A REVIEW OF POTENTIAL IMPACT OF TOTAL SUSPENDED SOLIDS ON SURFACE WATER QUALITY AND WATER USES IN THE VIETNAMESE MEKONG DELTA

Ha Thao Nguyen[1, 2], Nguyen Thanh Giao[1, *]

[1] *College of Environment and Natural Resources, Can Tho University*

[2] *Master student in Enivronment and Natural Resources Management, College of Environment and Natural Resources, Can Tho University*

[*] *Email: ntgiao@ctu.edu.vn*

ABSTRACT

The Vietnamese Mekong Delta (VMD) is an internationally significant region for agricultural production and biodiversity, yet it faces escalating challenges to its water resources. Total Suspended Solids (TSS) represent a critical water quality parameter within this complex deltaic system, with profound implications for its ecological integrity and socio-economic activities. TSS in the VMD originate from a combination of natural processes, such as riverbank erosion and sediment resuspension and increasingly dominant anthropogenic activities, including intensive agriculture, aquaculture, urban and industrial wastewater discharge, upstream hydropower dam development leading to sediment trapping and localized sand mining. Elevated TSS concentrations and alterations in sediment composition directly degrade water quality by increasing turbidity, reducing light penetration essential for aquatic photosynthesis and acting as a transport mechanism for nutrients and various contaminants, including heavy metals and pesticides. These TSS-induced changes in water quality have substantial adverse consequences for key water uses. Agricultural productivity is affected through impacts on irrigation infrastructure and alterations to soil fertility due to reduced beneficial sediment deposition. Aquaculture operations face challenges related to fish and shrimp health, pond management and overall productivity. The suitability of surface water for domestic supply is compromised, necessitating more complex and costly treatment processes and posing potential health risks. Furthermore, TSS contributes to the degradation of aquatic ecosystem health by altering habitats, affecting biodiversity and disrupting fundamental ecological processes. The cumulative effect of these impacts, particularly the long-term reduction in sediment delivery to the delta, also threatens the VMD's geomorphological stability in the face of land subsidence and sea-level rise. Understanding and effectively managing TSS loads and their sources are therefore paramount for the sustainable development and environmental protection of the VMD.

Keywords: *Total Suspended Solids, Vietnamese Mekong Delta, water quality, water uses, environmental impact.*

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1. INTRODUCTION

The Vietnamese Mekong Delta (VMD), a vast and fertile plain at the terminus of the Mekong river, stands as a region of profound socio-economic and ecological importance. It is a global breadbasket, critical for Vietnam's food security through extensive rice cultivation and a burgeoning aquaculture industry, simultaneously harbors unique biodiversity within its intricate network of rivers, canals and estuaries [1 - 3]. The

delta's productivity and ecological character are intrinsically linked to the seasonal pulses of water and sediment delivered by the Mekong river. However, these vital resources are under mounting pressure from a confluence of factors, including rapid population growth, the intensification of agricultural and industrial activities, the far-reaching impacts of upstream hydropower development, the pervasive threats of climate change, notably sea-level rise and increased frequency of saltwater intrusion [4 - 7]. These stressors collectively jeopardize the quality of the VMD's water resources and consequently, the livelihoods of millions who depend upon them. The historical development trajectory within the VMD, particularly the widespread construction of dike systems to facilitate rice intensification and flood control since the early 1990s and more significantly after the major floods in 2000, has fundamentally altered local hydrological regimes and sediment dynamics [8, 9]. While these engineering interventions have supported agricultural expansion, they have also inadvertently modified how water and sediment are distributed and retained within the delta, potentially increasing the system's vulnerability to changes in upstream sediment inputs and contributing to the local generation and accumulation of suspended solids in certain areas [9]. This human-modified landscape now interacts with larger-scale pressures, creating a complex environmental scenario where water quality is a concern.

