



**MEKONG RIVER COMMISSION**

# **COASTAL MODELLING REPORT**

*Council Study Modelling Team*

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**Disclaimer:**

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## CONTENTS AMENDMENT RECORD

This report has been issued and amended as follows:

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1	0	First draft	17/07/2017	Jorma Koponen, Arto Inkala
2	0	Addition of baseline and scenario results for sediment transport, deposition, erosion and fisheries production	30/10/2017	Jorma Koponen
3	0	Report revision based on general Member Country questions and suggestions.	03/02/2018	Jorma Koponen



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## Abbreviations and acronyms

BDP	: Basin Development Plan
BDP2	: BDP Programme, phase 2 (2006 –10)
BDS	: (IWRM-based) Basin Development Strategy
BioRA	: Biological resource assessment team (under Council Study)
CCAI	: Climate Change and Adaptation Initiative (of the MRC)
CIA	: Cumulative Impact Assessment
CNMC	: Cambodia National Mekong Committee
CS	: Council Study
DMP	: Drought Management Programme (of the MRC)
DSF	: MRC Decision Support Framework based on hydrological, water resources and hydrodynamic models
EIA-3D	: WUP-FIN 3-dimensional hydrodynamic, water quality and productivity model
EP	: Environment Programme (of the MRC)
FP	: Fisheries Programme (of the MRC)
IQQM	: Integrated Quantity and Quality Model
IBFM	: Integrated Basin Flow Management (MRC study)
IKMP	: Information and Knowledge Management Programme (of the MRC)
IWRM	: Integrated Water Resources Management
IWRM-model	: Modelling framework integrating DSF, SOURCE and WUP-FIN for socio-economic and environmental indicators
ISH	: Initiative for Sustainable Hydropower (of the MRC)
JC	: Joint Committee (of the MRC)
LMB	: Lower Mekong Basin
LNMC	: Lao National Mekong Committee
M&E	: Monitoring and evaluation
MRC	: Mekong River Commission
MRCS	: Mekong River Commission Secretariat
MRC-SP	: MRC Strategic Plan
NMC	: National Mekong Committee
NMCS	: National Mekong Committee Secretariat
PMFM	: Procedures for Maintenance of Flow on the Mainstream
PWUM	: Procedures for Water Use Monitoring
SEDB	: Socio-economic database (of the MRC)
SIMVA	: Social impact Monitoring and Vulnerability Assessment (conducted by MRCS)
SoB	: State of Basin report (of the MRC)
SocEc	: Social Assessment team (of the Council Study)
SWAT	: Soil and Water Assessment Tool, hydrological and water quality model
TCU	: Technical Coordination Unit (of the MRCS)
TNMC	: Thai National Mekong Committee
UMB	: Upper Mekong Basin
UN	: United Nations
UNDP	: United Nations Development Programme
VNMC	: Viet Nam National Mekong Committee
WUP-FIN	: MRC Water Utilization Program Finnish component



# 1. Executive summary

Council Study Inception Report and Phase II Work Plan require coastal assessment of the CS development scenarios. The coastal study has been implemented utilizing 3D hydrodynamic, water quality and productivity model utilized before for many Mekong studies including Delta estuary assessment. Although the CS coastal study has been implemented with reduced budget compared to the original plan, the results show that selected approach suits well for development scenario coastal assessment and includes all relevant process and factors for the assessment:

- whole South and East Sea impact on Mekong coast
- tidal forcing
- waves
- sediment transport and deposition
- flow and wave dependent erosion
- stratification
- erosion and deposition
- fisheries production.

Most importantly the model provides fisheries production numbers that are in line with the actual fish catches.

Exact quantification of the development impacts would require much more involved study utilizing past research and monitoring. However, the model produces useful indication of expected impacts including increased erosion due to increased net erosion and very significant coastal fisheries production reduction of at least 230'000 t/a for main scenarios M2, M3 and M3CC as well as most of the sub-scenarios involving major sediment trapping. The exceptions are hydropower sub-scenarios H1a and H1b with significant sediment trapping mitigation.

Largest net erosion areas don't seem to be affected too much by the Mekong sediments, at least for the silt. However, in the long run sediment deposition decrease in the future scenarios can affect overall sediment balance in the Mekong coastal areas.

Additional ANNEX is based on earlier MRC modelling work and discusses salinity intrusion for sea level rise and dredging scenarios. It is interesting that based on detailed 3D hydrodynamic modelling salinity intrusion can be much more problematic for dredging than sea level rise.

## 2. Coastal assessment scope

Coastal modelling can assess coastal flooding, water quality, shoreline and bed erosion and fisheries productivity. As this Council Study modelling study nature is more demonstrative than definitive, the focus has been here on erosion and transport of Mekong sediments and their impact on fisheries production.

Coastal modelling requires accounting for large area sea current and wave impacts on the coast. Nested or adaptive grid technologies need to be applied in order to be able to resolve the Mekong coastal area with sufficiently high resolution while including the surrounding large sea area in the modelling.

The factors that have been included in the model are:

- river discharge, wind and tide as flow driving forces
- waves for erosion computation
- stratification (salinity only)
- erosion and deposition
- primary and fisheries productivity.

Because of the demonstrative nature of the modelling work, following constraints apply:

- no calibration or verification of any other parameters than tidal forcing has been conducted; however, modelled fisheries production corresponds to available production information
- wind fields have considerably variability over large regions; here only coastal wind from one location has been used for all the modeling domain
- tidal forcing on the model open boundaries is approximated from monitored water levels
- primary productivity is computed assuming sediments indicate nutrient availability; here Tonle Sap modelling has been used for guiding the primary and fisheries productivity simulation
- the study focuses on the upstream Mekong development impacts on the Mekong coast conditions; because of this sediment and nutrient loads from Vietnam and Cambodia have not been included in the model
- only bed erosion has been studied by the model; shoreline erosion due to wave breaking is out of the scope of this study
- only one simulation period June – September 2000 has been computed
- only scenarios M1, M2 and M3 have been included in the study
- TSS load is modelled as fine clay as the primary and fisheries production model depends on this fraction and it describes best nutrient and organic material inputs for production
- oxygen, nutrient cycling, harmful substance and other water quality variables are excluded from the study
- thermal stratification has not been included in the simulations.

In addition to the sea and coastal model constructed for the Council Study, earlier EIA-3D model application for Tieu River Mouth has been utilized to study salinity intrusion and effect of dredging and sea level rise on it (see ANNEX).

## 3. Model set-up

### 3.1. Model description

The model used in the study is the same EIA 3D model as used for the Tonle Sap and floodplains as well as various reservoirs and river reaches in the Mekong. The EIA 3D model is developed by Environmental Impact Assessment Centre of Finland Ltd (EIA Ltd.). The development work started 1974 when EIA Ltd. was still part of Technical Research Centre of Finland, the largest governmental research institute in Scandinavia. The EIA 3D model has two components: EIA 3D hydrodynamic model and EIA 3D water quality model.

The EIA 3D model is fully three-dimensional model based on rectangular grid representation. The system accommodates meteorological, hydrological, topographic, land use and infrastructure characteristics of any modelling area and produces 3D hydrodynamics and water quality. The modelling platform including data processing, model control, GIS, database control, model data products and visualization is de-coupled from the actual model engines. The model is able to describe the 3-dimensional characteristics of flooding, flow, water quality, erosion and sedimentation in the lakes, reservoirs, river channels, floodplains, estuaries, coastal areas and larger sea areas.

EIA 3D model can be classified as three-dimensional baroclinic multilayer model (Simons, 1980; Virtanen et al., 1986; Koponen et al., 1992) and is based on solving simplified Navier Stokes equations in rectangular model grid. The cell width can vary in x- and y-directions. It is possible to model whole domains with varying grid resolutions and couple them together. Hydrostatic assumption, Boussinesq approximation and incompressibility of water are used in the model formulation. The water mass is treated as vertical layers similarly to z-level models. This means that the layer depth remains constant over the whole model area except on the bottom where it varies freely. Because the Arakawa E horizontal grid is used in the model stagnation points are avoided and there is no need to utilize of coordinate system which has varying layer depths but constant number of layers in each grid point.  $\sigma$ -system using varying layer depths and same number of layers in all grid points is computationally not as efficient as z-grid because latter has usually much less calculation points. Also, it is advantageous to keep the vertical grid resolution constant over the calculation area because vertical properties are resolved in a consistent way over the whole model domain.

The currents in the model are determined by the following factors:

- wind force (or ice friction),
- atmospheric pressure at the surface,
- conservation and incompressibility of water,
- internal friction (viscosity),
- transport of velocity differences with water currents (advection),
- Coriolis force,
- density differences (salinity, temperature) and water level gradients (hydrostatic pressure),
- bottom friction,
- vegetation impact.

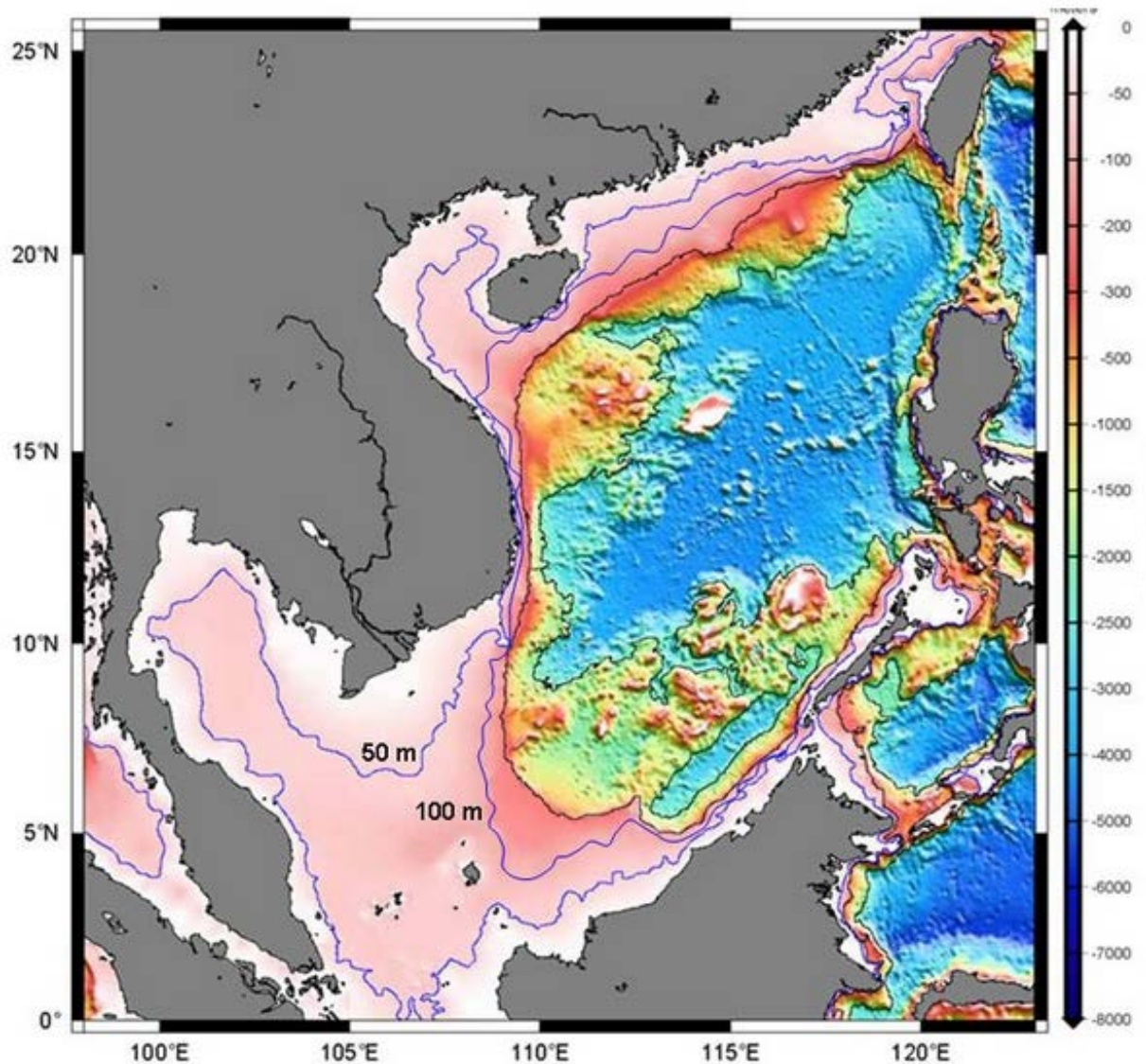
The model is solved numerically using implicit and explicit finite difference methods applied to control volumes (user has control which methods to use). For computational purposes the calculation of the 3D currents is divided into integrated 2D external mode (surface heights, depth integrated currents)

and to 1D internal mode (layer velocity differences). Model can also calculate directly the layer velocities which approach has been used in this study. Eddy viscosity can be computed with number of models. Here advanced  $k-\epsilon$  turbulence model has been applied. The advection of momentum has only minor effects on flows, when the flow velocities are small, and is therefore has not been applied in this study. Model has options for both diffusive and non-diffusive momentum and mass advection.

