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Sediment Dynamics During Low Flow Conditions in the Mekong River Estuary, Vietnam

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ABSTRACT

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Field studies of fine sediment dynamics carried out in the Mekong River estuary, Vietnam, during the low flow season in April 1996 show semidiurnal macro-tides and shallow water effects result in a tidal asymmetry with peak flood tidal currents 10% stronger than peak ebb tidal currents. The salinity intrusion extended 50 km up-river with vertical stratification in salinity occurring around slack tidal currents. The suspended sediment was mainly fine silt, with flocculation occurring in the saline region. The asymmetry of tidal currents, along with the baroclinic circulation, pump sediment upstream. The saline water region of the estuary was more turbid than the freshwater region and the location of the turbidity maximum varied spatially with the tides. Our study suggests that the proposed construction of about 100 hydroelectric dams and water diversion schemes on the Mekong River and tributaries will impact negatively on the Mekong delta.

ADDITIONAL INDEX WORDS: *Sediment dynamics, tidal currents, coastal turbidity.*

INTRODUCTION

The Mekong River (Figure 1) is the third longest river in Asia. It has its source in Tibet about 3000 m above sea level. It flows through China, Myannar, Laos, Thailand, Cambodia and Vietnam. The discharge at Phnom Penh, Cambodia, varies seasonally with the monsoon, reaching a maximum in October (typically 39,000 m^3s^{-1}) and a minimum in May (about 1,700 m^3s^{-1}) (BORLAND, 1973; GAGLIANO and MCINTIRE, 1968; MILLIMAN and MEADE, 1983; PHO and TUAN, 1995). The mean annual freshwater discharge is about 11,000 m^3s^{-1}. The sediment discharge is estimated at 160 $\times$ 10^6 t $year^{-1}$ (MILLIMAN and SYVITSKI, 1992) but the data are sparse.

The river splits in three main tributaries near Phnom Penh; some of these tributaries branch again forming a vast delta in Vietnam (Figure 1). At the mouth semi-diurnal, macro tides prevail (THUY, 1988). In the high flow season, a salt wedge forms in the delta near the mouth but does not penetrate more than a few kilometres inland. The estuary is virtually fresh up to the mouth and the bulk of the fine sediment is exported offshore where it deposits in shallow coastal waters (WOLANSKI *et al.*, 1996; ANIKIYEV *et al.*, 1986). No studies of fine sediment dynamics have to the authors knowledge been carried out in the low flow season.

A total of about 8 million Cambodians, 4 million Laotians, 32 million Vietnamese, 22 million Thais, and several millions Chinese live and work in its basin, most of them depending on the Mekong for their livelihood. The desire for hydro-power led China to construct the Manwan hydroelectric dam in 1993 on the main river and Thailand to build the Pak Mun dam in 1994 on the Mun River tributary. About 60,000 people may have been displaced by the construction of these dams. Biodiversity has also been affected, indeed up to 150 species of fish apparently disappeared in the headwaters after construction of the Pak Mun Dam (ROTHERT, 1995). As many as 100 dams, some for hydroelectricity, some for water diversion projects, are in various stages of planning or construction on the Mekong River and tributaries. In particular, four dams on the Mekong River are under construction in China and another ten are planned. Laos is planning 23 dams, 16 for the Sekong River tributary. The Mekong River Commission has proposed 9 mainstream dams. The water diversion schemes will reduce water flows in the dry season.

The environmental impact of these dams and water diversion schemes on the Mekong River estuary in Vietnam has apparently not been studied. No data are apparently available to assess in detail these impacts. While such a study is beyond our means, we undertook a field study of the estuarine water and sediment dynamics in the low flow season, in April 1996, to obtain some preliminary data on physical processes.

METHODS

The field study was carried out between April 14–18, 1996. Vertical profiles of temperature, salinity and sus-

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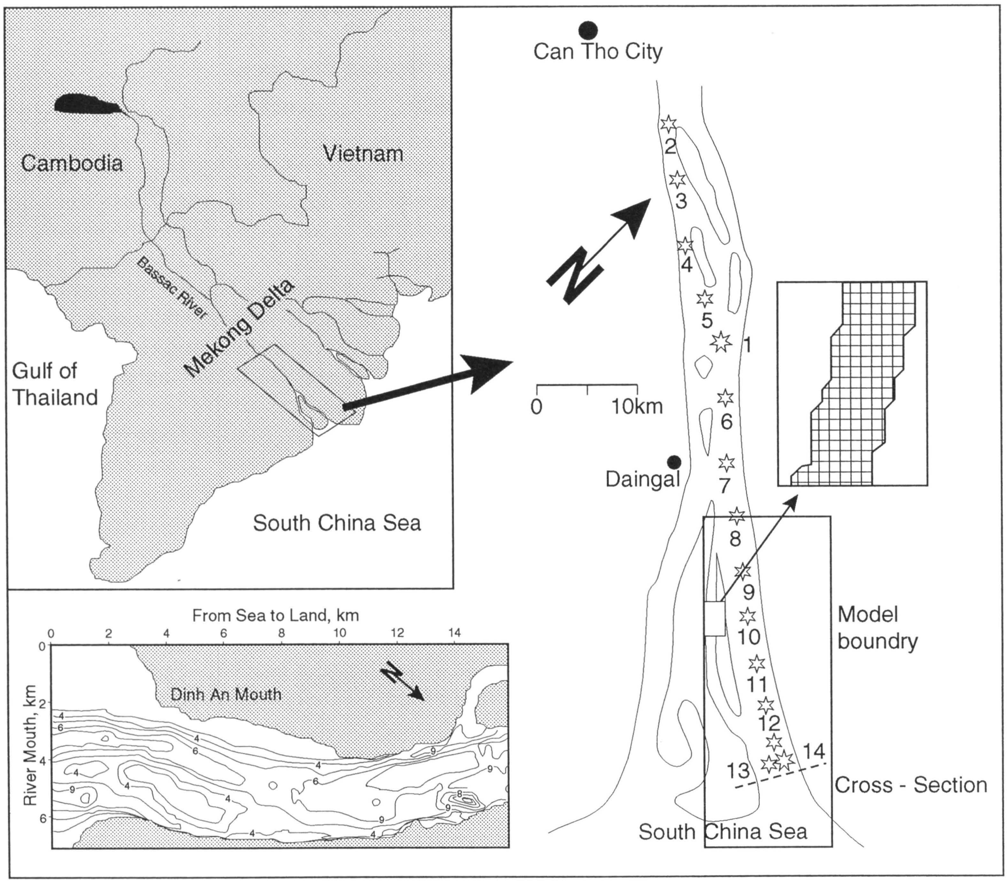