Within this context, Total Suspended Solids (TSS) emerge as a pivotal water quality parameter. TSS refers to the diverse array of particulate matter, both organic and inorganic, held in suspension within the water column. In natural deltaic environments, suspended sediments play a crucial constructive role, contributing essential nutrients to floodplain soils, facilitating land accretion that counteracts subsidence, and creating diverse habitats that support rich aquatic ecosystems [3, 10]. However, significant deviations in the quantity, composition, or timing of TSS delivery, largely driven by intensifying anthropogenic activities across the Mekong basin and within the delta itself, can transform these solids from a vital resource into a significant environmental stressor. There is growing scientific evidence and mounting concern regarding persistently elevated TSS levels and profoundly altered sediment regimes within the VMD [2, 11, 12]. These changes are increasingly linked to observable degradation in surface water quality and are exerting tangible negative impacts on the region's primary water-dependent sectors and overall ecological balance. The situation in the VMD reflects a broader global pattern where large river deltas are experiencing significant alterations to their sediment loads due to extensive damming, intensified land use and the effects of climate change, making the VMD a critical case study with implications for other similarly vulnerable systems worldwide [10].

The primary purpose of this review is to synthesize and critically evaluate the existing body of published scientific knowledge concerning the multifaceted impacts of TSS on water quality and its subsequent effects on key water uses-specifically agriculture, aquaculture, domestic water supply and the health of aquatic ecosystems-within the VMD.

2. RESEARCH METHODOLOGY

A systematic literature search was conducted using the Web of Science, Scopus, PubMed and Google Scholar databases for publications up to May 2025. Search terms were combined using keyword categories related to: (1) suspended solids (e.g., "TSS," "suspended sediment," "turbidity"); (2) geography (e.g., "VMD," "Can Tho"); (3) specific water uses (e.g., "agriculture," "aquaculture," "domestic water supply") and (4) impact drivers (e.g., "dam impacts," "sand mining," "climate change"). Stringent inclusion criteria were applied to select scientific sources. The primary criteria required that studies: (1) possess a Digital Object Identifier (DOI) for verification; (2) directly address the sources, concentrations, or impacts of TSS (or closely related parameters) on water quality or water uses within the VMD; (3) be published as a peer-

reviewed journal article (presenting original research, modeling, or reviews) or a high-quality, citable report (e.g., Mekong River Commission). An analysis was performed on the selected references. Data pertaining to TSS sources, characteristics, and its consequences - including effects on physicochemical parameters, agriculture, aquaculture, domestic water supply and ecosystem health - were systematically extracted and collated. This synthesis aimed to identify recurrent themes, cause-effect relationships and knowledge gaps, integrating findings from diverse methodologies (e.g., field monitoring, modeling, impact assessments) into a cohesive analytical narrative.

3. RESULTS AND DISCUSSION

3.1 Characteristics and sources of total suspended solids in the Vietnamese Mekong Delta

TSS concentrations in the surface waters of the VMD exhibit significant spatial and temporal variability, frequently surpassing national water quality standards and posing considerable environmental concern. Studies have reported TSS values reaching as high as around 146 mg/L in certain areas [13], with average concentrations in major rivers like the Tien river fluctuating seasonally, for instance, around 30 mg/L in the dry season and increasing to about 48 mg/L in the rainy season, often exceeding permissible limits for various water uses [11, 12]. In some coastal provinces, measured TSS values have been found to exceed allowable thresholds by around 1.05 to 6.52 times, underscoring the severity of the issue [14]. This variability is influenced by a complex interplay of factors including hydrological conditions, land use patterns and specific pollution sources. For example, urban areas and regions with intensive dike systems, which alter local hydrology, often exhibit higher pollution levels, including elevated TSS or turbidity [9, 13]. Seasonality plays a crucial role, with many studies indicating higher TSS concentrations during the rainy season due to increased surface runoff, soil erosion and the flushing of pollutants from terrestrial sources into water bodies [11, 12, 15, 16]. Conversely, in some confined canal systems or during periods of low flow, resuspension of settled materials can lead to elevated TSS even in the dry season [14]. The fundamental nature of TSS in the VMD is also undergoing a significant transformation; there is a discernible shift from a system historically dominated by natural fluvial sediments to one increasingly influenced by locally generated, often finer, and more organically enriched or polluted suspended particles due to reduced upstream sediment influx and increased local anthropogenic inputs [2, 3, 5, 10, 13, 17 - 22].