Detailed characteristics of the model are:

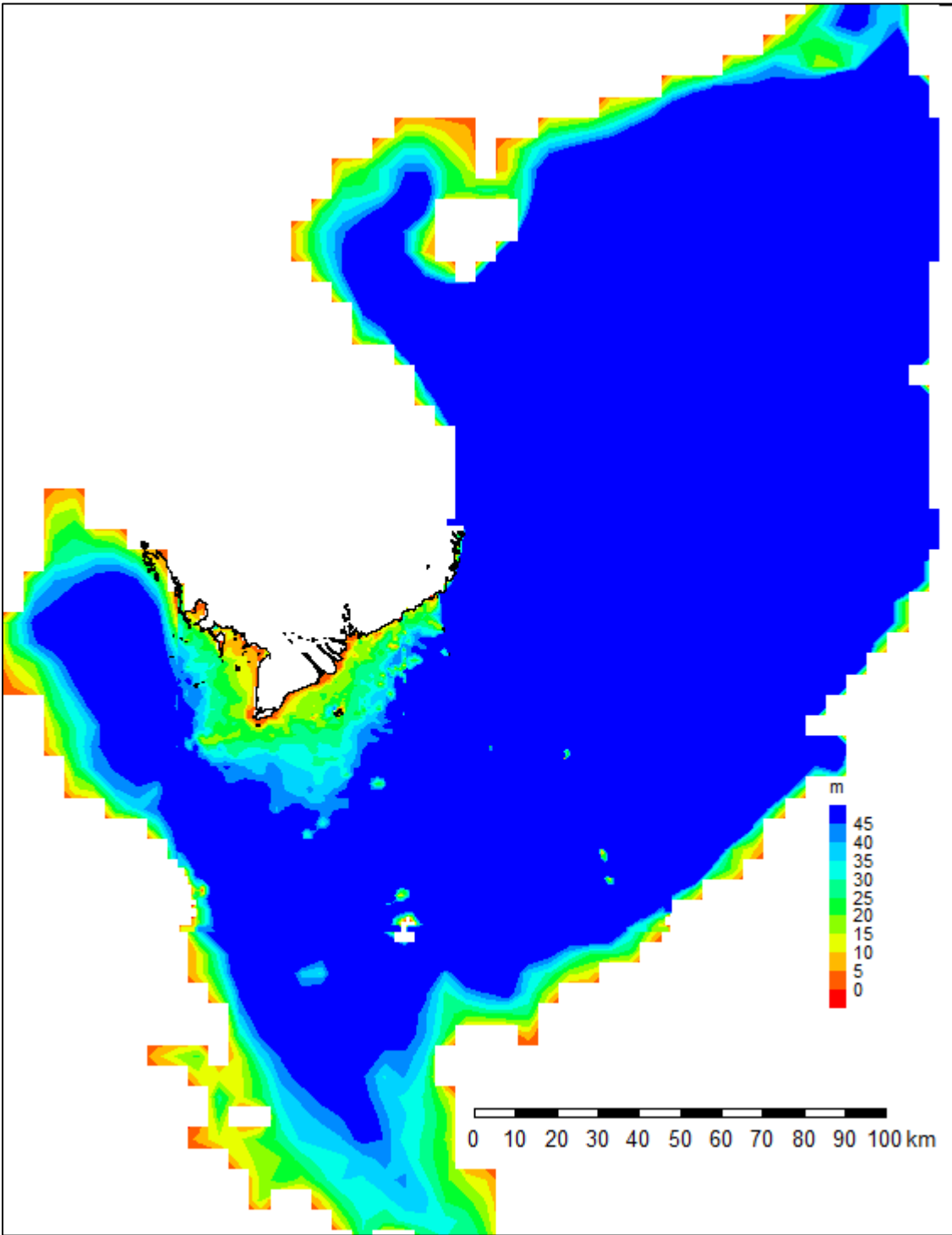
- 6 vertical turbulence models (e.g.  $k-\epsilon$ )
- 5 horizontal turbulence models (e.g. Smagorinsky)
- 2 integrated wave models (others in specialized applications)
- 2 wind fetch models
- 3 erosion models
- 4 bottom friction models
- Vegetation friction in different water layers
- Surface friction (e.g. ice)
- Radiation and heat
- Hydraulic controls (dikes, gates, water intakes, outlet points etc.)
- Wetting and drying
- Morphological changes due to sedimentation and erosion
- Cohesive sediment simulation
- Bed load simulation
- Specialized 3D reservoir model
- Water quality modelling including nutrients and dissolved oxygen
- Primary and fisheries production
- Oil spill modelling
- Sea rescue modelling
- Chemical processes e.g. evaporation, dissolution, emulsification on surface, in the water column and on bottom
- Diagnostic calculation from irregular data
- 2 isopycnal modes for stratification
- Hybrid stratification calculation (combined normal and isopycnal modes)
- 6 momentum advection modes (e.g. TVD)
- 3 transport calculation modes (e.g. TVD and flux correction)
- Integrated statistical analysis
- Algorithmic and code optimization resulting in fast execution times
- Parallelization for multi-processor machines
- Flexible, fully coupled nesting for better local accuracy
- Transportable code (tested from supercomputers to PC's)
- Code developed and tested over 20 years in over 200 applications.

### 3.2. Model grid

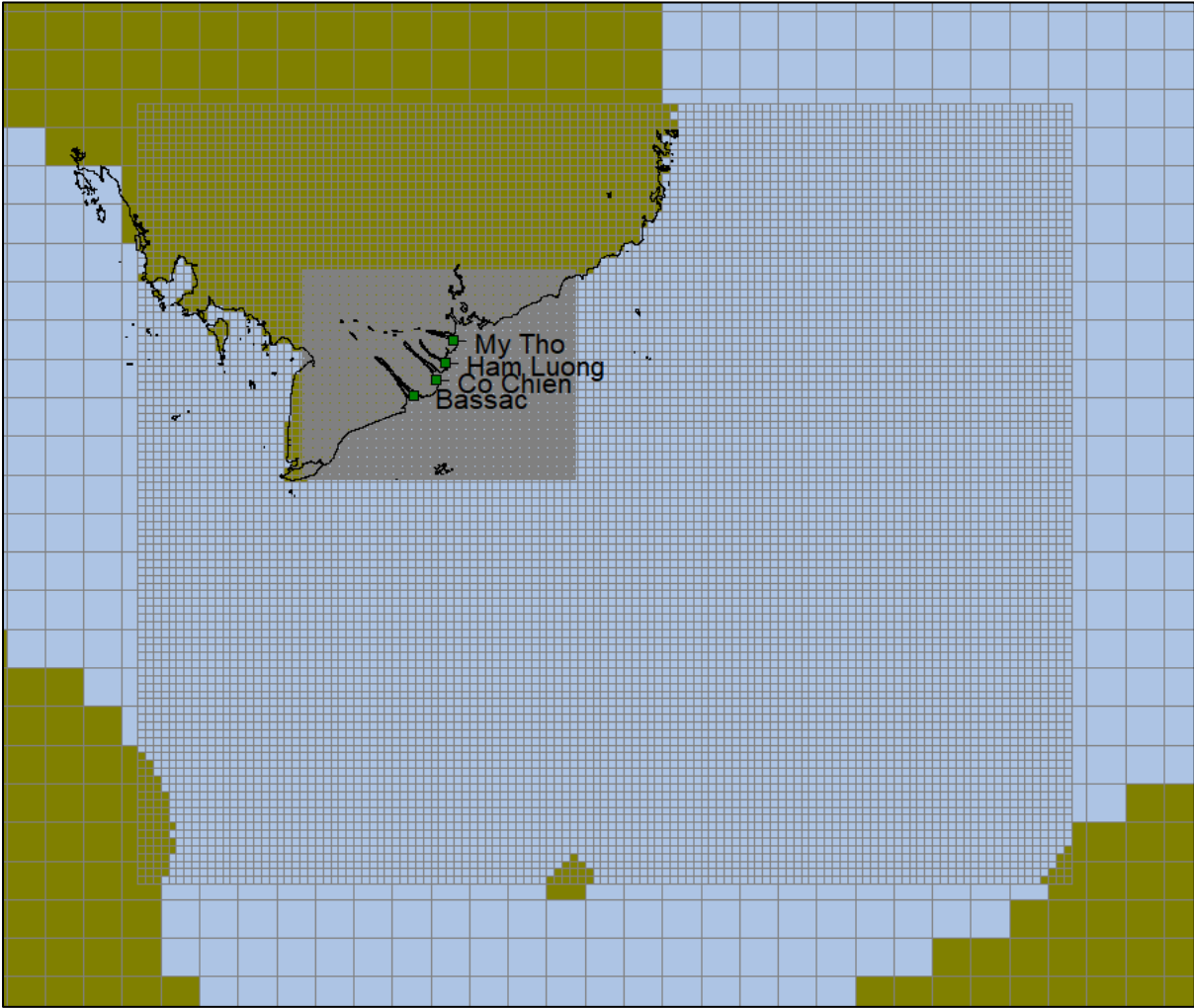


**Figure 1.** Bathymetry used in the model.

Model bathymetry has been derived from global datasets (**Figure 1**). The corresponding grid depths are shown in **Figure 2**. The model grid structure is shown in **Figure 3**: the model consists of 3 nested fully coupled areas which are modelled with 2 km, 10 km and 50 km resolutions. This approach enables taking into account fully South and East Sea impact on the Mekong coast while maintaining reasonable resolution on the focal area. Total number of grid cells is 50'000 of which approximately half are active (water). Vertical grid layer depths are 1, 2, 3, 5, 9, 15, 25, 40, 65, and 100 m. The active water layer in computation is thus limited to 100 m depth. The vertical and horizontal grid structures can be modified at will when more accurate modelling is required.



**Figure 2.** Model grid depths.



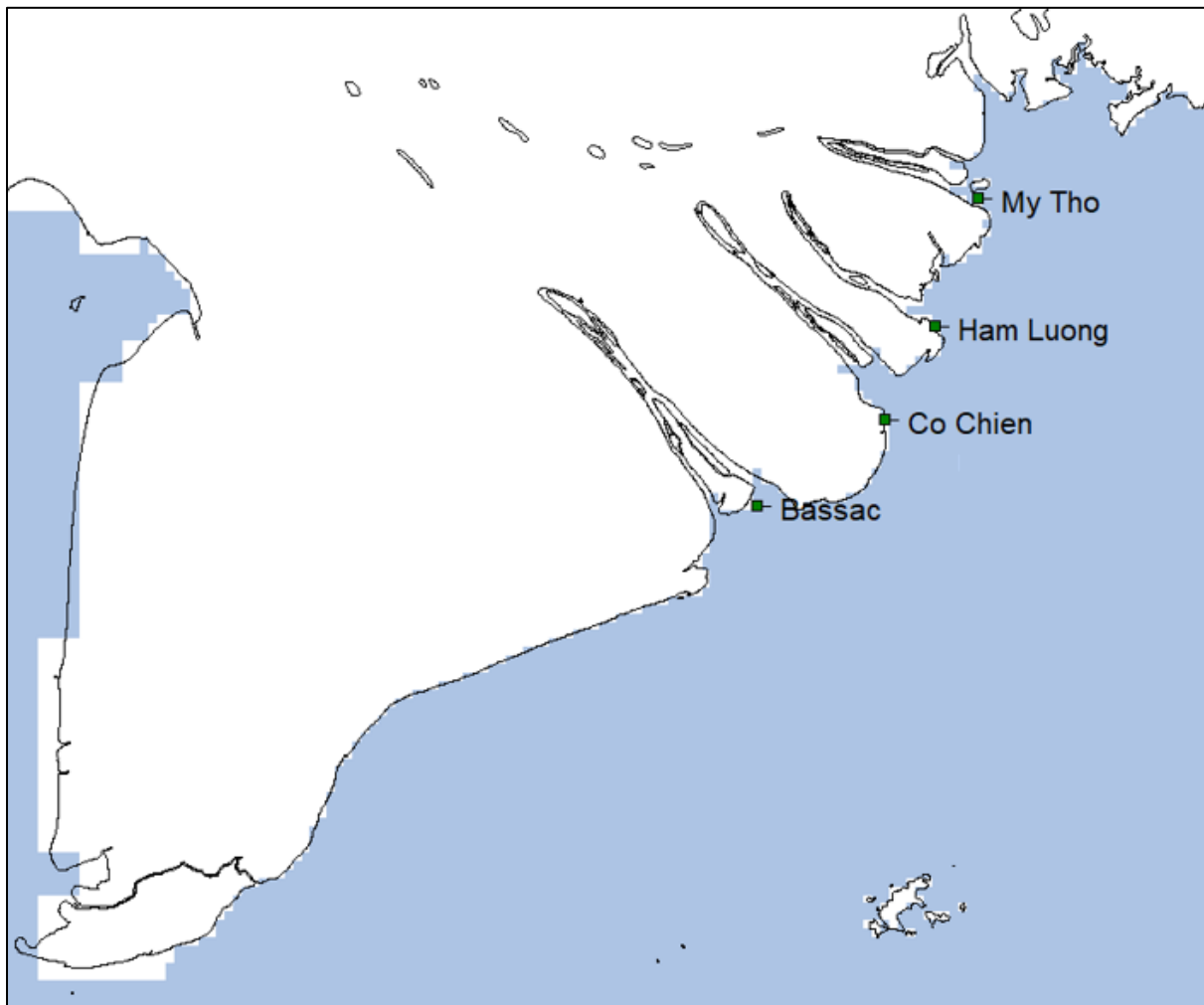
**Figure 3.** Model grid structure. Nested model grid sizes 2 km, 10 km and 50 km.

### 3.3. Model boundary values

Model boundary values drive flows, waves, salinity and sediments in the model. The most critical factors are Mekong river inputs as well as open boundary tidal water levels. As the study focuses on upstream development impacts on the coast, following approach has been adopted for the Mekong discharge and loads:

- Discharges and sediment concentrations are obtained from DSF model Kratie results
- Kratie discharges are divided into for Mekong branches with following percentages (see WUP-JICA, 2004), **Figure 4**:
  - Bassac 50%
  - Co Chien 28%
  - Ham Luong 16 %
  - Cua Dai (My Tho) 6%,

Tidal forcing has been estimated on the Northern boundary from water level monitoring data in Davao and on the Southern border from in Singapore.



**Figure 4.** Mekong branch boundaries in the model.



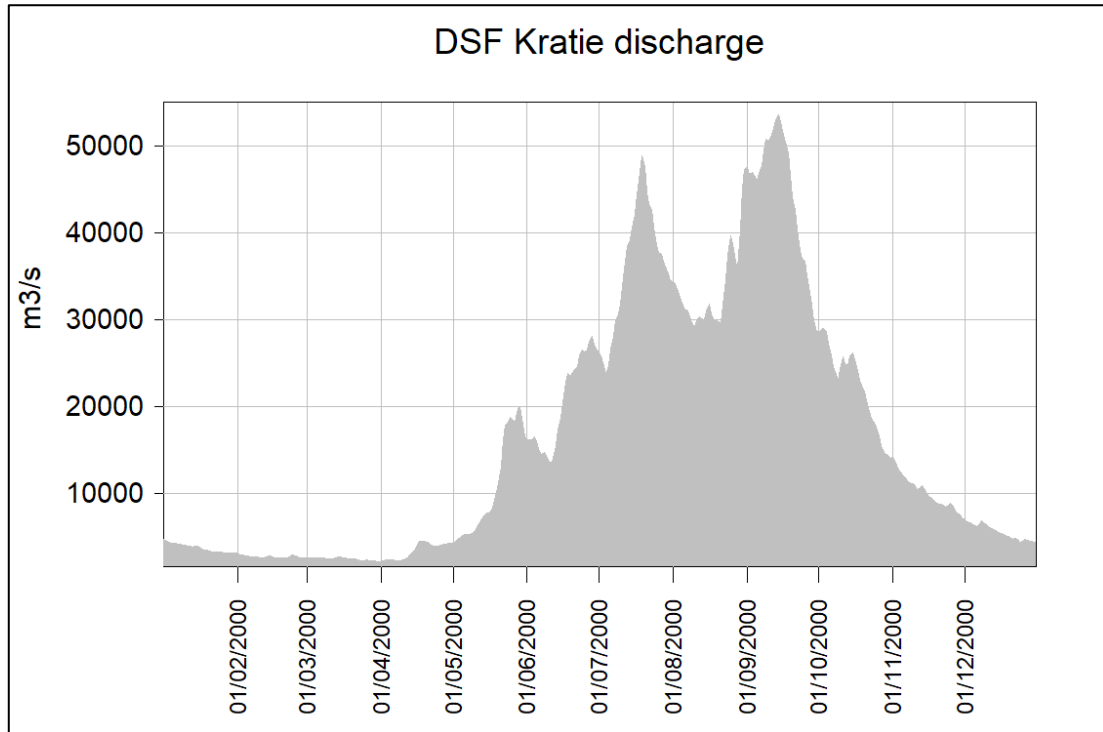
The tidal boundaries can be obtained from number of sources, for instance from SODA5,6 (Simple Ocean Data Assimilation), ECCO7 (Estimating the Circulation and Climate of the Ocean), NCEP-GODAS8 (Global Ocean Data Assimilation System), HYCOM9 (Hybrid Coordinate Ocean Model) and CORA (China Ocean Reanalysis). REDOS seems to be currently the best available dataset: "Here we present a 19-year (1992–2010) high-resolution ocean reanalysis dataset of the upper ocean in the South China Sea (SCS) produced from an ocean data assimilation system. A wide variety of observations, including in-situ temperature/salinity profiles, ship-measured and satellite-derived sea surface temperatures, and sea surface height anomalies from satellite altimetry, are assimilated into the outputs of an ocean general circulation model using a multi-scale incremental three-dimensional variational data assimilation scheme, yielding a daily high-resolution reanalysis dataset of the SCS. Comparisons between the reanalysis and independent observations support the reliability of the dataset." (Zeng, X. et al., 2014, Scientific Data 1, Article number: 140052). The problem with REDOS is that it is available as daily fields and extraction of data for modelling purposes is challenging. The open boundary data will be implemented in the future if sufficient resources for the work become available.

