for future research to investigate how these global-scale factors could have contributed to the existing problems of drought and SI of the VMD. In the following sections, we briefly discuss some recommendable management implications to cope with the situation.

Transboundary water diplomacy

The first and arguably most challenging barrier that the VMD faces is how to practically negotiate the shared water resources with the competing upstream users, those who benefit directly/indirectly from the hydropower dams. Theoretically, this can be done via multinational diplomatic platforms, namely, the Mekong River Commission (MRC), the Greater Mekong Subregion Program, and Association of Southeast Asian Nations (ASEAN). However, in reality, this has not been as productive as intended due to discrepancies between the member countries in terms of political and economic interests (Kansal et al. 2019). Plus, not all geographically related countries are keen on multilateral dialogs. Instead, they opt for bilateral diplomacies, making the unanimity in sharing the resources within the MRB even harder to achieve (Kuenzer et al. 2012). Nevertheless, it is strongly recommended that the impacts of the upstream dams should be constantly discussed at regional and international forums so that the negative impacts of these structures on the MRB environment, including the intensified salinity can be effectively communicated. In doing so, the VMD stakeholders can generate support from the international community, essential for the transboundary water diplomacy plan.

Halting the delta from sinking

The VMD is sinking (and shrinking) at a faster rate than we have ever expected. First, the exploitation of groundwater has evidently contributed to the delta-wide subsidence (Minderhoud et al. 2017, 2018) while concurrently making the aquifers more vulnerable to acidity (Ha et al. 2018), arsenic contamination (Stuckey et al. 2016), or SI itself (Tran et al. 2020). It is therefore urgent to identify alternative water resources, such as improving the rural water supply network (Wilbers et al. 2014) or promoting infrastructure development such as rainwater harvesting (Özdemir et al. 2011). Second, it is expected that the VMD riverbed incision rate is likely to increase due to the accelerating excavation activities to meet the growing demands for construction sands from both domestic and international markets. Consequently, bank erosions (Jordan et al. 2019; Binh et al. 2020c; Hackney et al. 2020), alterations of flood regimes (Tu et al. 2019; Binh et al. 2020b; Park et al. 2020) and intensification of SI (Eslami et al. 2019) have become increasingly prevalent. These have called for bold, nation-wide actions to decisively control the exports of the riverbed sediments while raising the disciplinary actions against illegal mining to effectively halt the sinking rate of the delta and safeguard the livelihood of millions of inhabitants. For instance, Loc et al. (2020a) remarked that sand mining is a major driver yet predominantly underestimated. This is because the mining volume is commonly underestimated due to illegal mining and under-reported values from the operators to dodge the tariffs (Bravard et al. 2013; Binh et al. 2020a, c). With the growing demand for sand that stems from construction, land reclamation and exports in the Mekong (Jordan et al. 2019; NG et al. 2021), we speculate that the VMD will continue to bleed sand in the future. Realizing the adverse effects of sand mining on the sustainability of the VMD, the government of Vietnam has increasingly implemented regulation actions to control sand mining, especially from illegal sand miners (Binh et al. 2020d; Bravard et al. 2013). The regulations actions have become more intensive since 2011 (Binh et al. 2020a).

Promoting sustainable agricultural practices

The VMD agriculture mainly based on rice could essentially benefit from strategic reforms towards the diversification of crops and animal livestock to reduce risks of monoculture, thus enhancing overall resiliency. More specifically, novel ecosystem-based agricultural models have been increasingly adopted by local farmers, especially in those coastal areas with limited freshwater resources. Among these, the prawn rice rotational cropping system constitutes a perfect example, turning the SI affected rice fields that were once considered of little usefulness into the favorable habitats for artisanal shrimp farming during the dry months (Loc et al. 2017, 2018a, 2020b; Nguyen et al., 2019; Pham et al. 2020; Van Tan et al. 2020). However, the questionable adaptability of the farmers (financially and technically), the potential water conflicts between different agricultural models, or the environmental pollution emerging from intensive farming and processing of aquaculture products should be carefully considered while transforming the agricultural models (Loc et al., 2017, 2018a, 2020b; Nguyen et al., 2019). Nevertheless, the adoption of ecosystem-based approaches would generate more sustainable outcomes, both in terms of tangible and intangible benefits (Loc et al. 2018b, 2020b; Yee et al. 2021).