The sources of TSS in the VMD are diverse, stemming from both natural processes and a wide range of anthropogenic activities. Natural sources include the erosion of riverbanks and channel beds, a process that can be significantly exacerbated by altered hydrological regimes and a deficit in the natural sediment load arriving from upstream [10, 18]. The reduction in sediment supply from upstream, primarily due to sediment trapping by hydropower dams, increases the erosive power of the river water downstream leading to enhanced scour of riverbeds and banks within the delta itself [3]. This internally generated sediment then contributes to local TSS concentrations, creating a feedback mechanism where an upstream anthropogenic intervention (dam construction) amplifies a natural process (erosion) within the delta, thereby compounding the TSS problem. Resuspension of bottom sediments due to tidal currents, wind-induced wave action, navigation, particularly in shallow canals and estuarine areas, also contributes to natural TSS levels [23, 24].

Anthropogenic activities, however, are increasingly dominant contributors to the TSS load in the VMD. Intensive agricultural practices, especially rice cultivation, which covers vast areas of the delta, lead to significant soil erosion and the discharge of particulate organic and inorganic matter into adjacent waterways during irrigation and rainfall events [2, 9, 13]. Effluents from the rapidly expanding aquaculture sector, including shrimp and catfish farming, release substantial quantities of TSS in the form of uneaten feed, fecal matter and eroded pond sediment [2, 12, 25].

Urban and industrial wastewater, often discharged with inadequate or no treatment from densely populated areas and industrial zones, introduces high concentrations of suspended solids and organic pollutants into the river and canal network [2, 12, 13]. Furthermore, the construction of extensive high-dike systems for flood control and agricultural intensification, while beneficial for crop production, has altered local hydrodynamics. These systems can trap finer sediments and associated pollutants within canal networks, particularly during periods of low flow or specific sluice gate operations, leading to chronic localized high TSS levels and degraded water quality [8, 9]. This represents a more diffuse and less immediately obvious source of TSS compared to direct point source discharges. A major driver of altered sediment regimes at the delta scale is the construction of numerous hydropower dams in the upper Mekong basin. These dams trap enormous quantities of sediment, drastically reducing the natural sediment flux to the VMD [3, 5, 10, 17, 22, 26]. Estimates suggest that full hydropower development could trap as much as around 94 - 96% of the river's sediment load, with significant reductions already observed at downstream monitoring stations [5, 10]. This sediment starvation not only impacts TSS levels directly but also contributes to increased coastal and riverbank erosion. Concurrently, in-stream sand mining activities within the delta directly extract vast quantities of riverbed material and cause significant resuspension of fine sediments, further elevating local TSS concentrations and altering channel morphology [18, 20].

3.2. Impacts of total suspended solids on water quality in the Vietnamese Mekong Delta

The presence of TSS in the waters of the VMD exerts multitude impacts on their physical, chemical and biological characteristics, often leading to significant degradation of overall water quality. Physically, the most direct and observable impact of elevated TSS is increased turbidity and reduced water clarity [9, 14, 27]. This reduction in clarity significantly limits light penetration into the water column, which has profound implications for aquatic ecosystems by inhibiting the photosynthetic activity of submerged aquatic vegetation and phytoplankton, the primary producers at the base of the aquatic food web [27]. While less commonly highlighted, very high TSS concentrations may also cause minor alterations in water temperature profiles due to increased absorption of solar radiation, although this effect is generally secondary to other factors. The diminished clarity also negatively affects the aesthetic quality of water, which have a concern for domestic users and potential recreational activities.