Figure 1. Mekong River delta. Location map, positions of sampling stations, details of the bathymetry near the mouth, model boundary and an example of the gridding for the numerical model showing the fine scale of the model.

pended sediment concentration were obtained at a number of stations (Figure 1) using a Seabird CTD fitted with an Analite optical fiber nephelometer which is more sensitive than the Seabird nephelometer. The nephelometer data were converted into suspended sediment concentration values using a calibration curve. Position fixing was by dead reckoning. At stations 1 and 14, a 13 hour station was maintained from a boat at anchor using the CTD. In addition at these two stations vertical profiles of currents were measured with 1 m vertical resolution using a Vertusca current meter suspended from the boat. We also undertook one cross-channel CTD, suspended sediment concentration and velocity survey at station 14.

Floc size was also measured. In-situ floc cameras could not be used because the strong tidal currents would cause floc breakage and the high concentrations would cause excessive floc overlap (EISMA, 1993). Instead to measure floc size we used the technique of WOLANSKI and GIBBS (1995). We collected water using a specially modified, wide mouth, 5 litre Niskin bottle. We immersed in this bottle a slide with a well. The slide was capped underwater and photographed using a macro-lens camera.

Tidal data were obtained from HYDROMET for Mythanh (at the mouth), Daingai (km 42) and Can Tho (km 103 upstream). Freshwater discharge data were also provided by HYDROMET. Wind data were obtained in-situ using a hand-held anemometer.

RESULTS

Tides, Wind and Runoff

At the mouth (Mythan) semi-diurnal tides prevailed with a range of 2.6 m and a maximum diurnal inequality of about 0.6 m (Figure 2). The tides moved within the estuary as a progressive wave, decreasing in amplitude with distance upstream. At Daingai and Can Tho the tides showed a marked asymmetry, with the water level rising faster at flood tide that it fell at ebb tide. The freshwater runoff in this channel was estimated at about 1,200 m^3s^{-1}. The wind was typically easterly to northeasterly at 2 to 7 m s^{-1} (Figure 3).

Salinity and Currents

From our data (Figure 4) the salinity intrusion length was about 50 km, with salinity (in ppt throughout this paper) varying between 7 and 23 (Figure 3) at station 14 near the

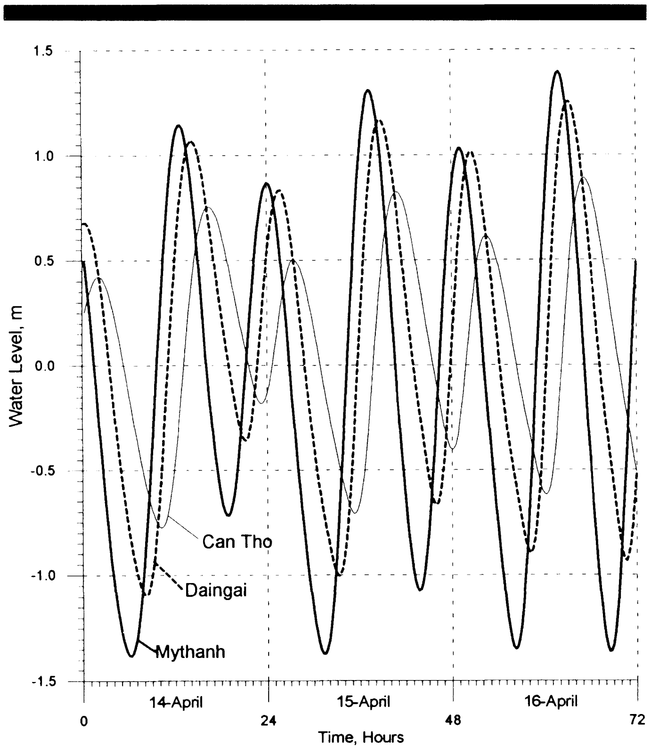

Figure 2. Time series plot of the sea level during the field study in April 1996. The locations of the stations are shown in Figure 1.

mouth. Vertical stratification in salinity occurred at intra-tidal frequency, with a maximum difference of salinity from the surface to bottom of 4 when the currents were smaller than 0.5 m s^{-1}. However the waters were vertically well-mixed in salinity during and immediately following peak currents at both flood and ebb tide. Our current meter had no direction sensor, but an examination of the current speed data (Figure 3) suggests that the flow was unidirectional most of the time from top to bottom. However around the time of reversals of currents (at 10 and 15 h) when there was a salinity stratification, the near-bottom currents were stronger than the currents higher up, suggesting the existence of an estuarine baroclinic circulation with an up-river current prevailing near the bottom and a down-river current near the surface. The depth-averaged currents were tidally asymmetric (Figure 5), with the peak currents being 10% larger at flood tide (1.12 m s^{-1}) than at ebb tide (1.03 m s^{-1}). There was a lag of 2 hours between slack tide and current reversals.

At station 1, near the salinity intrusion limit, the waters were also vertically stratified in salinity when the currents were smaller than 0.5 m s^{-1} (Figure 6). Thus, the upper reaches of the saline region of the estuary were also stratified at intra-tidal frequency.

Across-channel gradients of currents and salinity were also observed (Figure 7) but there may be some tidal aliasing due to the fact it took 2 hours to complete the sampling. Temperature on the other hand was practically uniform in this transect as well as in all the other CTD casts.

Suspended Sediment

The suspended sediment was not flocculated in the freshwater region (not shown) but was flocculated in the saline region (Figure 8). Mean floc size d_{50} was 82 μm, d_{10} and d_{90} respectively 28 and 85 μm. These floc characteristics thus resembled those in the high flow season (WOLANSKI *et al.*, 1996).