Tidal information is available from global observation system (GLOSS) and MIKE 21 Global Tide model. Global Tide Model is available in  $0.125^\circ \times 0.125^\circ$  resolution. The model includes the following 10 constituents: Semidiurnal: M2, S2, K2, N2 - Diurnal: S1, K1, O1, P1, Q1 - Shallow water: M4.

Similarly to the open boundary ocean values, wind fields can be obtained from reanalysis data such as ECMWF ERA data. Here coastal Ba Tri station winds have been used for the whole sea area (**Figure 10**). It should be observed that this corresponds poorly to real wind fields over the area.

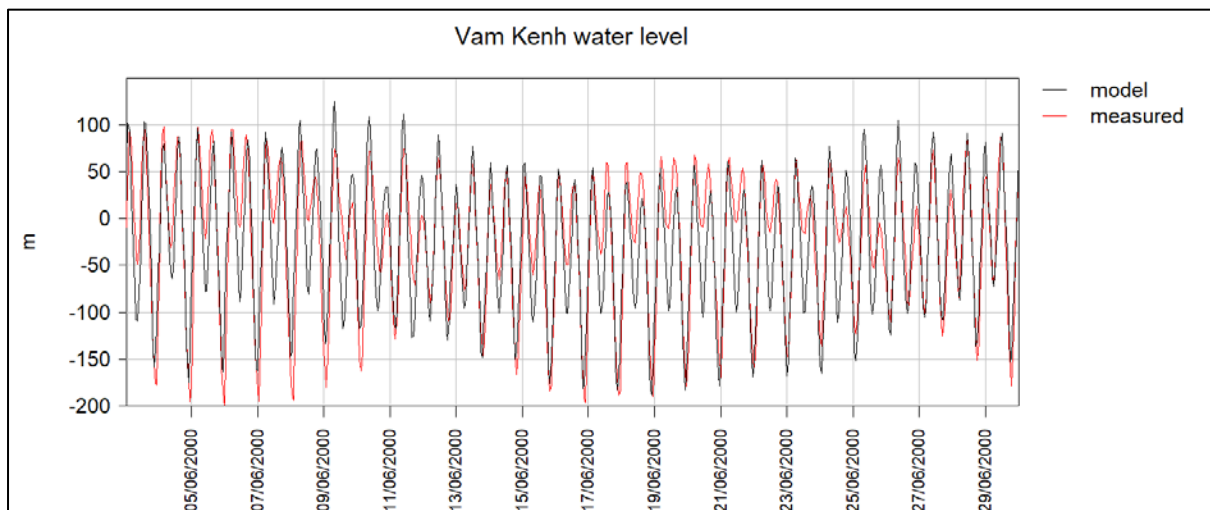
## 4. Coastal flow conditions

The selected simulation period June – September 2000 represents 80% of the whole year sediment load to the Delta (**Figure 5**).



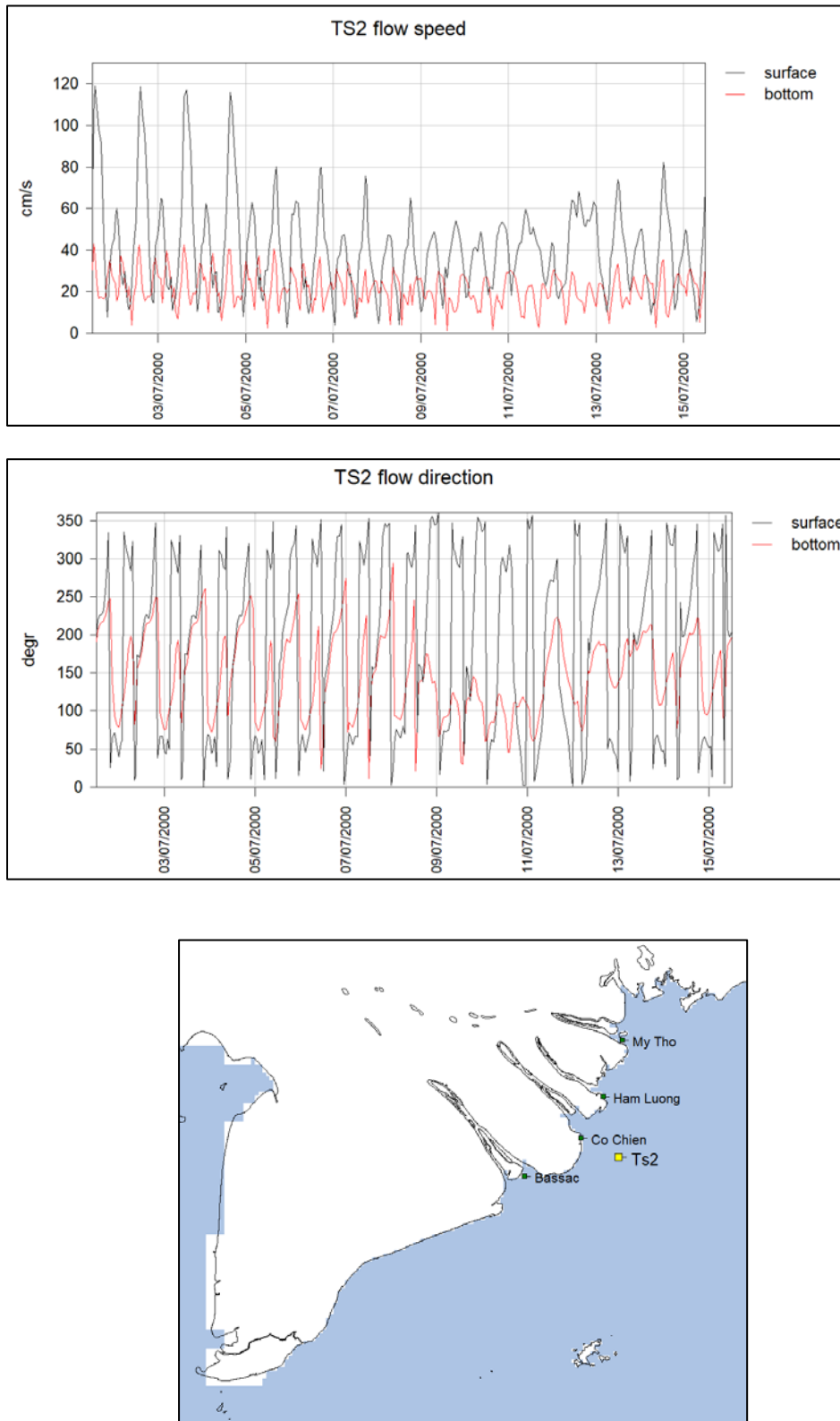
**Figure 5.** DSF computed discharge in Kratie for the year 2000.

Tidal forcing has the largest impact on flows on the Mekong coast. Model represents tide dominated water levels relatively well despite the approximate character of the tidal open boundary values (**Figure 6**).



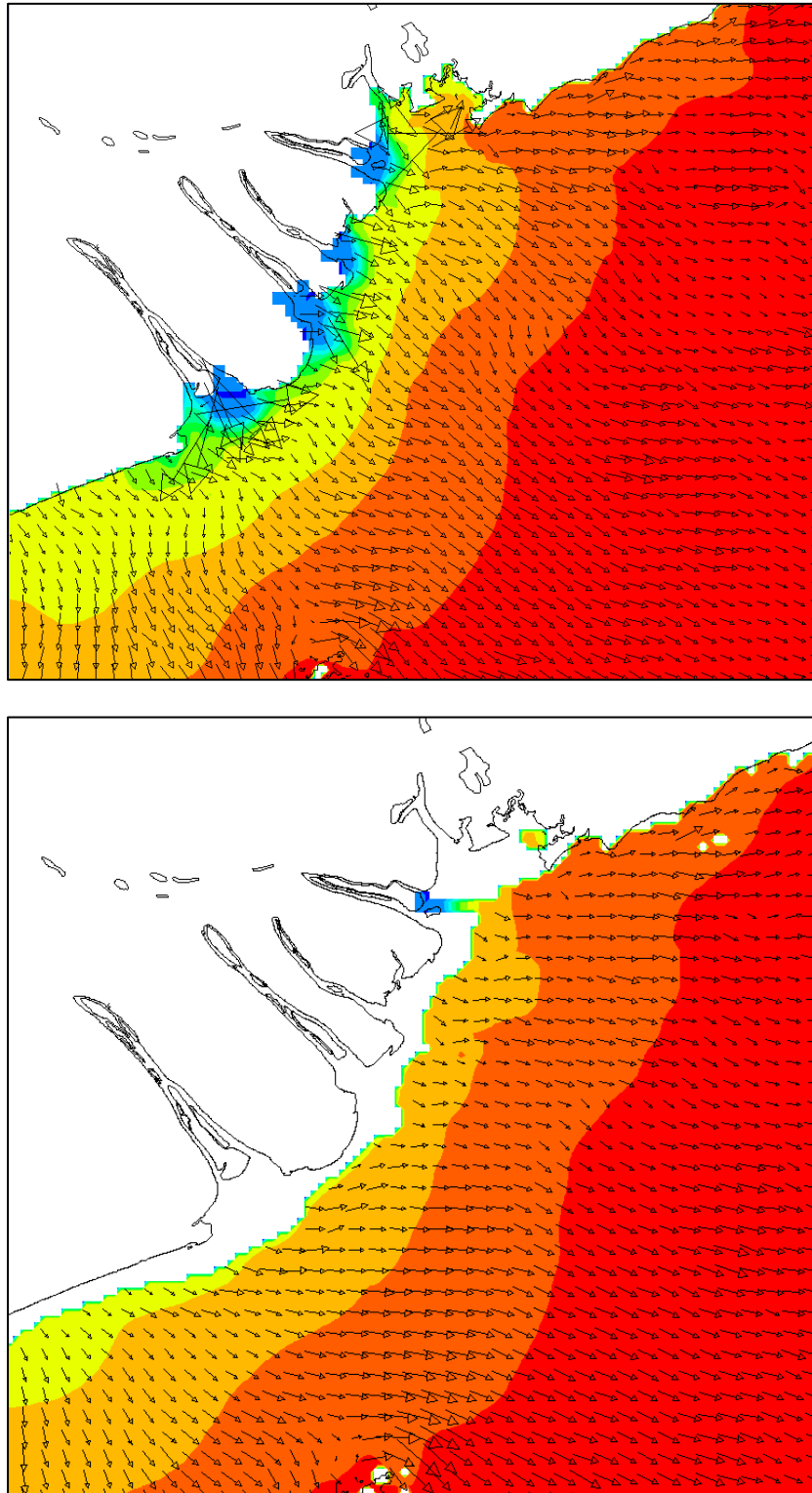
**Figure 6.** Measured and modelled water levels at Vam Kenh near Tan Tieu River Mouth ("My Tho" in **Figure 4**).

The strong impact of tidal forcing can be observed clearly from **Figure 7** where flow speed and direction vary diurnally.



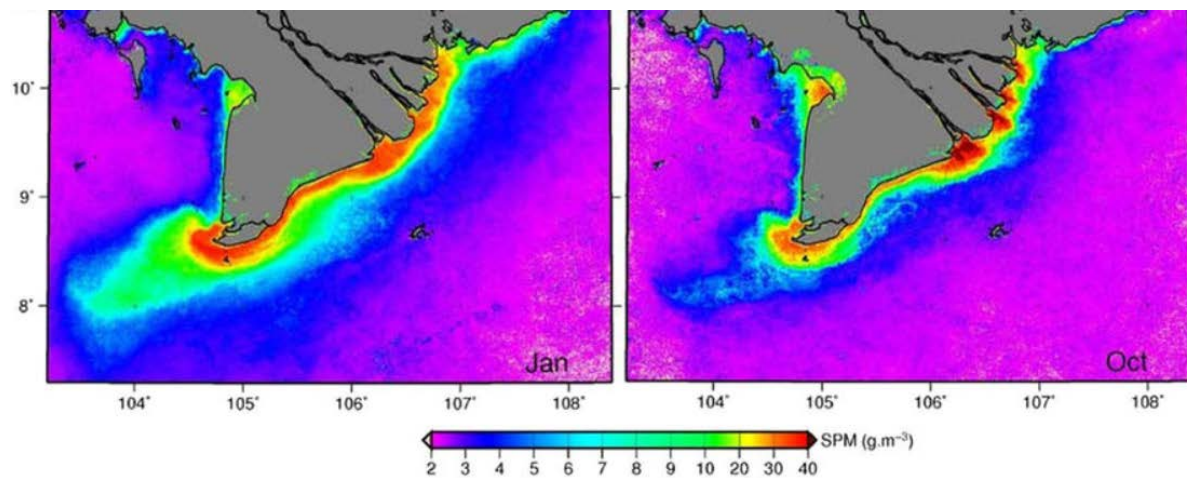
**Figure 7.** Flow speed and direction near Co Chien (location TS2 in the figure).

Near-coast flow field during ebb (receding tide) is shown in **Figure 8**.



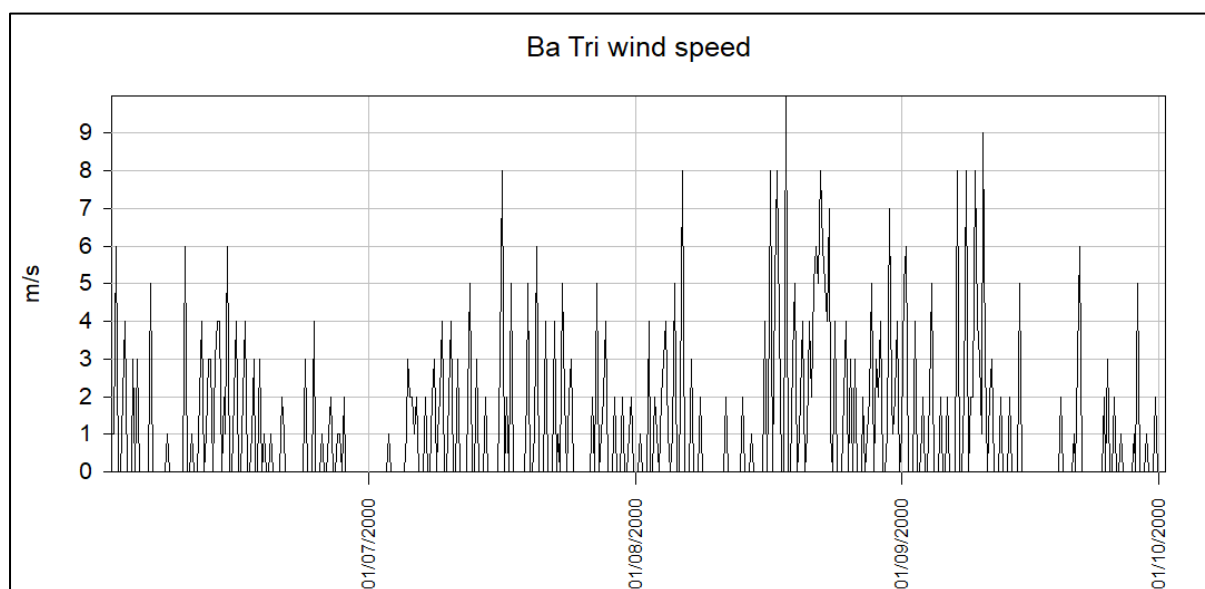
**Figure 8.** Flow and salinity on the surface (upper figure) and 4 m depth (lower figure) during ebb (receding tide).