SUMMARY AND CONCLUSION

The VMD is constantly being threatened by drought-infused SI (SI), in which both its intensity and frequency are increasing. The 2020 saline water intrusion is recognized as the worst in recent decades. In this paper, we first synthesized SI-related findings from the literature integrated with our extensive field survey data of water level and multi-temporal channel bathymetry and identified the four key drivers of SI in the VMD as upstream hydropower dams, riverbed mining, land subsidence, and climate change-driven sea-level rise. Our analysis of the power spectrum of hourly water level series at the two major stations close to the coast (My Thuan and Dai Ngai) revealed the recent amplification of tidal signals in the VMD. We evaluated the relative importance of the different drivers in the intensifying SI and preliminarily concluded that riverbed incision might contribute more directly and rapidly to the SI than others. Finally, we highlight possible management strategies to cope with the intensifying SI at the transboundary and national scales, including developing early warnings, restricting illegal sand mining activities, alleviating pressures on groundwater resources, and diversifying agriculture.

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REFERENCES

Apel, H., M. Khiem, N.H. Quan, and T.Q. Toan. 2020. Brief communication: Seasonal prediction of salinity intrusion in the Mekong Delta. *Natural Hazards and Earth System Sciences* 20: 1609–1616.

Arias, M.E., G.W. Holtgrieve, P.B. Ngor, T.D. Dang, and T. Piman. 2019. Maintaining perspective of ongoing environmental change in the Mekong floodplains. *Current Opinion in Environmental Sustainability* 37: 1–7.

Binh, D.V., S. Kantoush, and T. Sumi. 2020. Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. *Geomorphology* 353: 107011.

Binh, D.V., S.A. Kantoush, M. Saber, N.P. Mai, S. Maskey, D.T. Phong, and T. Sumi. 2020. Long-term alterations of flow regimes of the Mekong River and adaptation strategies for the Vietnamese Mekong Delta. *Journal of Hydrology Regional Studies* 32: 100742.

Binh, D.V., B. Wietlisbach, S. Kantoush, H.H. Loc, E. Park, G.D. Cesare, D.H. Cuong, N.X. Tung et al. 2020. A novel method for riverbank detection from Landsat satellite data: A case study in the Vietnamese Mekong Delta. *Remote Sensing* 12: 3298.

Binh, D.V., S. Kantoush, T. Sumi, N. P. Mai, and L. V. Trung. 2020d. Riverbed incision in the Vietnamese Mekong Delta due to altered flow regime and sediment load. *Proceedings of the 22nd IAHR-APD Congress 2020*, Sapporo, Japan.

Binh, D.V., S.A. Kantoush, T. Sumi, N.P. Mai, N.A. Trieu, T.V. La, and A.D. Tran. 2021. Effects of riverbed incision on the hydrology of the Vietnamese Mekong Delta. *Hydrological Processes*. https://doi.org/10.1002/hyp.14030.

Bravard, J.-P., M. Goichot, and S. Gaillot. 2013. Geography of sand and gravel mining in the Lower Mekong River: First survey and impact assessment. *EchoGéo* 26: 1–8.

Brunier, G., E.J. Anthony, M. Goichot, M. Provansal, and P. Dussouillez. 2014. Recent morphological changes in the Mekong and Bassac river channels, Mekong delta: The marked impact of river-bed mining and implications for delta destabilisation. *Geomorphology* 224: 177–191.

Carew-Reid, J. 2007. *Rapid assessment of the extent and impact of sea-level rise in Viet Nam*, 82. Brisbane: International Centre for Environment Management (ICEM).

CGIAR Research Program on Climate Change, Agriculture and Food Security—Southeast Asia (CCAFS SEA). 2016. Assessment Report: The drought and salinity intrusion in the Mekong River Delta of Vietnam. Hanoi, Vietnam: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Darby, S.E., C.R. Hackney, J. Leyland, M. Kummu, H. Lauri, D.R. Parsons, J.L. Best, A.P. Nicholas, et al. 2016. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. *Nature* 539: 276–279.