The suspended sediment concentration (SSC) at the mouth (Figure 3) varied temporally and vertically. Erosion occurred during accelerating currents, deposition during decelerating currents. Following the slack current period, accelerating currents eroded the sediment from the bottom for the first hour but this sediment remained in the bottom metre of the water column. It was not until 2 hours after slack currents that this turbid bottom layer thickened measurably as a result of vertical mixing. During decelerating currents, settling occurred as soon as the currents were smaller than 0.6 m s^{-1}. Settling occurred much faster than upwards entrainment. Near slack water a near-bottom turbid layer formed precisely at the time when the waters were stratified in salinity and a baroclinic circulation apparently prevailed pumping sediment upstream. SSC values were always in the range of enhanced settling (SSC <1200 mg l^{-1}) and never reached values (>5000 mg l^{-1}) that would be typical of hindered settling (MEHTA, 1986). The peak depth-averaged SSC value was larger at flood tide than at ebb tide, and there was about a 2 hour lag between currents and SSC fluctuations (Figure 5).

Near the salinity intrusion limit, the SSC also fluctuated in time and vertically (Figure 6). The peak near-bottom SSC value was 1400 mg l^{-1} which is still in the range of enhanced settling. The depth-averaged SSC lagged the depth-averaged currents by about 2 hours.

Cross-channel SSC gradients appear significant, with higher near-bottom SSC values in the thalweg than in shallower regions (Figure 7).

In the freshwater region, SSC values (not shown) were measured to be in 100–200 mg l^{-1} range. Thus the freshwater region was less turbid than saline region of the estuary.

WATER AND SEDIMENT DYNAMICS

From the data for the tidal cycle at station 14, the tidally-averaged net sediment flux was small (<1 %) compared to the peak instantaneous fluxes, nevertheless it is important as it determines the siltation patterns of the estuary. The estimate is unreliable however because the time series is short, and numerical modelling was needed to improve this estimate. The hydrodynamics-cohesive sediment dynamics model of WOLANSKI *et al.* (1995) was applied and its application is described below.

The depth-averaged currents driven by the freshwater discharge and the tides were modelled using the finite-difference, non-linear model of NHAN (1995). The model domain (Figure 1) extended from the mouth to station 8, in

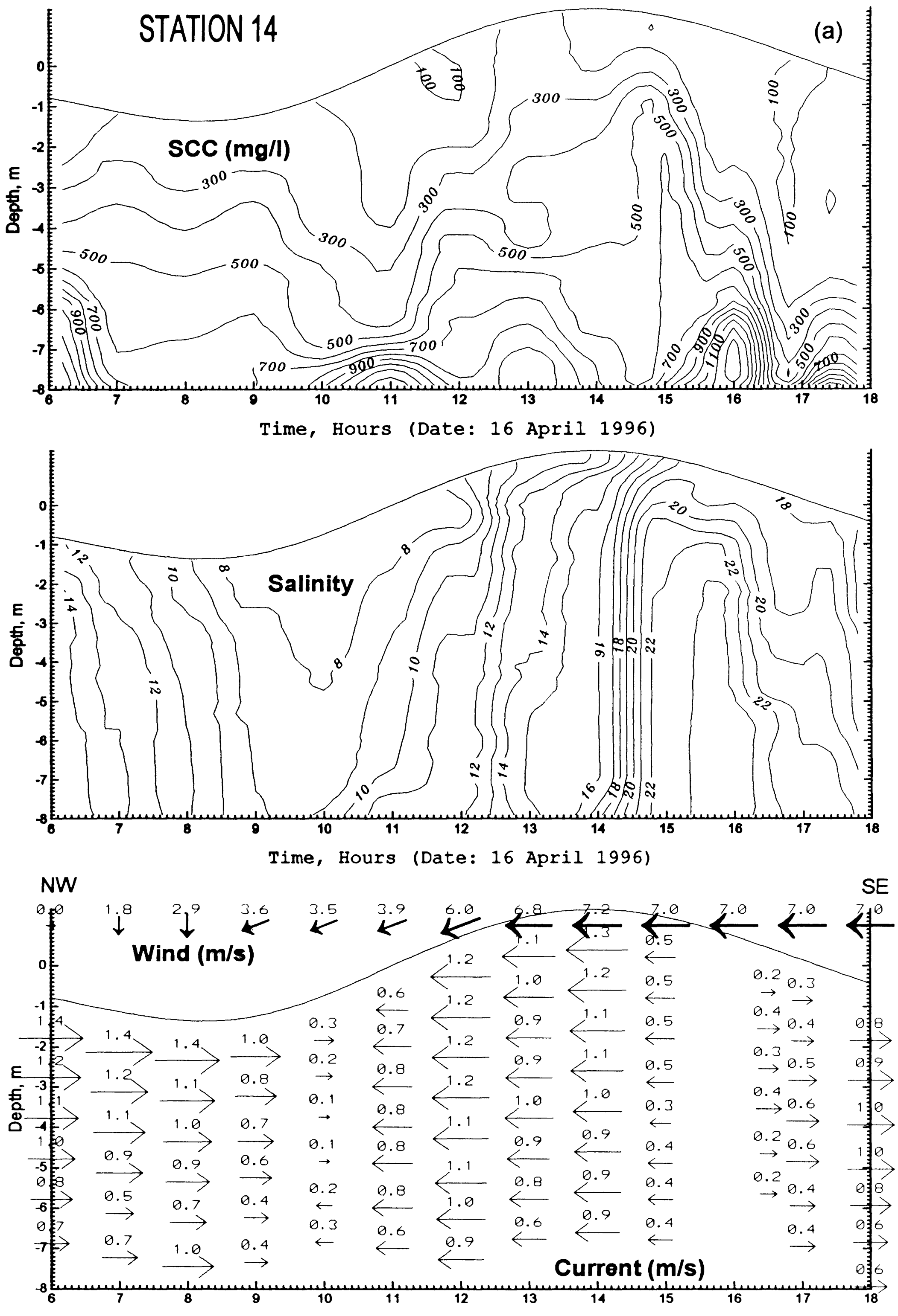

Figure 3. Time series plot of the distribution of suspended sediment concentration (SSC, in mg l^{-1} or g m^{-3}), salinity (ppt), wind and currents at station 14 near the river mouth on April 16, 1996. The current meter measured speed but not the direction. Hence it was not possible to determine if the near-bottom currents were oriented the opposite direction from the surface currents around slack tide; at the surface the current direction was estimated visually because the water flowed either seaward or landward.