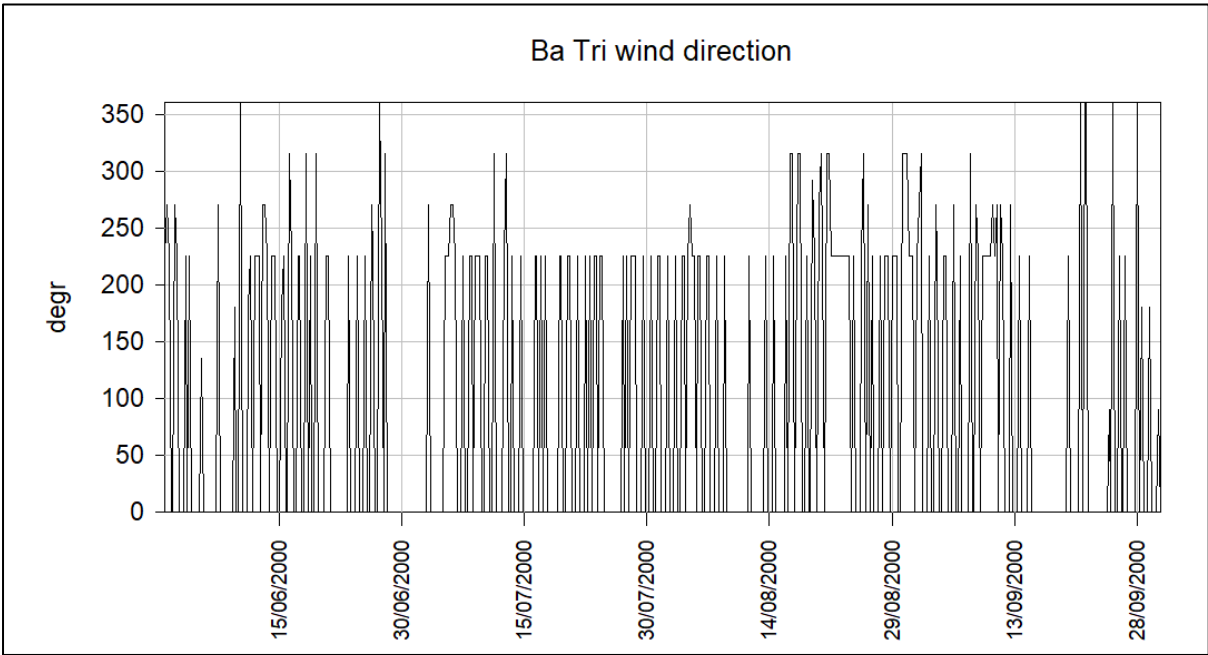
The prevailing wind modifies flow and transport depending on the season as can be seen in. In January prevailing winds are from North-East direction and October from South-West direction.



**Figure 9.** ENVISAT estimated Suspended Particulate Matter (SPM) in January (left) and October (right) (Anthony et. al. 2015)

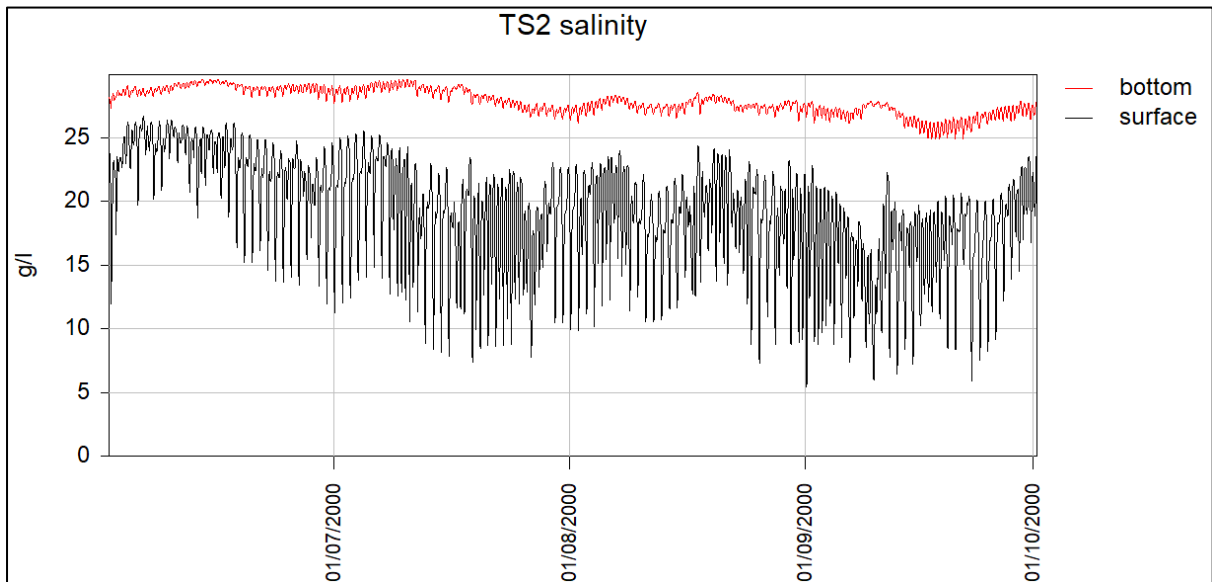
The coastal wind used in the model has prevailing SW direction during the simulation period (**Figure 10**).





**Figure 10.** Coastal wind speed and direction.

The flow is clearly stratified near the coast as can be observed from the salinity near the surface and bottom in **Figure 11**.



**Figure 11.** Computed salinity near Co Chien.

The stratification dampens viscosity as it is evidenced by the near-surface turbulent viscosity values in **Figure 12**.

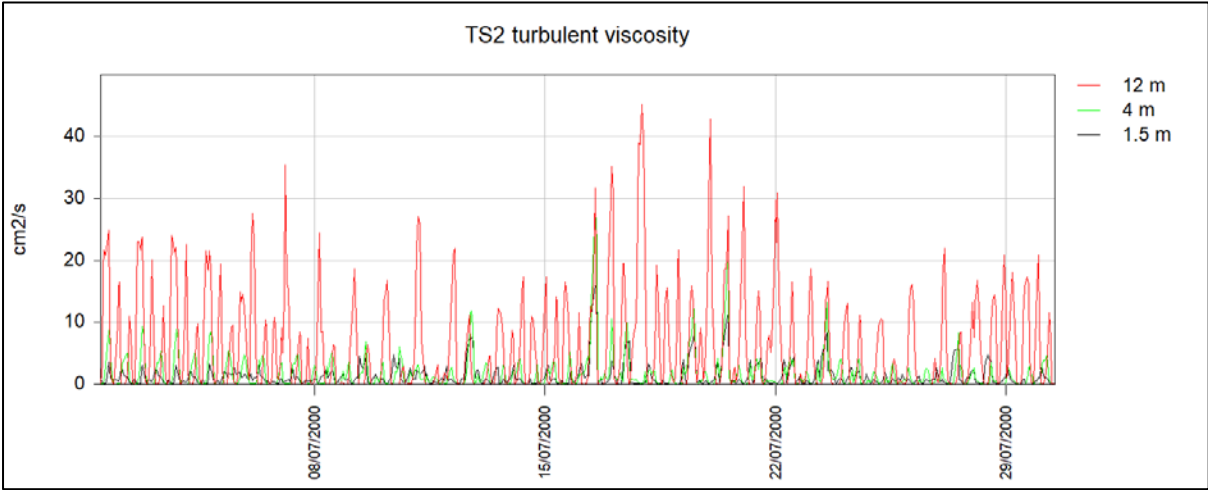
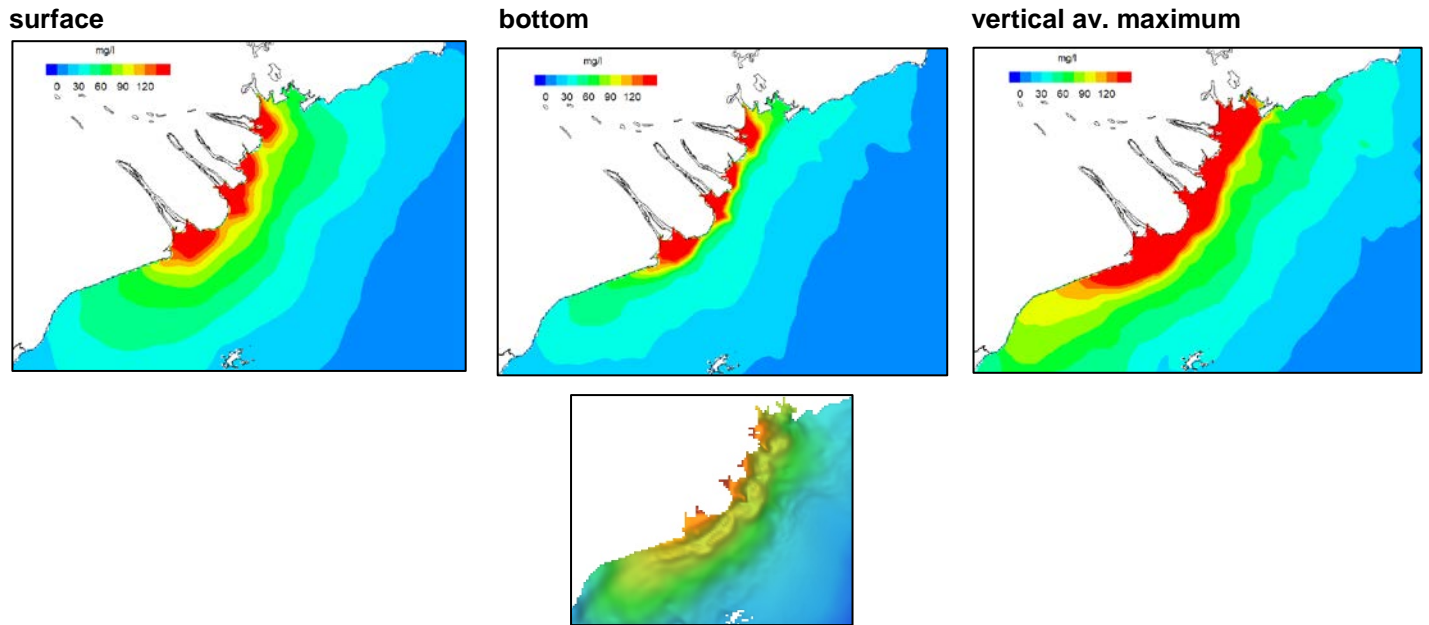


Figure 12. Computed turbulent viscosity in TS2.

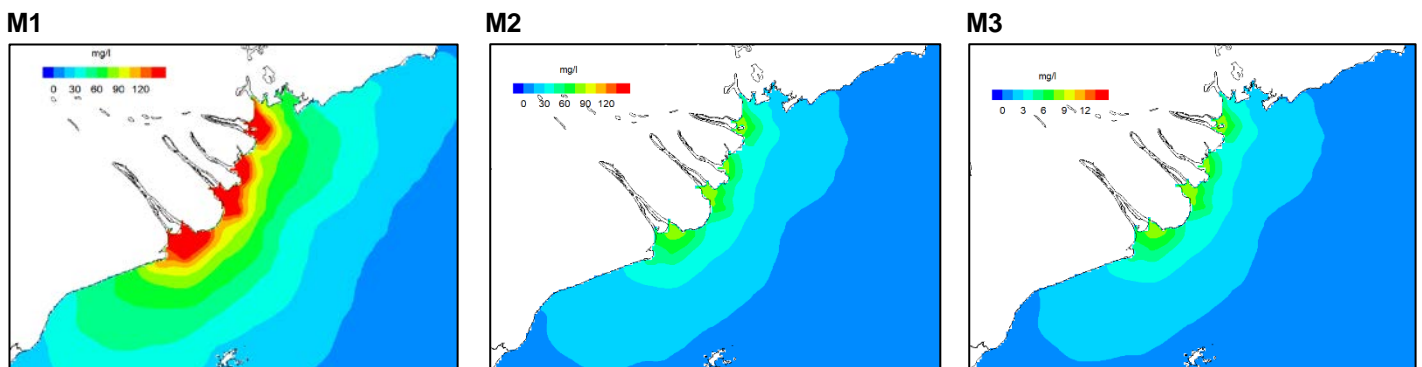
## 5. Coastal sediment transport, deposition and erosion

Figure 13 shows sediment concentrations on the surface and bottom as well as vertical average concentration maximum for the simulation period. It should be noted that these are averages so any given time concentrations may differ significantly from the average figures such as shown in the bottom row in the figure. It should be noted that computed concentrations show *contribution of sediments from the upper part of the Mekong upstream Kratie only!*



**Figure 13.** Modelled sediment transport. Surface (upper row left), bottom (upper row middle) and vertical average maximum concentrations for the computation period June – September 2000. Lower row shows transport snapshot end part of September.

Sediment trapping in the future development scenarios can collapse the concentrations (**Figure 14**). It needs to be emphasized that contributions from Cambodian floodplains and well as Delta need to be added to show total concentrations as the simulation represents only sediments from upstream Kratie.