Dung, T.D., G. van Halsema, P.J. Hellegers, L.P. Hoang, and F. Ludwig. 2019. Long-term sustainability of the Vietnamese Mekong Delta in question: An economic assessment of water management alternatives. *Agricultural Water Management* 223: 105703.

Erban, L.E., S.M. Gorelick, and H.A. Zebker. 2014. Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta. *Vietnam. Environmental Research Letters* 9: 084010.

Eslami, S., P. Hoekstra, N.N. Trung, S.A. Kantoush, D.V. Binh, D.D. Dung, T.T. Quang, and M.V.D. Vegt. 2019. Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Scientific Reports* 9: 18746.

GS0 - Governmental Statistics Office. 2016. National Socioeconomic Development Report, 2016, accessed in 2020, Hanoi, https://www.gso.gov.vn/default.aspx?tabid=621ItemID=16067

Ha, T.P., C. Dieperink, V.P. Dang Tri, H.S. Otter, and P. Hoekstra. 2018. Governance conditions for adaptive freshwater management in the Vietnamese Mekong Delta. *Journal of Hydrology* 557: 116–127.

Hackney, C.R., S.E. Darby, D.R. Parsons, J. Leyland, J.L. Best, R. Aalto, A.P. Nicholas, and R.C. Houseago. 2020. Riverbank instability from unsustainable sand mining in the Lower Mekong River. *Nature Sustainability* 3: 217–225.

IPCC Climate Change. 2007. In: Solomon, S. et al. editor, The Physical Science Basis. Cambridge: Cambridge University Press.

Jordan, C., J. Tiede, O. Lojek, J. Visscher, H. Apel, H.Q. Nguyen, C.N.X. Quang, and T. Schlurmann. 2019. Sand mining in the Mekong Delta revisited-current scales of local sediment deficits. *Scientific Reports* 9: 1–14.

Kantoush, S., D.V. Binh, T. Sumi, and L.V. Trung. 2017. Impact of upstream hydropower dams and climate change on hydrodynamics of Vietnamese Mekong Delta. *Journal of Japan Society of Civil Engineers Series B1 (Hydraulic Engineering)* 73: 109–114.

Kuenzer, C., I. Campbell, M. Roch, P. Leinenkugel, V.Q. Tuan, and S. Dech. 2012. Understanding the impact of hydropower developments in the context of upstream-downstream relations in the Mekong river basin. *Sustainability Science* 8: 565–584.

Kummu, M., and O. Varis. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology* 85: 275–293.

Le, V.T., N.H. Quan, H.H. Loc, N.T. Thanh Duyen, T.D. Dung, H.D. Nguyen, and Q.H. Do. 2019. A multidisciplinary approach for evaluating spatial and temporal variations in water quality. *Water* 11: 853.

Lima, I.B.T., R.R. Rosa, F.M. Ramos, and E.M.L. de Moraes Novo. 2003. Water level dynamics in the Amazon floodplain. *Advances in Water Resources* 26: 725–732.

Loc, H.H., N.T.H. Diep, N.T. Can, K.N. Irvine, and Y. Shimizu. 2017. Integrated evaluation of ecosystem services in prawn-rice rotational crops, Vietnam. *Ecosystem Services* 26: 377–387.

Loc, H.H., K.N. Irvine, N.T.H. Diep, N.T.K. Quyen, N.N. Tue, and Y. Shimizu. 2018. The legal aspects of Ecosystem Services in agricultural land pricing, some implications from a case study in Vietnam's Mekong Delta. *Ecosystem Services* 29: 360–369.

Loc, H.H., T.J. Ballatore, K.N. Irvine, T.H.D. Nguyen, T.C.T. Truong, and S. Yoshihisa. 2018. Socio-geographic indicators to evaluate landscape Cultural Ecosystem Services: A case of Mekong Delta. *Vietnam. Ecosystem Services* 31: 527–542.