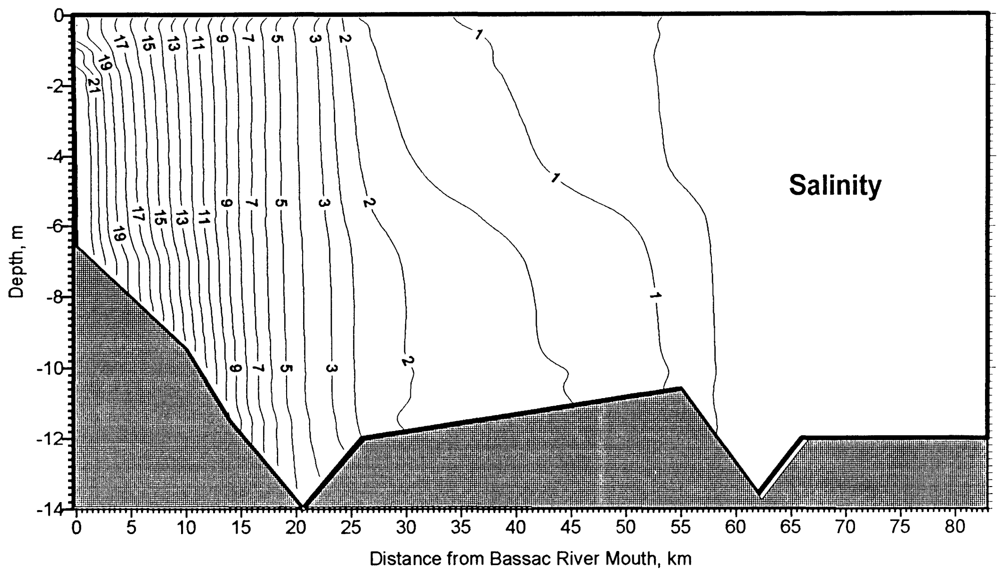

Figure 4. Along-channel salinity distribution of salinity at flood, spring tides, April 14–16, 1996.

the saline region. The measured tides, including the higher harmonics such as the M_4 tide, were imposed at each open boundary. The freshwater discharge was taken into account by imposing a higher mean sea level at the upstream end than at the mouth. The model was calibrated for the one unknown parameter, bottom friction, by comparing observed and predicted currents at site 14 (Figure 5).

While the above model calculates the barotropic currents, there were also baroclinic currents. The baroclinic circulation was probably unsteady, occurring at intra-tidal frequency. The peak tidally-averaged baroclinic currents can be expected to occur near the mouth. They were estimated by two methods. Firstly, the salinity stratification occurred only at intra-tidal frequency near slack currents for 2 hours. Well-mixed conditions occurred the rest of the time. This stratification is thus presumably due to the baroclinic circulation, starting from a well-mixed system and stratifying the system in about 2–3 hours. Knowing that the vertical salinity range reached 4, the amplitude of the baroclinic current can be estimated from Figure 4 since these currents must transport water with salinity 4 ppt higher to site 14 in 2–3 hours. A second estimate yielding a similar value was obtained using the model of FISHER *et al.* (1972).

The estuarine hydrodynamics-sediment dynamics model of WOLANSKI *et al.* (1995) was applied. Following HYDROMET's river gauging data during the field study, a freshwater discharge of 1,200 m^3s^{-1} was assumed. The two unknown parameters were the erosion constant and the settling velocity. The settling velocity was not constant, and was assumed to increase with increasing SSC as is typical of cohesive sediment in the enhanced settling regime. The absolute values were taken to be equal to those for the silt-dominant Fly River sediment (WOLANSKI *et al.*, 1995). These values match those predicted from GIBBS (1985) from the known floc size (Figure 8). The only remaining parameter, the erosion constant, was calculated by trial-and-error until the predicted SSC values at station 14 reproduced satisfactorily the observations (Figure 9). In agreement with observations the predicted depth-averaged SSC distribution (Figure 10) showed no fluid mud occurring in the estuary and that the SSC values were largely controlled by the tidal currents. The saline region of the estuary was more turbid than the freshwater region, and the location of the turbidity maximum zone varied spatially with the tides.

The model reproduced with the observations that tidally-averaged sediment flux at the mouth of the estuary was very small, about 1%, compared to the peak instantaneous tidal flux of suspended sediment (6 tons s^{-1}).

SEASONAL CYCLE

For the Mekong River, the high flow (monsoon) season lasts from July to December. The freshwater discharge peaks at 33,000–66,000 $m^3 s^{-1}$ (PHO and TUAN, 1995). The discharge is so large that the estuary remains fresh nearly up to the mouth where a salt wedge is formed and the river plume lifts off the bottom. Typically suspended sediment concentrations (SSC) at Phnom Penh, Cambodia, are about 250 mg l^{-1}. Presumably the sediment load may be higher during the rising stages of the hydrograph because SSC values reaching 600 mg l^{-1} have been occasionally measured but the data is sparse (GAGLIANO and MCINTIRE, 1968). Most of the suspended sediment is silt, with clay accounting for <20% by volume. At least 95% of the suspended sediment may be exported to the sea and is deposited within 20 km of the coast. A measurable, but small, fraction of that