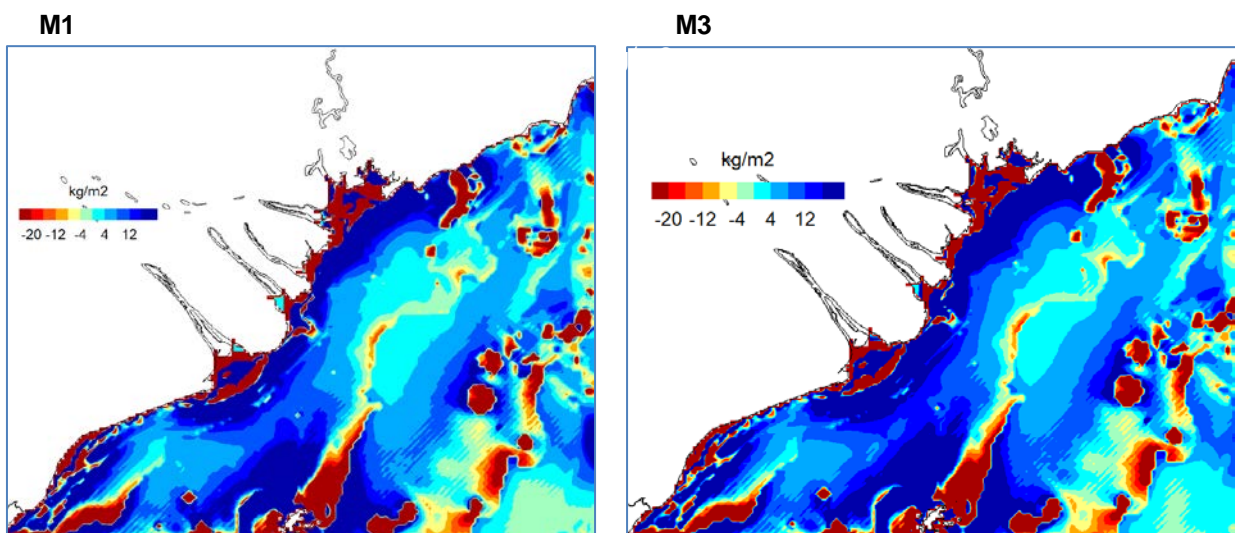
**Figure 14.** Modelled sediment transport. M1 (left), M2 (middle) and M3 scenarios (right). Observe order of magnitude smaller concentration in M3 than in M1 and M2.



The erosion model is set up for sea bed erosion only and excludes shore erosion due to breaking waves (this module is available for possible later study). As no model calibration has been conducted and the sediment transport doesn't include coarse fractions, the results are indicative only. Wealth of sediment and morphological monitoring results exists from the Mekong coast that can be used in the future to calibrate and verify the mode. An important constrain is also that the computation has been conducted for one month only but this obviously doesn't describe the long term evolution of the bottom and shore.

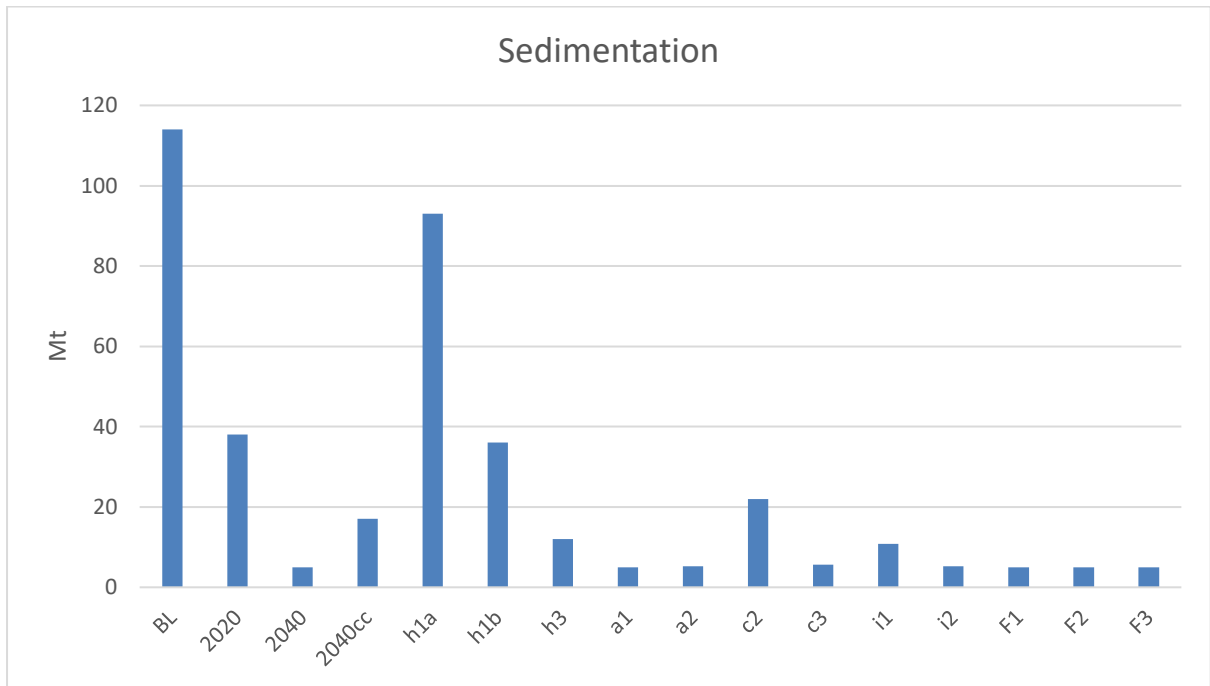
Net erosion taking into account sediment transport and deposition (settling) has been computed for silt sediment fraction. The threshold bottom shear velocity for erosion has been set to 35 cm/s. For fully consolidated sediments this is too low but is appropriate for loose sediments.

**Figure 15s** show deposition and erosion differences between baseline (M1) and 2040 (M3). Figure reveals hardly any differences in the erosion areas (brown and yellow) between the scenarios. On the other hand deposition (blue areas) is affected to some extent by the sediment trapping of the M3 scenario.



**Figure 15.** Deposition (blue colours) vs. erosion (warm colours) in M1 and M3 scenarios.

**Figure 16** shows estimated Mekong upstream Kratie annual silt contribution to coastal net sedimentation in the different scenarios. The estimates follow Kratie sediment loads because these are driving also the coastal loads.

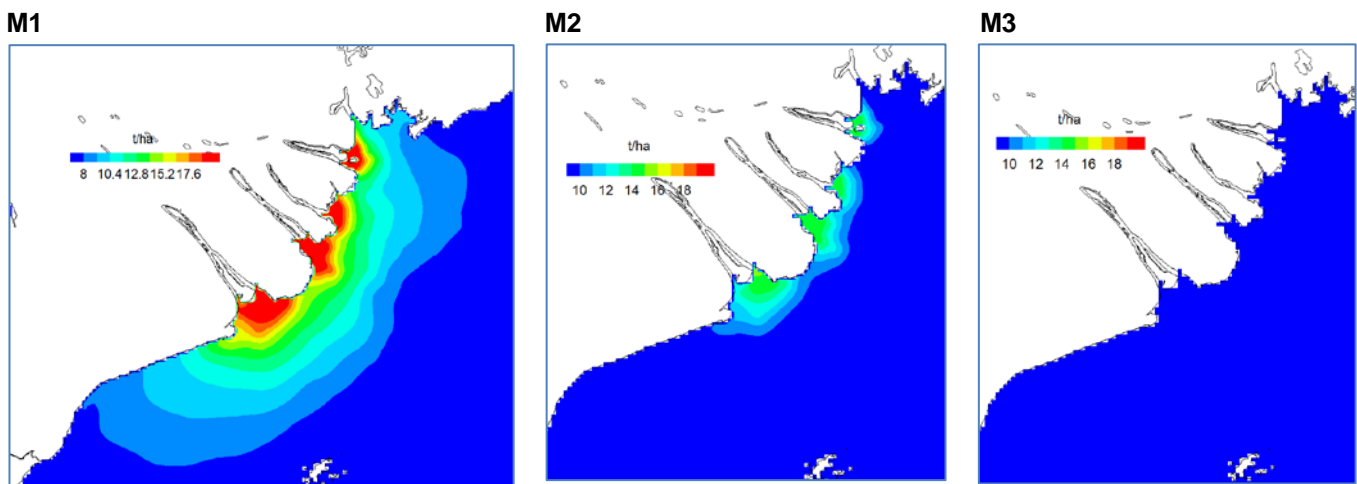


**Figure 16.** Estimated Mekong upstream Kratie annual silt contribution to coastal net sedimentation for the different scenarios.

## 6. Coastal fisheries production

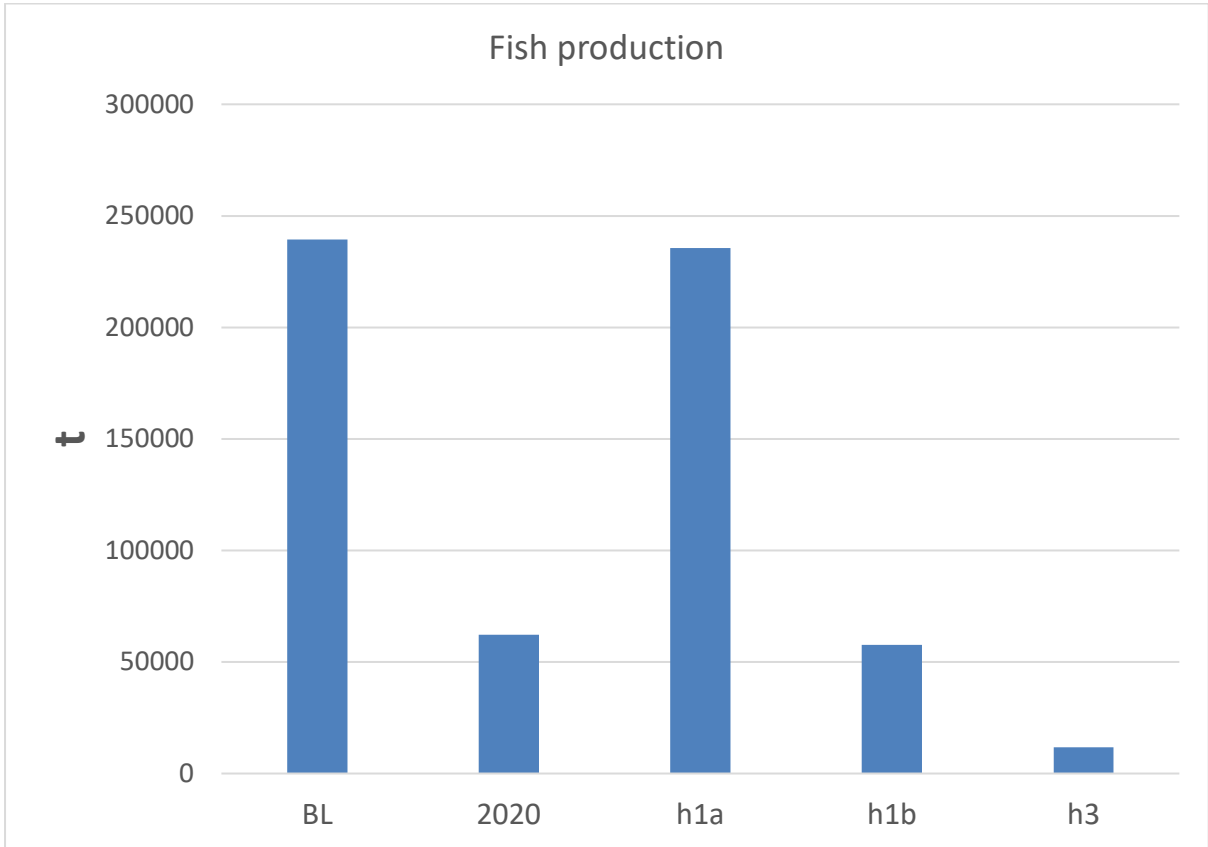
Similar to Tonle Sap 3D primary production and fisheries modelling, alluvium (sediments, organic material and nutrients) drives production in the coastal model. The relations are based on empirical data as well as physiological modelling (see WUP-FIN modelling report for further information).

**Figure 17** shows simulated annual production. It needs to be emphasized that total production is in reality larger because of large nutrient inputs from Cambodia and especially from Delta agriculture, industries and communities and also because of a sea area base production not dependent directly on the Mekong inflow.

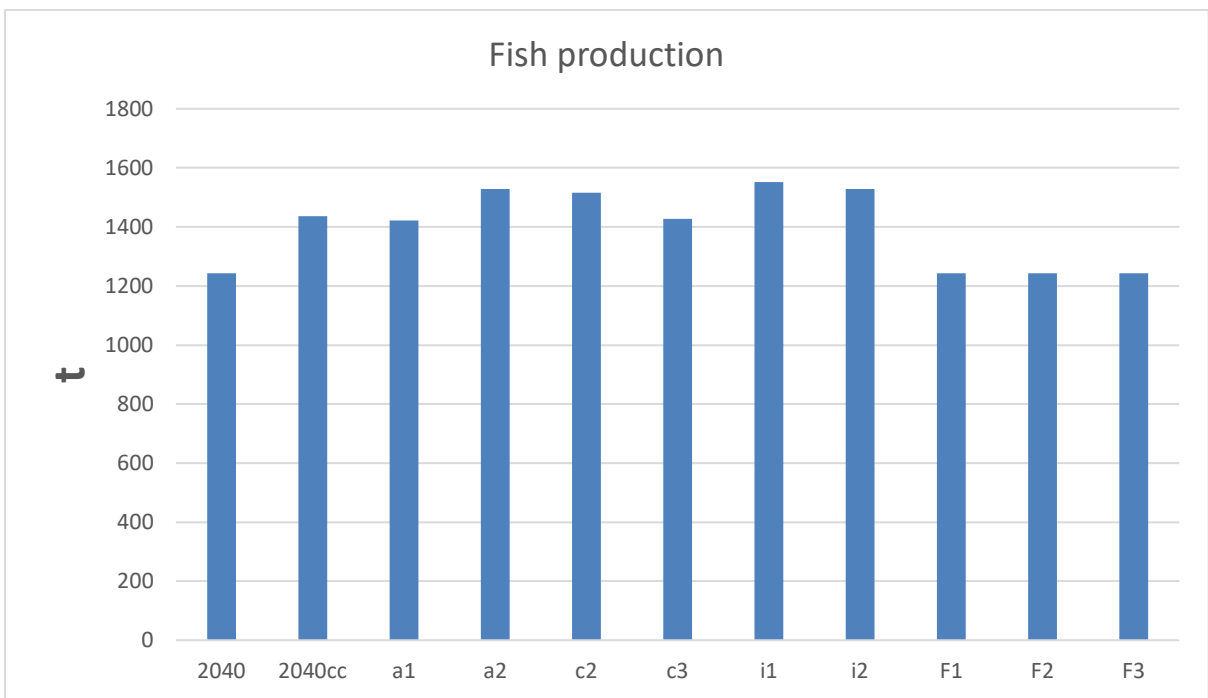


**Figure 17.** Modelled fisheries annual production. M1 (left), M2 (middle) and M3 (right) scenarios.

Mekong plume annual fish production for the scenarios is shown in **Figure 18** and **Figure 19**. The production is calculated for the upstream Kratie contribution only. Criteria for the plume is over 5 mg/l average silt concentration. In the baseline estimated total production in the plume is about 240'000 t. In the scenarios 2020 (M2) and H1b the production is reduced to about 60'000 t. In scenario H3 the production is reduced further to about 10'000 t. H1a (no dams in 2040) scenario maintains production on the baseline level. Scenarios 2040 (M3), 2040CC (M3CC), A1, A2, C2, C3, I1, I2, F1, F2 and F3 only 1200 t – 1600 t annual production.