Loc, H.H., E. Park, D. Chitwatkulsiri, J. Lim, S.H. Yun, and L. Maneechot. 2020. Local rainfall or river overflow? Re-evaluating the cause of the Great 2011 Thailand flood. *Journal of Hydrology* 589: 125368.

Loc, H.H., Q.H. Do, A.A. Cokro, and K.N. Irvine. 2020. Deep neural network analyses of water quality time series associated with water sensitive urban design (WSUD) features. *Journal of Applied Water Engineering and Research* 8: 313–332.

Loc, H.H., K.N. Irvine, A. Suwanarit, P. Vallikul, F. Likitswat, A. Sahavacharin, and C. Sovann. 2020. Mainstreaming ecosystem services as public policy in South East Asia, from theory to practice. In *Sustainability and Law*, ed. V. Mauerhofer, D. Rupo, and L. Tarquinio, 631–665. Cham: Springer.

Loc, H.H., D.V. Binh, E. Park, S. Shrestha, T.D. Dung, V.H. Son, N.H.T. Truc, N.P. Mai, et al. 2021. Intensifying saline water intrusion and drought in the Mekong Delta: From physical evidence to policy outlooks. *Science of the Total Environment* 757: 143919.

Loc, H.H., E. Park, T.N. Thu, N.T.H. Diep, and N.T. Can. 2021. An enhanced analytical framework of participatory GIS for ecosystem services assessment applied to a Ramsar wetland site in the Vietnam Mekong Delta. *Ecosystem Services* 48: 101245.

Mai, N.P., S. Kantoush, T. Sumi, T.D. Thang, L.V. Trung, and D.V. Binh. 2018. Assessing and adapting the impacts of dams operation and sea level rising on saltwater intrusion into the Vietnamese Mekong Delta. *Journal of Japan Society of Civil Engineers, Series B, (Hydraulic Engineering)* 74: 373–378.

Minderhoud, P.S.J., G. Erkens, V.H. Pham, V.T. Bui, L. Erban, H. Kooi, and E. Stouthamer. 2017. Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta. *Vietnam. Environmental Research Letters* 12: 064006.

Minderhoud, P.S.J., L. Coumou, L.E. Erban, H. Middelkoop, E. Stouthamer, and E.A. Addink. 2018. The relation between land use and subsidence in the Vietnamese Mekong delta. *Science of the Total Environment* 634: 715–726.

Minderhoud, P.S.J., L. Coumou, G. Erkens, H. Middelkoop, and E. Stouthamer. 2020. Mekong delta much lower than previously assumed in sea-level rise impact assessments. *Nature Communications* 10: 1–13.

Ng, W.X., and E. Park. 2021. Shrinking Tonlé Sap and the recent intensification of sand mining in the Cambodian Mekong River. *Science of The Total Environment* 777: 146180.

Nguyen, H.H., P. Dargusch, and P. Moss. 2016. A review of the drivers of 200 years of wetland degradation in the Mekong Delta of Vietnam. *Regional Environmental Change* 16: 2303–2315.

Nguyen, H.Q., D. Korbee, H.L. Ho, J. Weger, P. Thi Thanh Hoa, N. Thi Thanh Duyen, P. Dang Manh Hong Luan, T.T. Luu, et al. 2019. Farmer adoptability for livelihood transformations in the Mekong Delta: A case in Ben Tre province. *Journal of Environmental Planning and Management*, *62*, 1603–1618.

Özdemir, S., M. Elliott, J. Brown, P.K. Nam, V. Thi Hien, and M.D. Sobsey. 2011. Rainwater harvesting practices and attitudes in the

Mekong Delta of Vietnam. *Journal of Water, Sanitation and Hygiene for Development* 1: 171–177.

Park, E., H.H. Loc, T.D. Dung, X. Yang, E. Alcantara, E. Merino, and V.H. Son. 2020. Dramatic decrease of flood frequency in the Mekong Delta due to river-bed mining and dyke construction. *Science of The Total Environment* 123: 138066.