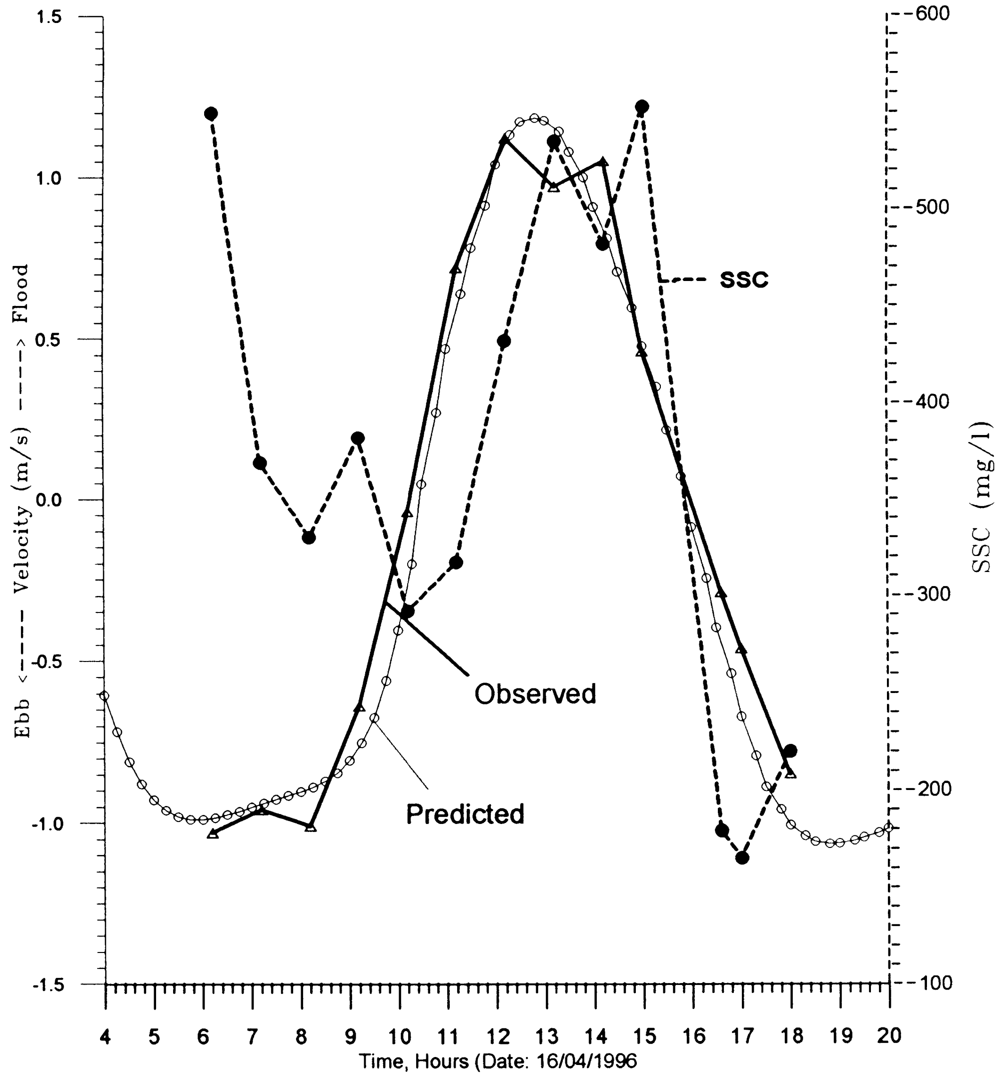

Figure 5. Time series plot of the depth-averaged suspended sediment concentration (SSC) and the observed and numerically predicted currents at station 14 near the river mouth, April 16, 1996.

sediment (possibly 5%) returns in the estuary with the salt wedge in the turbidity maximum zone at the toe of the wedge (WOLANSKI *et al.*, 1996). Fluid mud is not present, possibly because the silt-dominant sediment is weakly cohesive, however the sediment is flocculated in the saline region.

The low flow season lasts from February to May. The freshwater discharge reaches a minimum of 1,000–2,000 m^3s^{-1} (mean low water discharge = 1700 m^3s^{-1}), and about ¼ of this enters the Basaac River (the channel we studied). Data at Phnom Penh suggest SSC values typically 80–100 mg l^{-1}. Large tidal currents prevailed peaking at 1.4 m s^{-1}. From the data, as the tides progressed into the estuary from the South China Sea, they decreased in amplitude and increased in asymmetry (with swifter flood than ebb currents) with distance upstream. During our study the freshwater discharge was about 1,200 m^3s^{-1} in our study channel, hence we expect much smaller freshwater flows can occur in a dry year. The saline region extended 50 km up-river and a vertical stratification existed at intra-tidal frequency. The silt-dominant suspended sediment was flocculated in this region. SSC values in this region near the salinity intrusion limit varied at tidal frequency, the depth-averaged SSC peaked at 583 mg l^{-1} and maximum near-bottom SSC values were 1400 mg l^{-1}. At the river mouth salinity fluctuated with the tides between 7 and 23. Well-mixed conditions prevailed during peak currents but the waters were salinity-stratified during currents < 0.7 m s^{-1}. The SSC also varied at tidal frequency, lagging the currents by 2 hours as a result of erosion during accelerating currents and de-