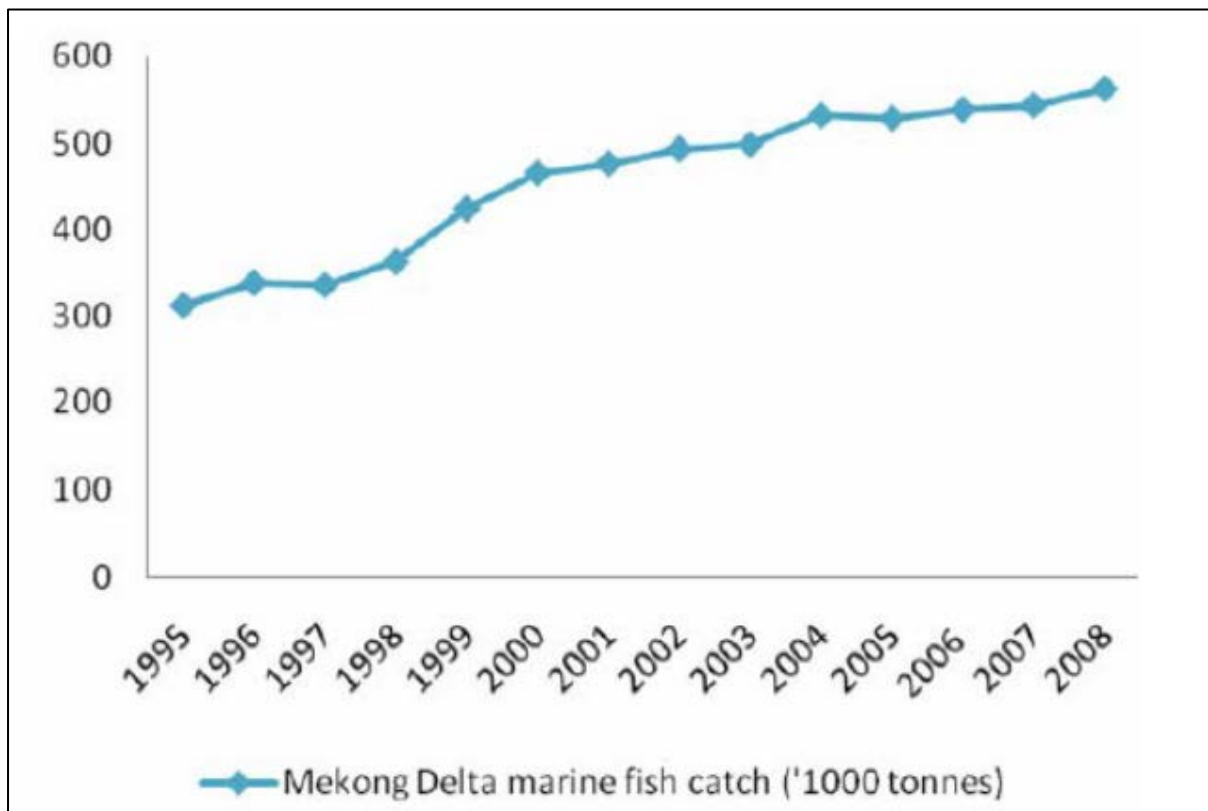


**Figure 18.** Modelled fisheries annual production for the Mekong plume for the scenarios BL, 2020, H1A, H1B and H3. Only upstream Kratie contribution shown.



**Figure 19.** Modelled fisheries annual production for the Mekong plume for the scenarios 2040 (M3), 2040CC (M3CC), A1, A2, C2, C3, I1, I2, F1, F2 and F3. Only upstream Kratie contribution shown.

The modelled 240'000 t upstream Kratie contribution to the fisheries production can be compared with the estimated Mekong marine annual fish catch 5000'0000 – 762'000 t (**Figure 20**). The value 240'000 t is plausible because it is computed only for the immediate Mekong plume and doesn't include contributions by the Cambodian and Vietnamese nutrients and surrounding sea area.



**Figure 20.** Estimated annual Mekong marine fish catch (ICEM MRC SEA report 2010).

## 7. Modelling limitations, initial findings and direction for future work

The Council Study has created a fully integrated assessment framework from bio-geo-physical characteristics of the Mekong Basin reaching up to the policy level. The assessment methodology is *evidence based and quantitative* as the large economic, social and environmental values of the Mekong development require a solid information basis. The assessment methodology is fully integrated as data and modelling are directly feeding into social, economic and environmental indicators and assessment and these in turn into the Thematic sectors. Other strong point of the Council Study is its thorough analysis of monitoring data, especially sediments and water quality, that has not been

executed before. At the same time there are limitations involved with the study that stem from lacking data and broad scope of the exercise which constraints how far modelling have been implemented.

It has not been possible to execute the coastal component in the original planned extent. Consequently the coastal modelling has focused on demonstrating feasibility and approach of coastal assessment and achieving indicative initial impact assessment results. The coastal study has established full South Sea 3D hydrodynamic model with high resolution Mekong coastal grid and full physics (stratification, turbulence, waves, tides, wind driven circulation etc.). The hydrodynamic model has been calibrated and verified initially with tidal monitoring data from the Mekong coast. Sediment, erosion and fisheries productivity modules have been coupled with the hydrodynamic model but it has been impossible to calibrate or verify these due to lack of data and resources. Specific constraints are listed below to guide possible further studies.

The main limitations and constraints for the **data** can be summarized as:

- No coastal data for suspended solids, nutrients, water temperature and salinity have been available;
- No detailed data on bottom topography and sediment composition have been available; for instance cohesive sediments and relation between coarse and fine sediments need to be studied;
- No data on actual erosion and deposition bottoms and shores has been available;
- Kratie sediment inflow has been used for the coastal sediment load; after further verification of the ISIS sediment results they should be used instead;
- No reliable data on sand mining has been available;
- Bottom load data on coarser sediments is lacking;
- The boundary tidal data is very limited; large scale oceanic modelling results should be utilized to obtain better data;
- No data on primary and fisheries productivity have been available;
- Wind data should be extended to the open sea (re-analysis data).

The main limitations and constraints for the **modelling** are:

- Simulation times are not enough for assessing long-term bottom development – 10 year simulation would take approximately 60 hours of computer time;
- Sediment, erosion and fisheries modules need to be calibrated and verified;
- Hydrodynamic model needs to be verified further with salinity, sediment or other “tracer”, temperature and flow monitoring data;
- Cohesive sediment model needs to be applied;
- Estuaries sediment dynamics is quite complicated and has consequences on the coastal conditions; this needs to be studied in the future.

Due to the demonstrative and indicative nature of the coastal study, it is not feasible to provide **policy messages** as these should be based on robustly proven and verified modelling results. The key initial findings that can be used as a basis for discussion are:

- In the short run increased erosion due to sediment trapping and decreased loads doesn't seem to be an issue. However, in the long run situation may be very different and justifies further study.

- Impacts of nutrient and sediment trapping on primary and fisheries production can be substantial but are mitigated with local Delta conditions (local loads). Further studies are necessary to establish reliably the extent of fisheries losses.

# 1. Annex 1 – Estuarine modeling

## 1.1. Application area and background

The Tieu River mouth serves as an example for estuarine processes. It is one of the main water way of the Mekong River and because the expansion of the river when it meets the sea results in increased sedimentation. The modelling aims at understanding physics of saline intrusion and role of dredging versus sea level rise increasing it.

Model computation is quite time consuming because it is necessary to execute simulations with high resolution, with small time step and including full set of physical processes such as stratification and turbulence. The temporal scales of the model application reach from a few days to a few months.

The model parameters are:

- 1) flow related physical parameters (3D flow, water depth, flooding)
- 2) salinity
- 3) sediment concentration, sedimentation and bed erosion
- 4) passive tracer indicating transport and dispersion of pollutants.

In this ANNEX only salinity results are presented. The presentation is based on earlier MRC modelling work.

## 1.2. Model set-up

Scope of the Tie River mouth application is shown in Figure 21. Model covers about 63 km of the river and 12 km of the coastal sea area.

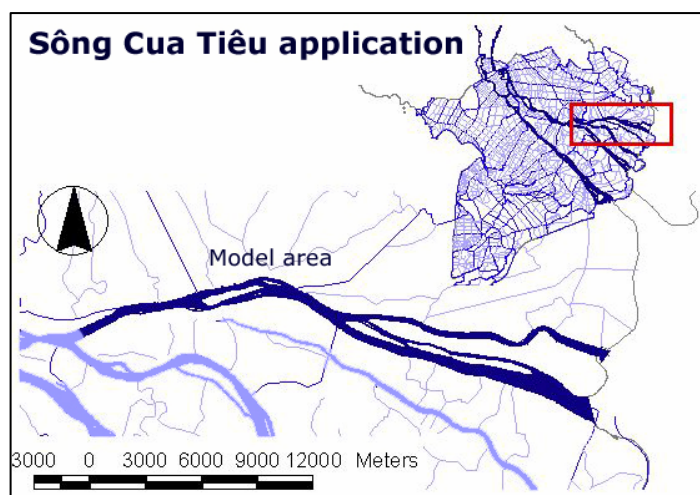


Figure 21. Tieu River mouth model area. Model includes the river stretch shown in dark blue + coastal areas until about 12 km offshore.

The floodplain grid is based on the SRTM DEM of 100 m horizontal resolution. The main channel cross-sections are obtained mostly from the Hydrographic Atlas. DSF model cross sections have been utilized for parts where no data exist in the Hydrographical Atlas. The coastal bathymetry has been obtained from the Vietnamese counterpart institutes.



The large extent of the model area compared to required grid resolution is problematic from computation time point of view. The optimum grid size was found to be 100 m. The number of grid cells in the horizontal plane is  $751 \times 250 = 187'750$ . In the vertical there are 10 layers which are 1 - 3 m thick. The thickness of the bottom layer varies depending on the total depth. Altogether there are 1'877'500 3D grid points.

The final model grid setup is shown in Figure 145. Grids were also generated for a larger area with 50 and 100 m resolution, Figure 146. The Large 50 m grid is too big to be run under 32 bit operating systems with their 2 GB limit for a process.

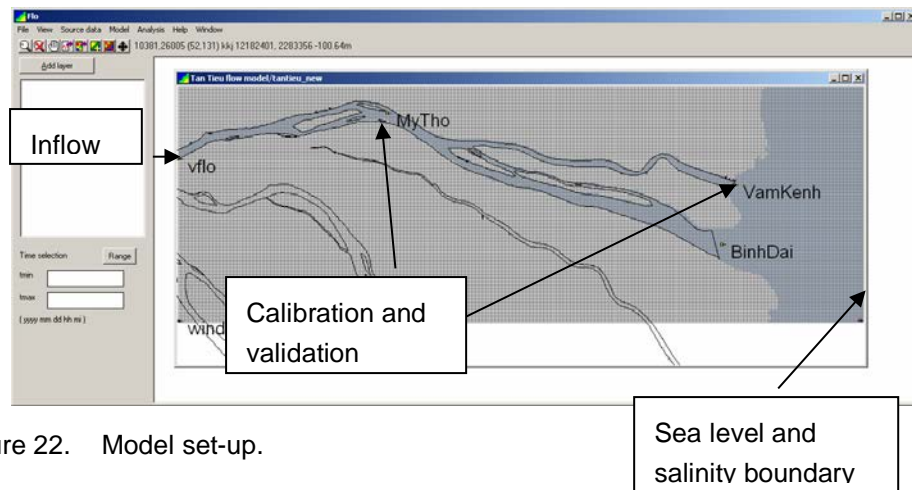


Figure 22. Model set-up.

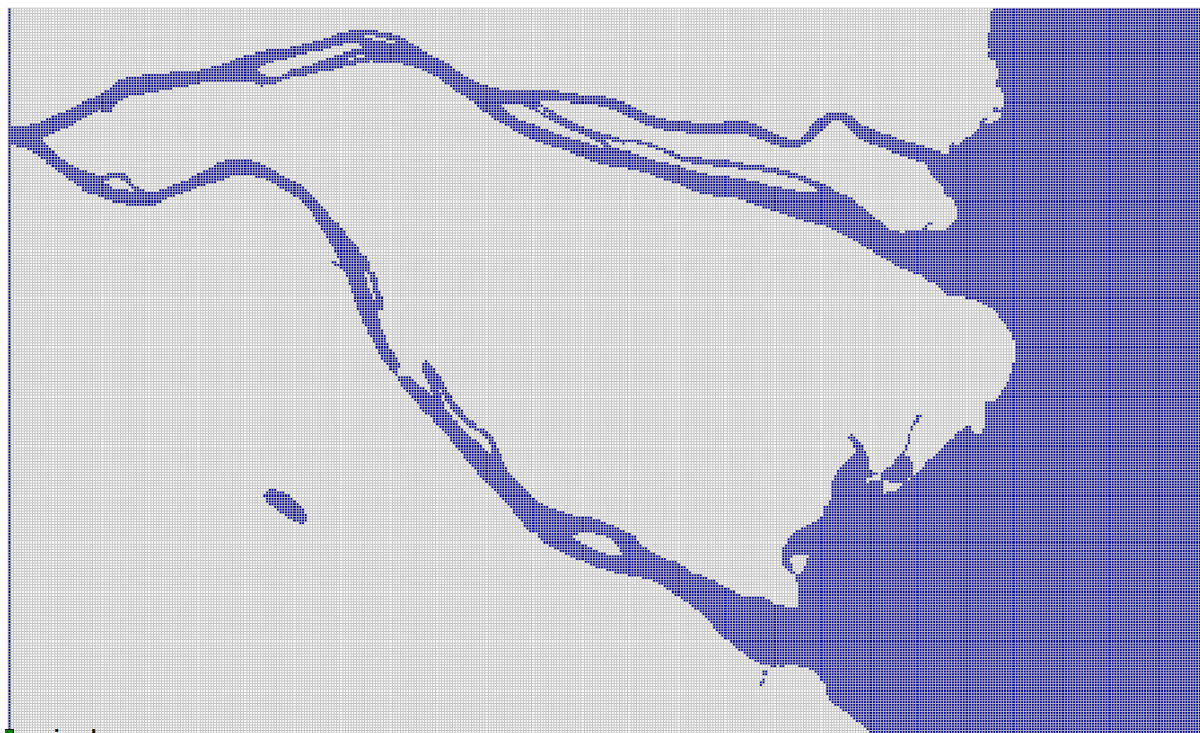


Figure 23. Tieu River Mouth larger model area.

The input data for model application was based on the monitoring data and simulated result from iSIS model, they are:

- Inflow boundary data from 1998 – 2000
- Water level at Vamkinh and Binhdai (1998 – 2000)
- Monitoring data at Vamkinh, Binhdai and Mytho stations (1998-2000)
- Salinity monitoring data at Vamkinh and Binhdai (1998-2000) and at Mytho (Mar to Apr 2000).

### **1.3. Model calibration and validation**

The Tieu River mouth combined a number of processes that are not easily modelled in a physical way. The processes include tide, density (salinity) driven currents, stratification, salinity advection, coastal currents, wind generated currents, tidal forcing and vertical and horizontal current and salinity distributions. A way out would be to use some more or less artificial approximations or parameterizations such as salinity diffusion to simulate salinity intrusion. The disadvantage of using such approach is the loss of realism in scenario runs – one can't be sure if the approximations function well enough in changed situations. The way taken in the current study provides the possibility to study the main river mouth processes in their full extent.