Pham, T.A.N., H.H. Loc, D.D. Tran, and N.H. Quan. 2020. The inefficiency of Vietnamese prawn-rice rotational crops: A slacks-based data envelopment analysis. *Journal of Agribusiness in Developing and Emerging Economies* 11: 60–71.

Piesse, M. (2019). The Mekong Delta: Land Subsidence Threatens Vietnam's "Food Basket". In, Strategic Analysis Paper. Australia.: Future Directions International

Pritchard, D.W. 1952. Salinity distribution and circulation in the Chesapeake Bay estuarine system. 1. *Journal of Marine Research* 11: 106–123.

Restrepo, J.D., E. Park, S. Aquino, and E.M. Latrubesse. 2016. Coral reefs chronically exposed to river sediment plumes in the southwestern Caribbean: Rosario Islands, Colombia. *Science of the Total Environment* 553: 316–329.

Savenije, H.H.G. 2012. *Salinity and tides in alluvial estuaries*, 163. Delft, The Netherland: Delft University of Technology.

Smajgl, A., T.Q. Toan, D.K. Nhan, J. Ward, N.H. Trung, L.Q. Tri, V.P.D. Tri, and P.T. Vu. 2015. Responding to rising sea levels in the Mekong Delta. *Nature Climate Change* 5: 167–174.

Toan, T.Q. 2014. Climate change and sea-level rise in the Mekong Delta: flood, tidal inundation, salinity intrusion, and irrigation adaptation methods. In *Coastal disaster and climate change in Vietnam*, ed. N.D. Thao, H. Takagi, and M. Esteban, 199–218. Oxford: Elsevier.

Toan, T.Q. 2017. The historical drought in 2016 and its implications to the Vietnam Mekong Delta. Proceedings of the Annual Conference of Science. Vietnam Academy of Water Research. Ministry of Agricultural and Rural Development, Hanoi, Vietnam. (in Vietnamese)

Torrence, C., and G.P. Compo. 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society* 79: 61–78.

Tran, D.A., M. Tsujimura, D. Kambuku, and T.D. Dang. 2020. Hydrogeochemical characteristics of a multi-layered coastal aquifer system in the Mekong Delta, Vietnam. *Environmental Geochemistry and Health* 42: 661–680.

Tri, V.P.D., N.H. Trung, and V.Q. Thanh. 2013. Vulnerability to flood in the Vietnamese Mekong Delta: mapping and uncertainty assessment. *Journal of Environmental Science and Engineering* 2: 229–237.

Triet, N.V.K., V.D. Nguyen, H. Fujii, M. Kummu, B. Merz, and H. Apel. 2017. Has dyke development in the Vietnamese Mekong Delta shifted flood hazard downstream? *Hydrology and Earth System Sciences* 21: 3991.

Tu, L.X., V.Q. Thanh, J. Reyns, S.P. Van, D.T. Anh, T.D. Dang, and D. Roelvink. 2019. Sediment transport and morphodynamical modeling on the estuaries and coastal zone of the Vietnamese Mekong Delta. *Continental Shelf Research* 186: 64–76.

United Nation. 2020. Vietnam drought and saltwater intrusion in the Mekong Delta. Joint Assessment Report date: 15-17 January 2020.

Van Tan, L., T. Tran, and H.H. Loc. 2020. Soil and water quality indicators of diversified farming systems in a Saline Region of the Mekong Delta, Vietnam. *Agriculture* 10: 1–16.

Welch, P. 1967. The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified period grams. *IEEE Transactions on Audio and Electro Acoustics* 15: 70–73.

Wilbers, G.J., Z. Sebesvari, and F.G. Renaud. 2014. Piped-water supplies in rural areas of the Mekong Delta, Vietnam: water quality and household perceptions. *Water* 6: 2175–2194.

Yee, J.Y., H.H. Loc, Y.L. Poh, T. Vo-Thanh, and E. Park. 2021. Socio-geographical evaluation of ecosystem services in an ecotourism destination: PGIS application in Tram Chim National Park, Vietnam. *Journal of Environmental Management* 291: 112656.

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