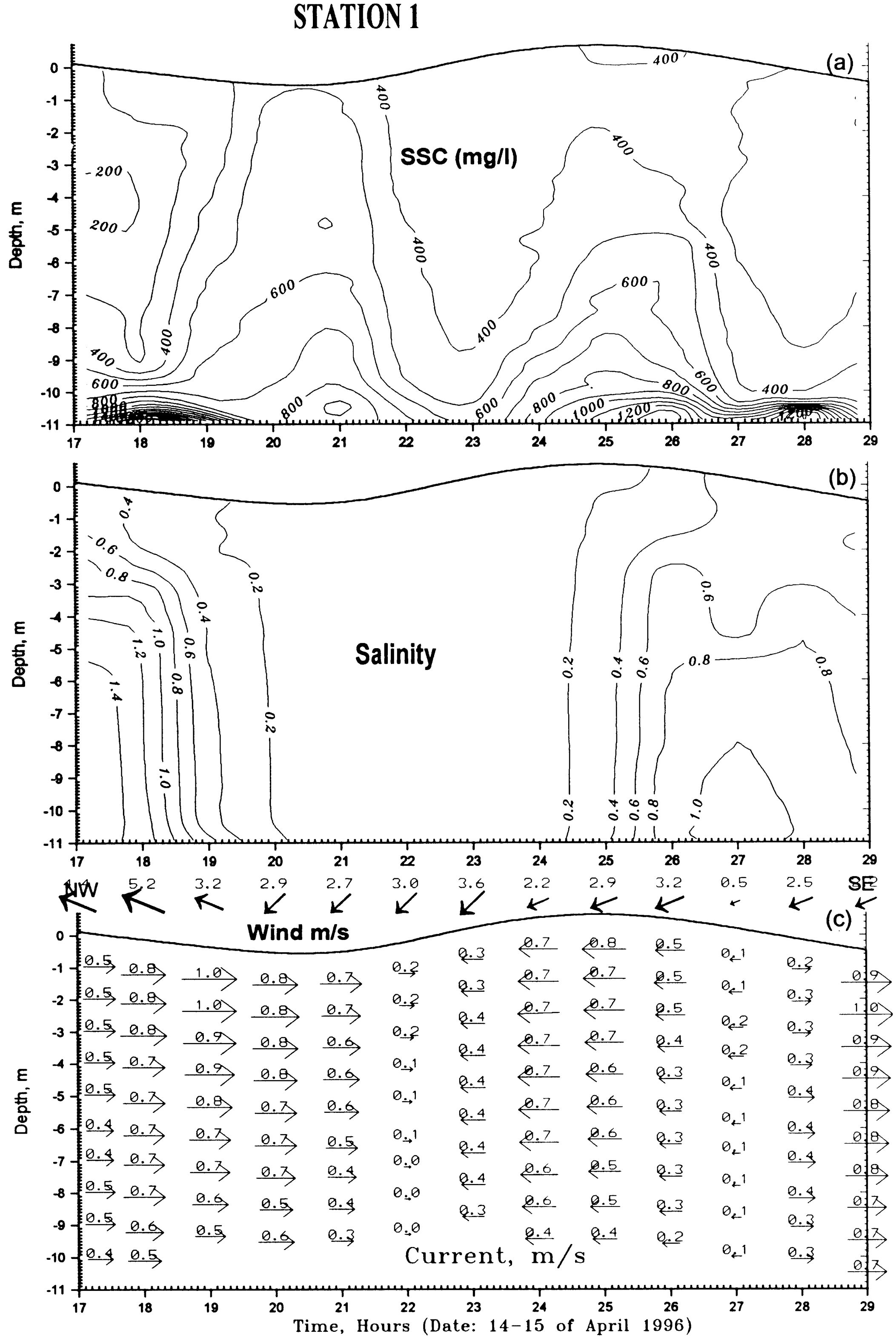

Figure 6. Time series plot of the distribution of suspended sediment concentration (SSC, in mg l^{-1} or g m^{-3}), salinity, wind and currents at station 1 near the salinity intrusion limit on April 14–15, 1996. The current meter measured speed but not the direction.

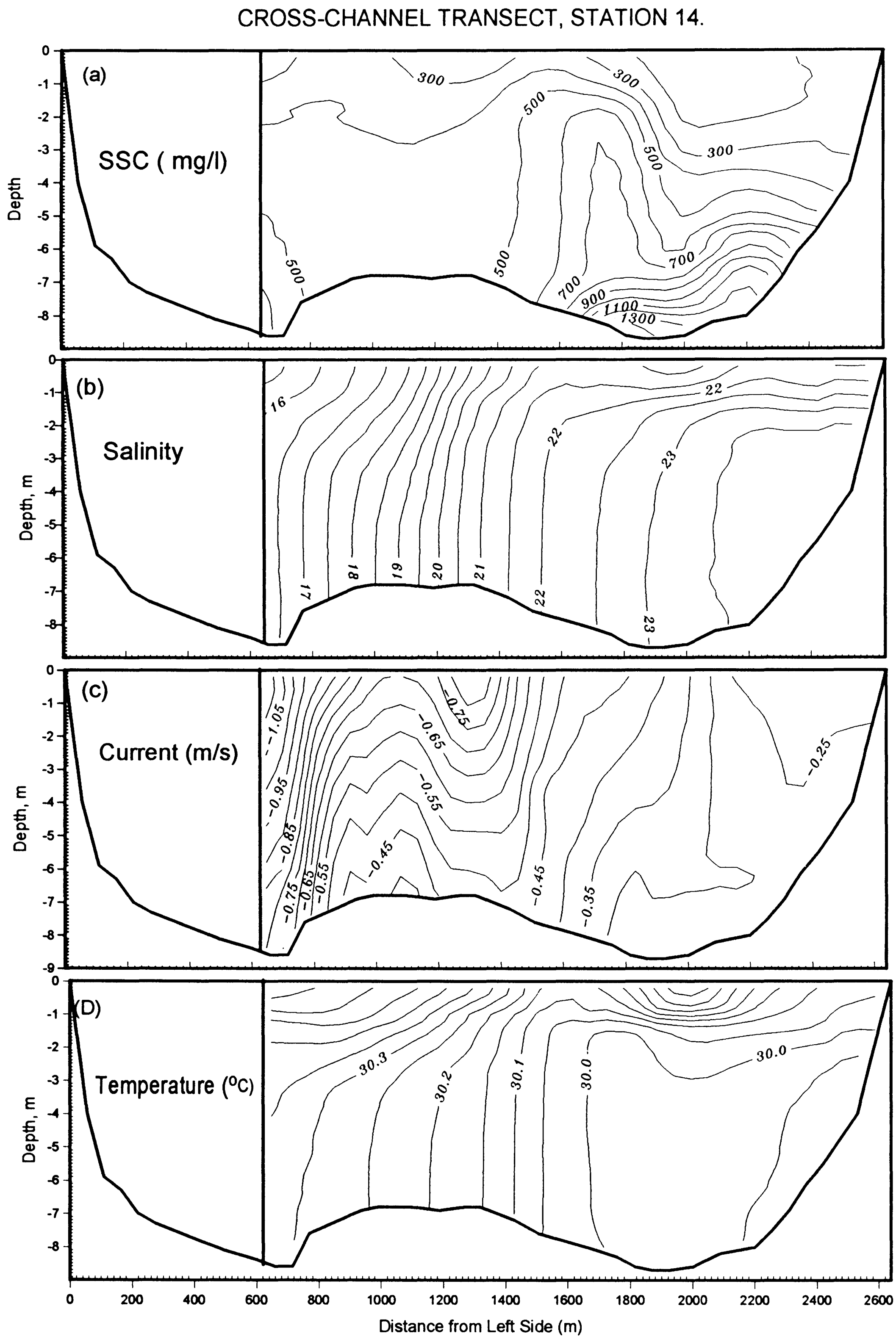

Figure 7. Cross-sectional distribution of suspended sediment concentration (SSC, in mg l^{-1} or g m^{-3}), salinity, currents and temperature along a transect past station 14, 1400–1600h, April 16, 1996.