In addition to the physical factors and parameters the calibration of the model has included a number of unknown characteristics of the area. The large number of unknowns has made the calibration very difficult. These difficulties are aggravated by the fact that all model variables have to correspond to the measurements at the same time and different factors affect the variables in different ways. Despite the difficulties the calibration has turned out to be very successful, as can be seen from the results below.

The calibrated factors include:

- bottom friction type and coefficient
- vertical and horizontal viscosity/ turbulence
- upper boundary inflow condition (magnitude)
- outer sea tidal condition (magnitude and timing)
- coastal current
- to some extent the bottom topography especially in the river mouth

The observed vs. simulated water levels during the month of April are presented in Figure 147 and Figure 25. The correlation is very good during the whole simulation period.

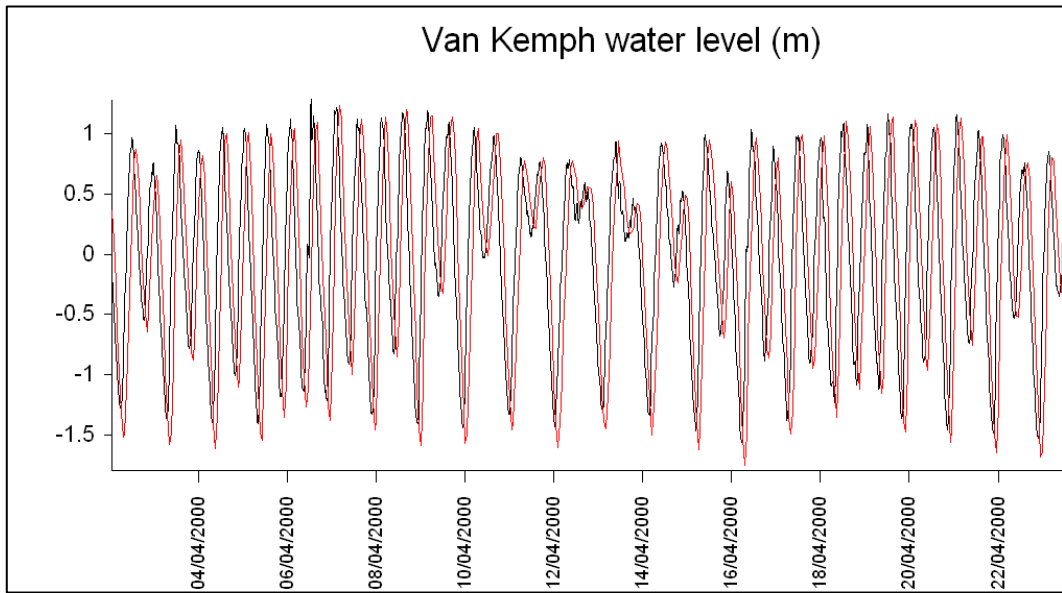


Figure 24. Measured (red) and calculated (black) water levels in Vam Kenh.

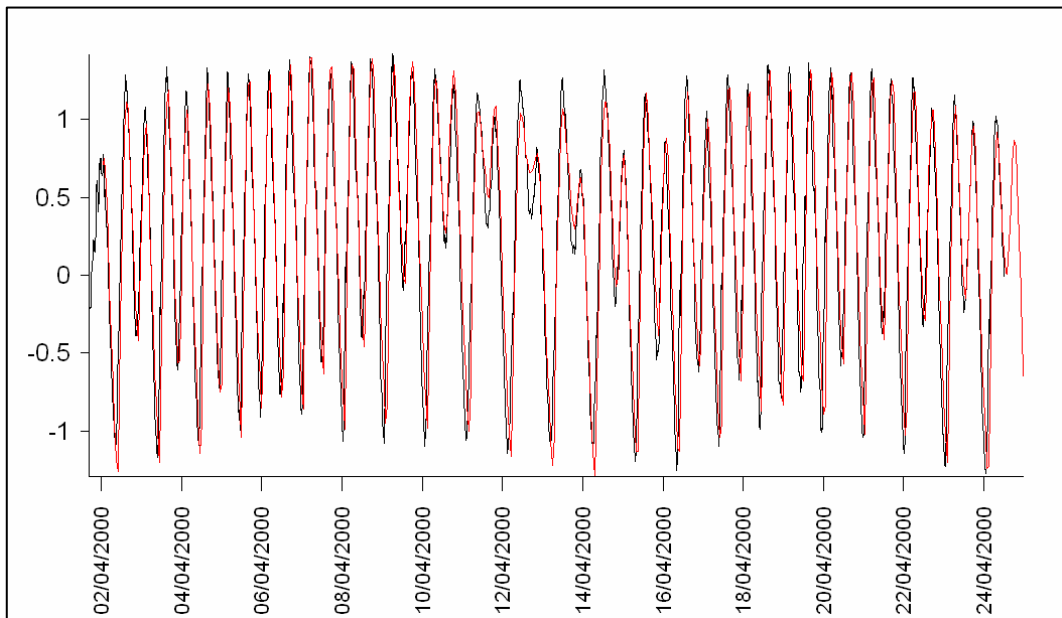


Figure 25. Measured (red) and calculated (black) water levels in My Tho.

The calculated salinity concentrations are presented in Figure 26 and Figure 27 for Vam Kenh and My Tho, respectively. The computed values are very well in the same range than the measured ones. Exact replication of the measured values would require hydrographic survey because the simulated concentrations are very sensitive to the channel and coastal topography.

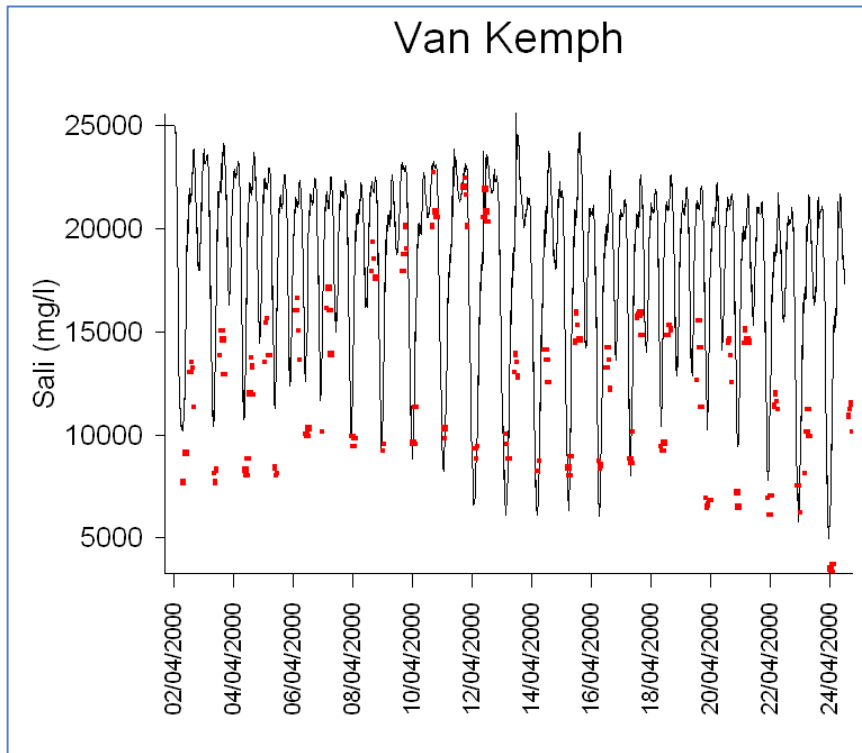


Figure 26. Calculated surface layer salinity in Vam Kenh. Measured values between 8'000 – 23'000 mg/l.

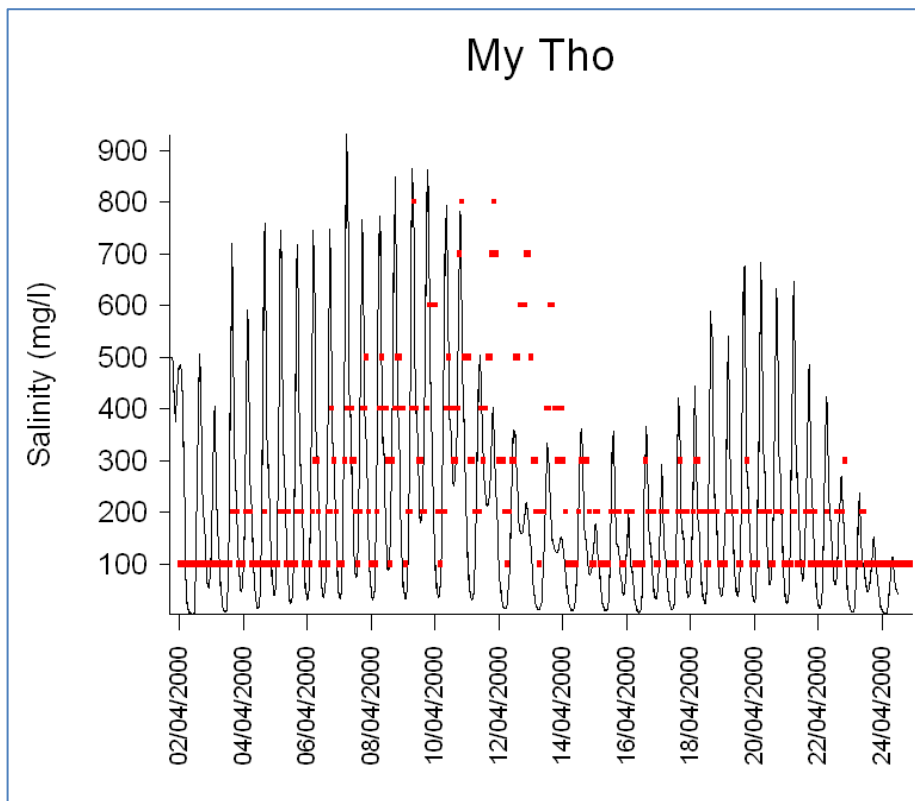


Figure 27. Calculated salinity in My Tho. Measured values between 0 – 800 mg/l.

## 1.4. Scenario simulation

The simulated scenarios are:

- Baseline year 2000
- Excavation scenario: An excavation of 90 m wide and 1 m depth at the river mouth was introduced to allow the normal navigation condition of ships on the river during the dry season.
- Sea water level rise scenario: based on available studies on the impact of sea water level rise, an addition of 10 cm of sea water level rise was assumed and the high development scenario for hydrological condition was combined.

### 1.4.1. Baseline year 2000 scenario

The simulated result for salinity on Baseline year 2000 development condition by time and space was shown on figure 5 to 9

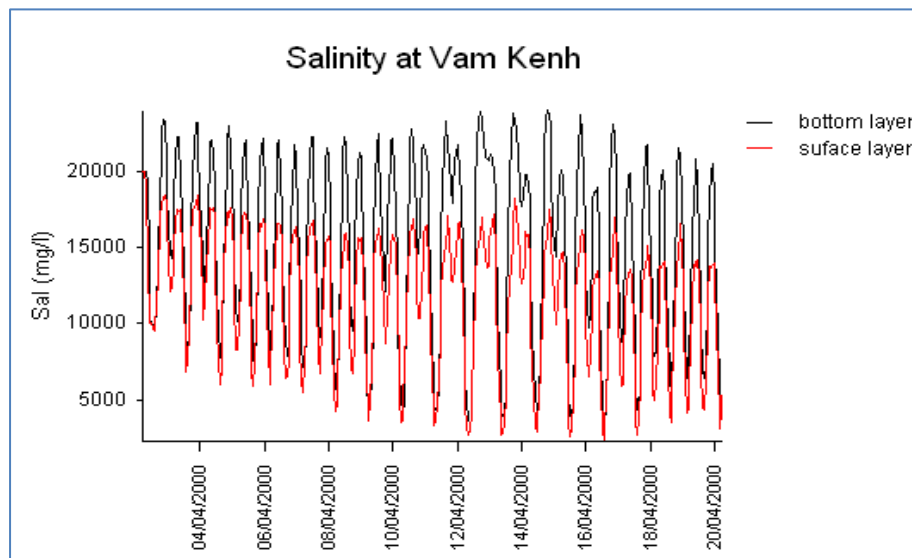


Figure 28. Salinity concentration on the surface and bottom layers at Vam Kenh

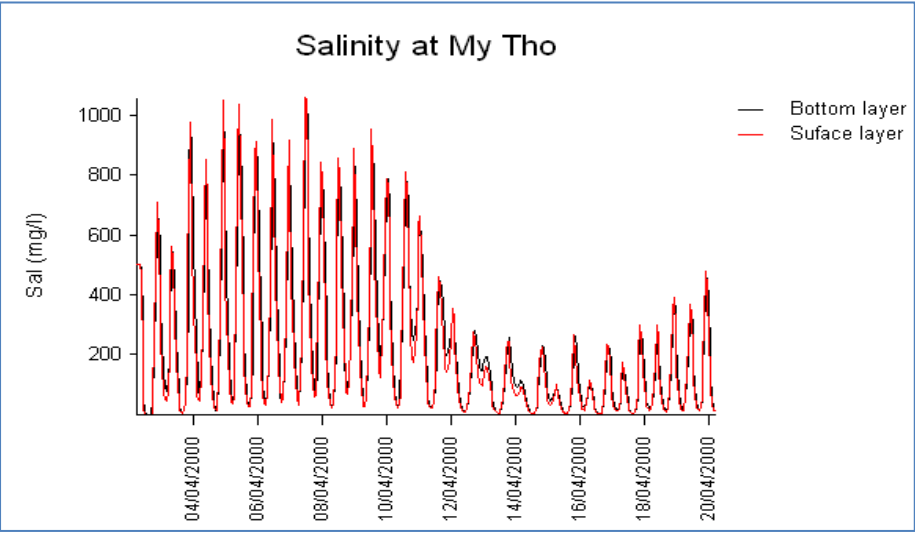


Figure 29. Salinity concentration on the surface and bottom layers at My Tho

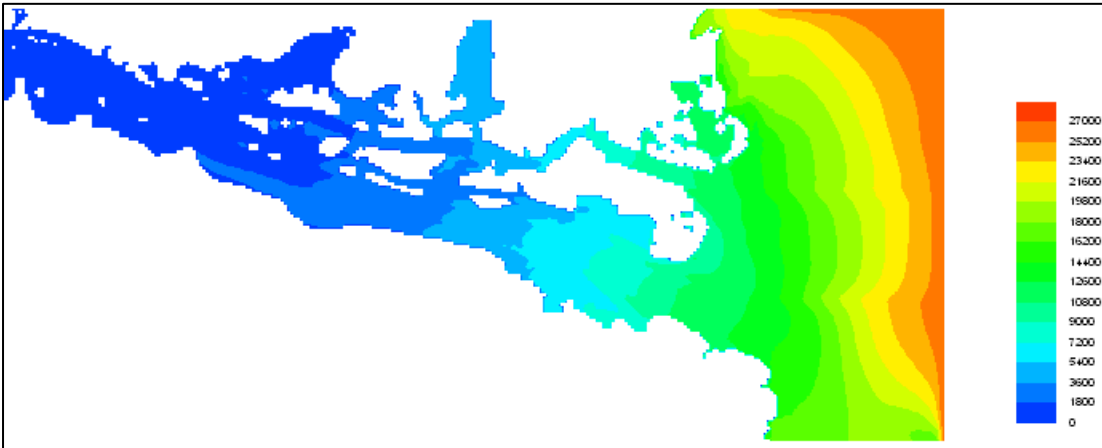


Figure 30. Average of salinity intrusion concentration on the surface layer in April /2000