Chemically, TSS plays a crucial role as both a carrier and a reactor for various substances in the aquatic environment. The nature of the suspended particles, whether they are predominantly inorganic clays, silts, or organic detritus, dictates their chemical reactivity and their capacity to adsorb or desorb nutrients and contaminants. Fine-grained inorganic particles, such as clays, possess large surface areas that readily adsorb nutrients like phosphorus and nitrogen compounds, as well as various pollutants [10, 16, 23]. Organic components of TSS also bind pollutants and serve as a substrate for microbial activity. Consequently, TSS significantly influences nutrient dynamics; it can transport essential nutrients vital for fisheries and agriculture, but excessive loads or altered sediment types can also contribute to nutrient imbalances, potentially leading to eutrophication in receiving waters or, conversely, nutrient depletion in areas starved of natural sediment input [10, 13]. Suspended particles are well-documented vectors for a range of contaminants, including heavy metals such as arsenic, iron and others, as well as pesticides originating from agricultural runoff [2, 4, 12, 28]. The association of these pollutants with TSS facilitates their dispersal throughout the delta's waterways and eventual deposition into bed sediments. This transport mechanism influences the bioavailability, persistence and potential toxicity of these contaminants. For instance, contaminants adsorbed to TSS can settle and accumulate in sediments, creating a long-term

reservoir of pollution. Subsequent resuspension events, triggered by high flows, dredging, or boat traffic, can reintroduce these contaminants into the water column, leading to secondary pollution episodes even if the primary sources have been curtailed [8, 27]. This creates an effect where past pollution associated with TSS continues to impair water quality over extended periods. Furthermore, TSS interacts with salinity in estuarine environments, where changes in ionic strength can induce flocculation of fine particles, altering settling velocities and patterns of deposition [23, 24].

Biologically, high concentrations of TSS, particularly those rich in organic matter, can lead to a significant depletion of dissolved oxygen (DO) in the water column as microorganisms decompose the organic material [2, 11, 13, 16, 29]. This oxygen depletion can create hypoxic or even anoxic conditions, which are detrimental to most aquatic organisms. The reduction in light penetration due to high turbidity, as previously mentioned, directly curtails primary production by phytoplankton and submerged macrophytes. This not only reduces the autochthonous food supply at the base of the aquatic food web but also diminishes an important source of dissolved oxygen generated through photosynthesis during daylight hours. This creates a detrimental synergy that reduced oxygen production combined with increased oxygen consumption from organic TSS decomposition significantly elevates the risk of low DO conditions. The physical abrasion by suspended particles can also directly harm aquatic organisms, for example, by clogging fish gills and filter-feeding apparatus of invertebrates. Finally, the settling of suspended solids can lead to habitat alteration by smothering benthic environments, covering spawning grounds, and changing the substrate composition, thereby affecting the communities of organisms that inhabit the river and canal beds [10].

3.3. Consequences of altered water quality due to total suspended solids for water uses in the Vietnamese Mekong Delta

The degradation of water quality stemming from elevated and altered TSS regimes in the VMD has far-reaching consequences for essential human water uses and the overall health and stability of the delta's ecosystems. These impacts are often interconnected, creating a cascade of challenges for the region's inhabitants and its natural environment. For instance, water quality deterioration driven by agricultural runoff with high TSS loads can subsequently impair downstream aquaculture operations, affect the suitability of water for domestic abstraction and degrade the general ecological condition of receiving waters, underscoring the need for integrated management approaches that recognize these linkages [2, 4].

In the agricultural sector, high TSS levels in irrigation water can lead to the clogging of irrigation canals, intake structures and pumping equipment, thereby reducing the efficiency of water delivery systems and incurring increased operational and maintenance costs [4]. While direct evidence on canal clogging specific to the VMD was not prominent in the selected literature, the principle is well-established for sediment-laden irrigation waters and the mention of silt and suspended solids complicating water treatment processes implies broader usability issues [4]. Perhaps more critically, the long-term reduction in the deposition of nutrient-rich natural sediments on floodplains, a consequence of upstream dam construction trapping a significant portion of the Mekong rivers sediment load (of which TSS is a component), is leading to a decline in inherent soil fertility [3, 10]. This necessitates increased reliance on synthetic chemical fertilizers by farmers to maintain crop yields, which in turn can contribute to further water pollution through runoff if not managed properly, potentially creating a maladaptive cycle. Poor water quality, including the presence of contaminants adsorbed to TSS or conditions of low dissolved oxygen in irrigation water, can also negatively affect crop productivity and health. Furthermore, delta subsidence, partly linked to sediment starvation, exacerbates saline intrusion, which severely

impacts rice farming and other agricultural activities [4, 15].