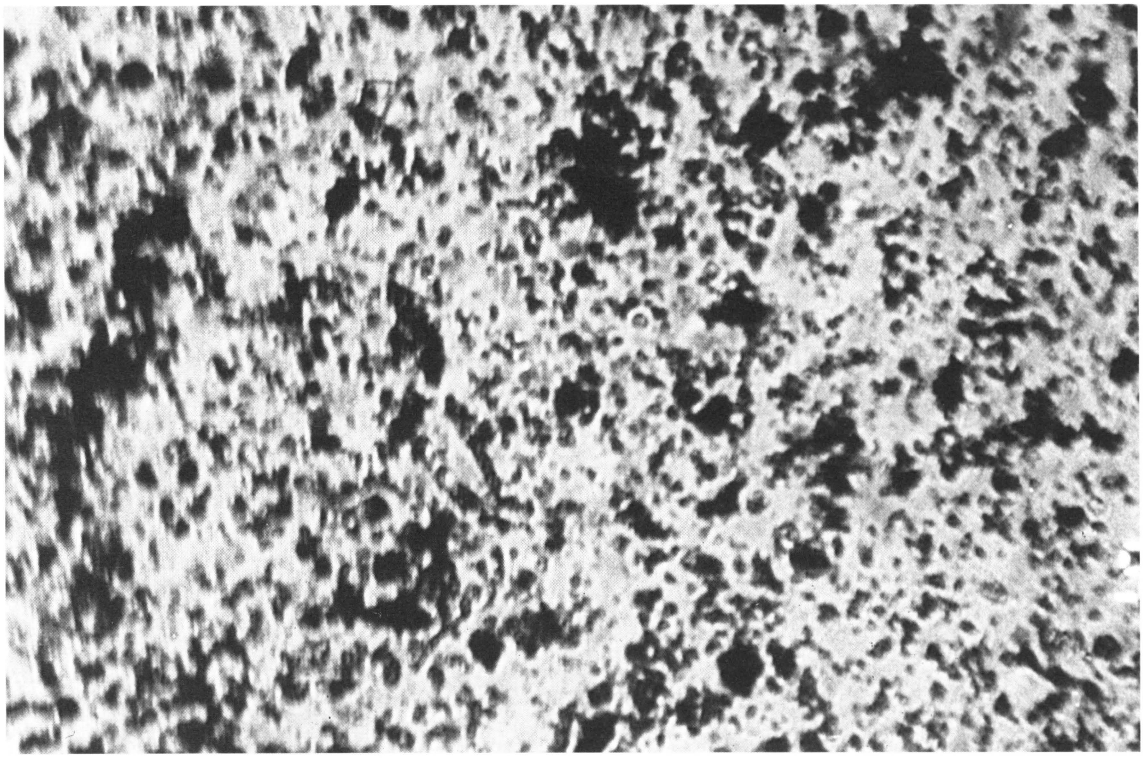

Figure 8. The suspended sediment in the saline region of the Mekong River estuary was flocculated as is shown in this typical microphotograph of suspended sediment, April 16, 1996. The width of the picture is 1816 μm. The sediment was mainly fine silt with a mean particle size of about 4–7 μm (according to location and stage of the tide) with clay accounting typically for 20–40% (by volume). The median floc size was about 30–40 μm.

position during decelerating currents. Peak near-bottom SSC values were 1200 mg l^{-1} and the depth-averaged SSC peaked at 553 mg l^{-1}. Fluid mud was not encountered at any of the sampling sites. SSC values in the estuary in the low flow season were typically 2–4 times higher than those observed in the high flow season.

From the data for the tidal cycle that was sampled at station 14, the tidally-averaged net sediment flux was small (<1%) compared to the peak instantaneous fluxes, nevertheless it is important as it determines the siltation patterns of the estuary. Because the time series is short, numerical modelling was needed to improve this estimate. For a freshwater discharge into this channel of 1200 m^3s^{-1} during this study, the tidally-averaged flux was predicted to be about 1% the peak instantaneous tidal flux from the results of the hydrodynamics-cohesive sediment transport model of WOLANSKI *et al.* (1995). The model was verified against the available data.

Based on the model, sediment may be pumped at a measurably increased rate from coastal waters into the estuary with decreasing freshwater discharge. The predicted increased dry season siltation rate in this channel alone can be as high as 72 million tons $year^{-1}$ if the freshwater discharge was halved. Such a decrease is possible if water diversion schemes are implemented upstream. The increased siltation would exacerbate navigation problems which are already severe and would require dredging. In the high flow season the freshwater discharge will be decreased by the hydroelectric dams, so that as a result sediment flushing out of the estuary will decrease. The situation may in fact be worse because smaller freshwater discharges will lead to an increase of the salinity intrusion in the estuary, and hence to larger baroclinic currents pumping sediment upstream.

DISCUSSION

There is room for concern about environmental degradation and resulting social and economic implications for millions of people in Vietnam's Mekong River delta following construction of the 100 or so proposed hydroelectric dams and water diversion schemes on the Mekong River and tributaries in China, Thailand, Cambodia and Laos (ROTHERT, 1995). These problems deserve much more detailed investigations than the short study described here. However, our low flow season data, together with the high flow season data of WOLANSKI *et* al. (1996), may be the only estuarine dynamics data available to make an assessment, albeit limited, of the physical impacts at this stage.

Water diversion schemes would increase the salinity intrusion into the estuary and this would affect farming and irrigation in the low flow season.

The hydroelectric dams would decrease peak water dis-

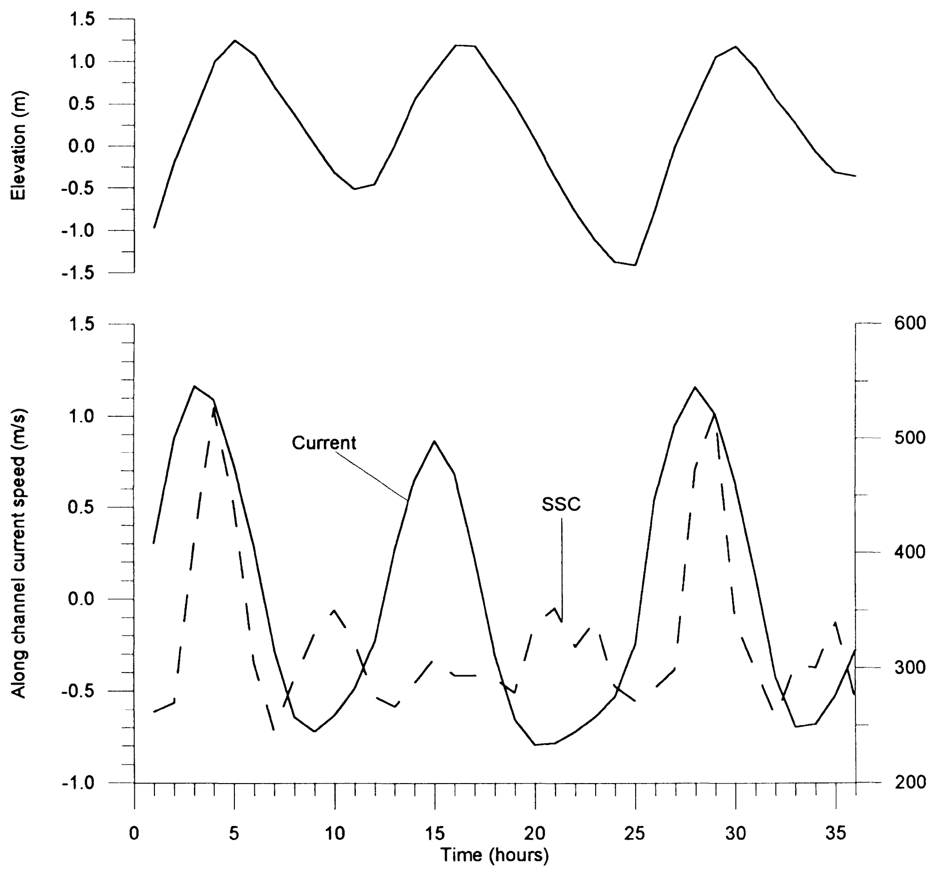

Figure 9. Time series plot of sea level and numerically predicted depth-averaged currents and suspended sediment concentration (SSC).

charges during the high flow season, and hence decrease the seasonal flushing of acid sulfates formed in the dry season in the top layer of the soils in the upper delta. Acid sulfate is already a significant hindrance to farming in the dry season (PHO and TUAN, 1995).

The bulk of the Mekong River fine sediment discharge in the high flow season deposits in shallow coastal waters. This sediment protects the coast from wave-induced erosion. This sediment moves on the shelf and does not necessarily remain on site, however at present it is renewed annually by the Mekong River sediment discharge in the wet season. The longshore drift of this sediment may vary seasonally from northward to southward with the prevailing wind (WOLANSKI *et al.*, 1996). Removal of this sediment from an area leaves it more prone to wave-induced erosion. Indeed this is happening, and has been happening for the last forty years, in the northern region of the delta (NGUYEN NGOC THUY, unpub. data). The proposed hydroelectric dams will presumably trap sediment in the man-made lakes, decrease the sediment discharge reaching the estuary and in this manner starve the coast of sediment and lead to increased coastal erosion.

These various effects, together with their socio-economic implications for millions of people as well as fisheries and other ecological effects, all deserve detailed investigations in view of the massive water management schemes under construction and/or under planning.

CONCLUSION

We observed that the Mekong River estuary was shallow, partially well-mixed in salinity, and that a tidal asymmetry resulted with stronger peak flood than ebb tidal currents. This asymmetry resulted in suspended sediment being pumped into the Mekong River estuary from coastal waters of the South China Sea. This sediment was presumably deposited in shallow coastal waters during the previous high flow season and prevents coastal erosion. The proposed dams and water diversion schemes in the Mekong River basin are likely to result in the erosion of the coastline, siltation in the saline intrusion region in the estuary, and lengthening of the duration and extent of salinity intrusion in the estuary.

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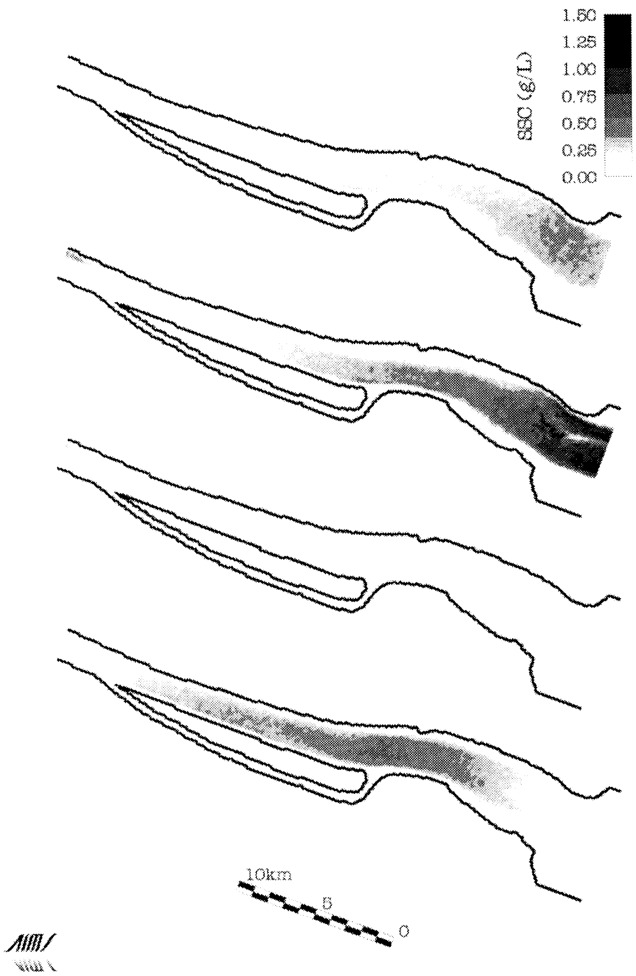

Figure 10. Distribution of numerically predicted, depth-averaged suspended sediment concentration at four times during the spring tide cycle of April 17, 1996.

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