Aquaculture, a cornerstone of the VMD's economy, is particularly vulnerable to TSS-related water quality issues. High concentrations of suspended solids in source water or within culture ponds can directly harm farmed species such us fish and shrimp by abrading and clogging gills, reducing feeding efficiency and inducing physiological stress, thereby increasing their susceptibility to diseases [2, 25]. The management of pond water quality becomes more complex and costly when source water has high TSS levels, as this can lead to increased turbidity within ponds, limit natural primary productivity which can be a food source and elevate oxygen demand from the decomposition of organic particulate matter [2]. Ultimately, degraded water quality attributable to TSS and associated pollutants can lead to reduced growth rates, lower survival, and diminished overall productivity and economic viability of aquaculture enterprises [2, 10].

The provision of safe domestic water supply is also significantly challenged by high TSS. Elevated levels of suspended solids in raw water sources necessitate more sophisticated and expensive treatment processes, typically involving enhanced coagulation, flocculation, sedimentation and filtration stages to achieve acceptable clarity and remove particulate-bound contaminants [4, 15]. Turbid water is aesthetically unappealing to consumers and can harbor microorganisms. More importantly, various contaminants, including pathogens, heavy metals and pesticides, can be adsorbed onto suspended particles. If these are not effectively removed during water treatment, they can pose significant health risks to the population relying on these water sources for drinking and other domestic purposes [4, 12]. The economic burden of these impacts, such as increased costs for canal dredging, water treatment, reduced agricultural and aquacultural outputs and potential health expenditures, often disproportionately affects the rural and economically vulnerable populations of the VMD.

Finally, the impacts of TSS on ecosystem health are pervasive. Changes in water clarity, dissolved oxygen levels, nutrient balances and the physical structure of aquatic habitats, all influenced by TSS, can lead to shifts in aquatic species composition, reductions in biodiversity and the overall degradation of ecosystem integrity [3, 10, 13]. The smothering of benthic habitats by excessive sedimentation can destroy critical spawning and nursery grounds for fish and invertebrates, while reduced light penetration due to persistent turbidity negatively affects submerged macrophytes, which provide food and shelter for many aquatic organisms [6, 13]. These alterations disrupt fundamental ecological processes, including nutrient cycling and food web dynamics. On a larger and longer timescale, the significant reduction in the total sediment supply to the delta, a phenomenon in which TSS dynamics play a part, is a critical factor contributing to coastal erosion, land subsidence and increased vulnerability to sea-level rise. These geomorphological changes fundamentally threaten the physical existence and ecological functioning of the entire delta ecosystem, highlighting the profound and existential threat posed by altered sediment regimes [3, 5, 10, 17, 18, 20, 22, 30].

4. CONCLUSIONS

This review confirms that TSS represent a critical water quality concern in the VMD, with profound environmental and socio-economic consequences. TSS concentrations frequently exceed standards, driven largely by anthropogenic pressures. These include sediment trapping by upstream hydropower dams, intensive local agriculture and aquaculture, widespread sand mining and inadequately treated wastewater discharges. The impacts are multifaceted. Elevated TSS increases turbidity, reducing light penetration and suppressing primary productivity. Suspended particles also act as vectors for contaminants (e.g., heavy metals, pesticides) and contribute to dissolved oxygen depletion. These water quality deteriorations adversely affect key sectors such as agriculture faces irrigation challenges and reduced soil fertility; aquaculture

contends with compromised aquatic health and lower yields and domestic water supplies require more complex, costly treatment. Critically, the systemic reduction in sediment delivery exacerbates land subsidence and coastal erosion, threatening the VMD's long-term geomorphological stability, particularly in the context of climate change. Significant knowledge gaps persist regarding the synergistic impacts of TSS with climate change and the full socio-economic costs of this degradation. Future research should prioritize integrated monitoring, predictive modeling under future scenarios, and assessing the efficacy of mitigation measures. The findings indicate the VMD is approaching a critical environmental threshold. Addressing these interconnected challenges demands holistic, adaptive and transboundary management strategies to ensure the region's sustainable development.

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