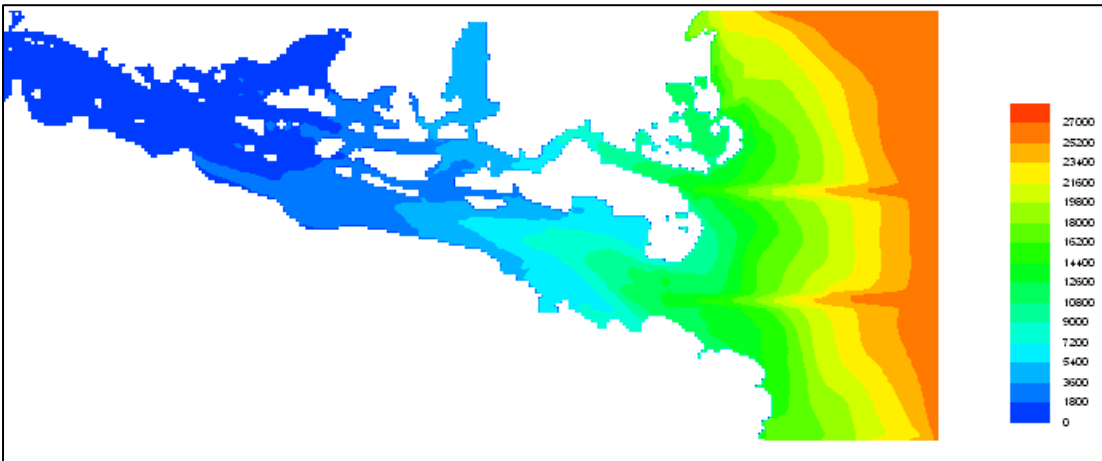


Figure 31. Average of salinity intrusion concentration on the bottom layer in April 2000

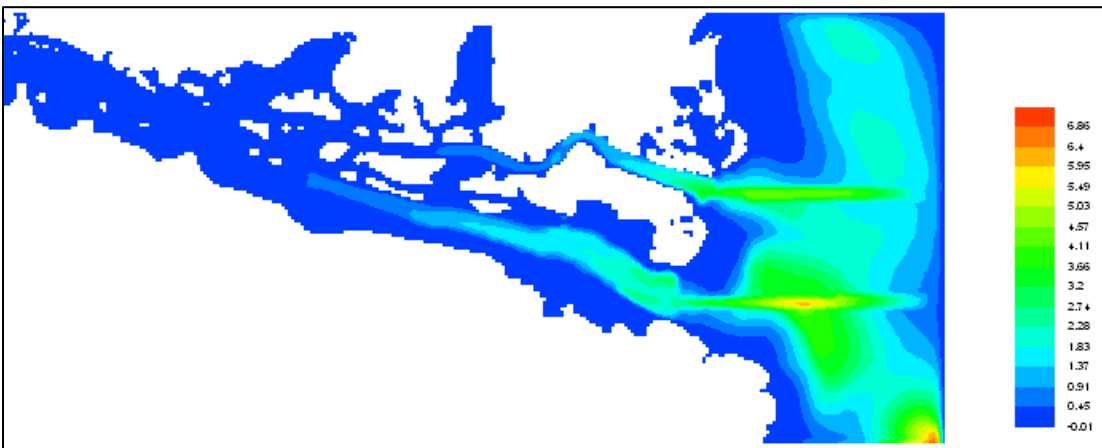


Figure 32. Difference of salinity intrusion concentration on the surface and bottom layers in April /2000

### 1.4.2. Sea water level rise scenario (FR4)

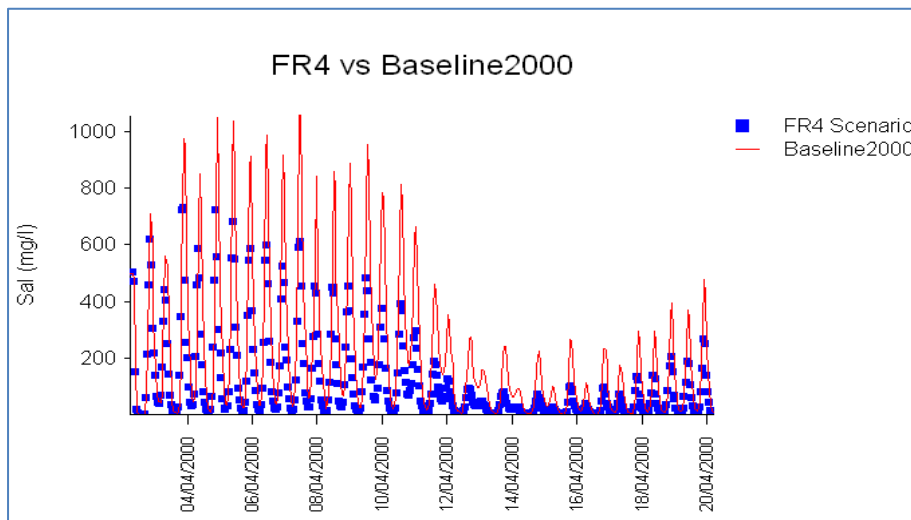


Figure 33. Comparison of salinity concentration (mg/l) in baseline 2000 and sea water level rise scenario in 4/2000 at Mytho

As can be seen from the figure 10, it was found out that salinity intrusion concentration on sea water level rise scenario was reduced in comparison with the Baseline 2000 condition, the maximum salinity concentration at Mytho was 7.3 mg/l compared with 10.2 mg/l in Baseline 2000. The reason for that is: there is additional flow from the upstream into the delta due to the regulation of the Chinese dams. This simulated result was also similar to that of iSIS model simulated results.

### 1.4.3. Dredging scenario

In dredging scenario, the cross-section area of the river at its mouth was increased, and the salinity concentration at the lower layer is also always higher than that of the above layers, therefore salinity water intrudes more to the inland. The simulated result was shown that the maximum salinity concentration at Mytho was 10.8 mg/l in compared with 10.2 mg/l in Baseline scenario (Fig. 10).



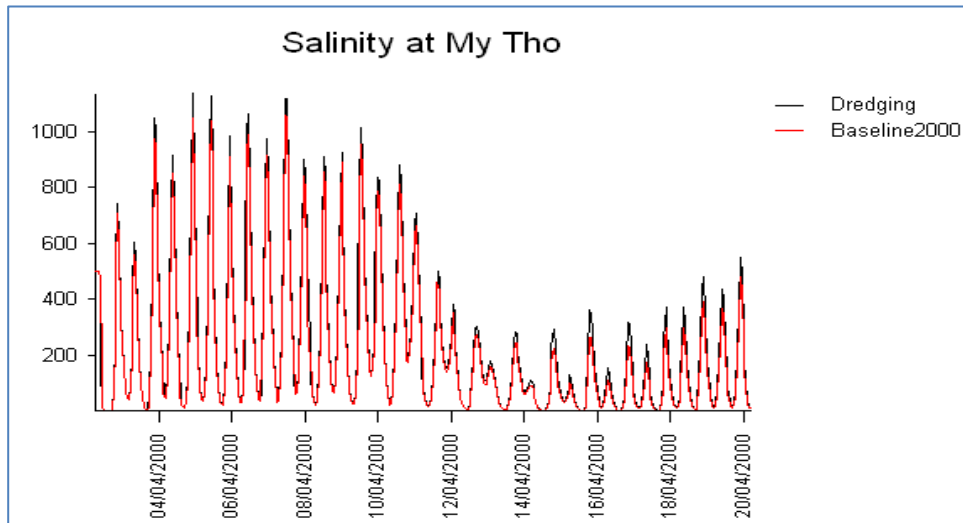
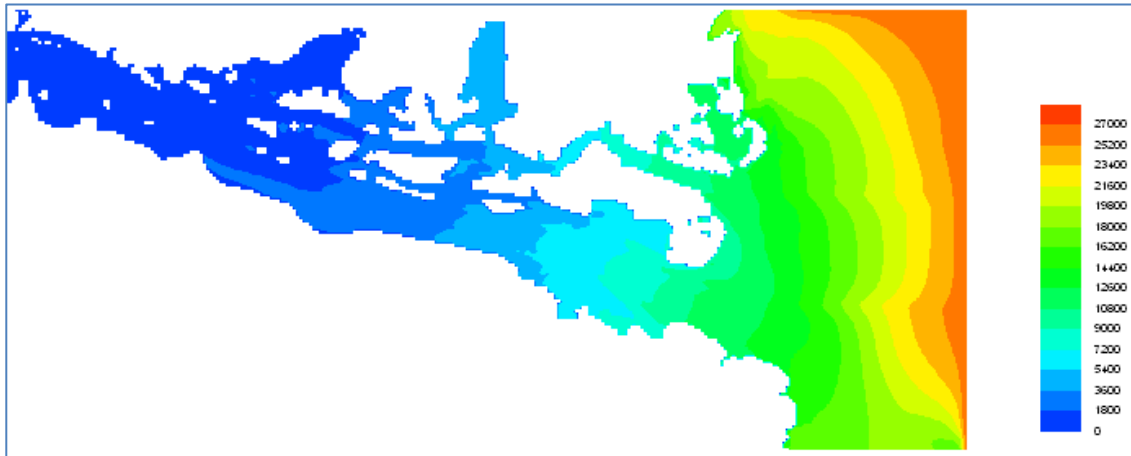
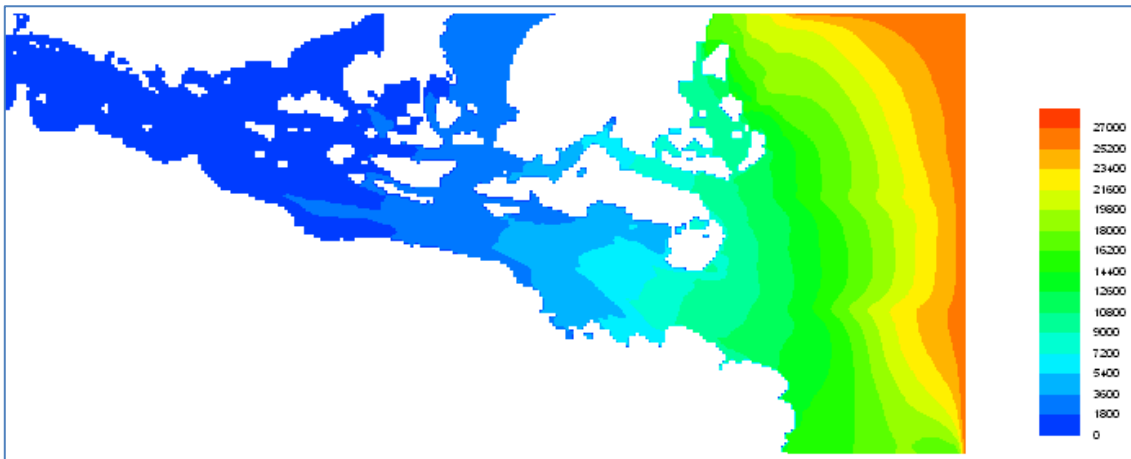


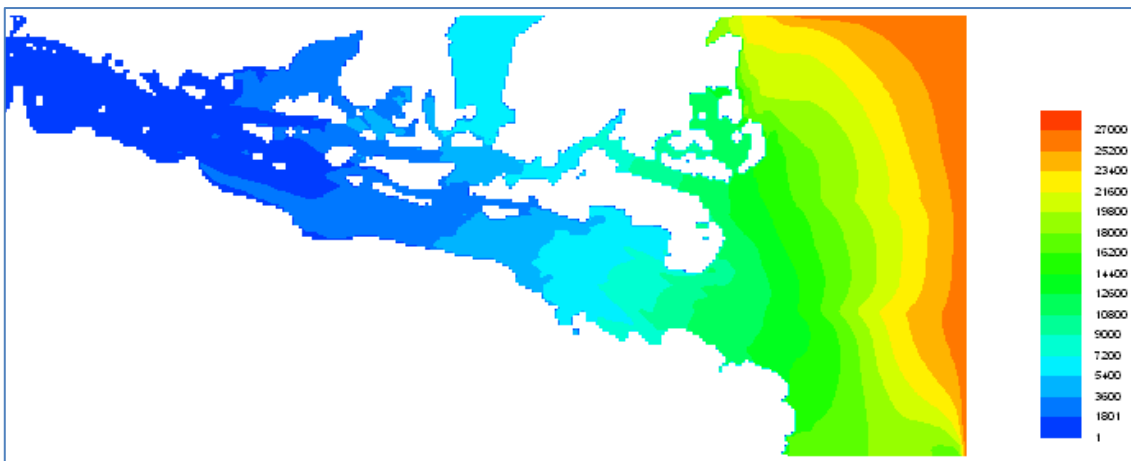
Figure 34. Comparison of salinity concentration (mg/l) at My Tho in Baseline 2000 scenario and dredging scenario



a)

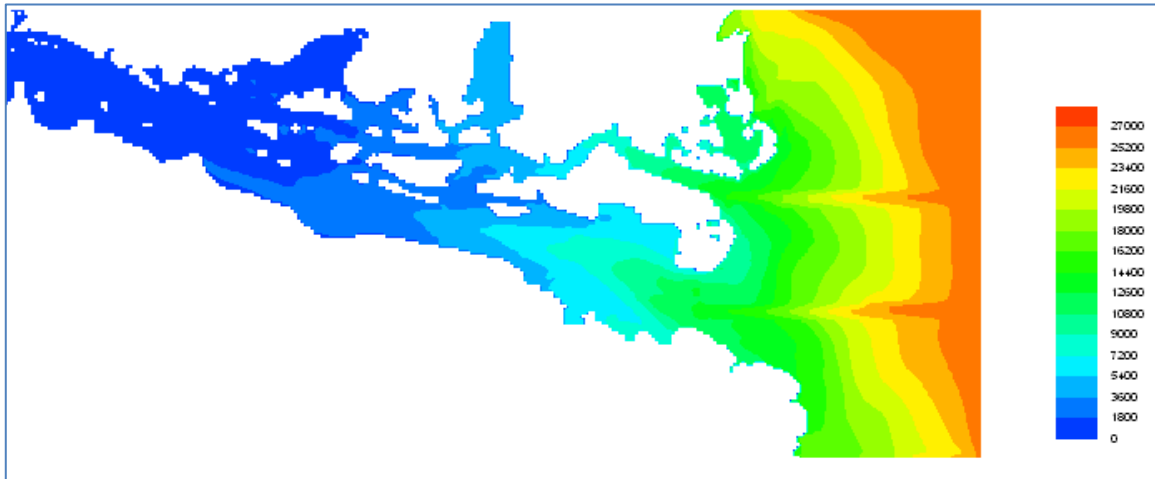


b)

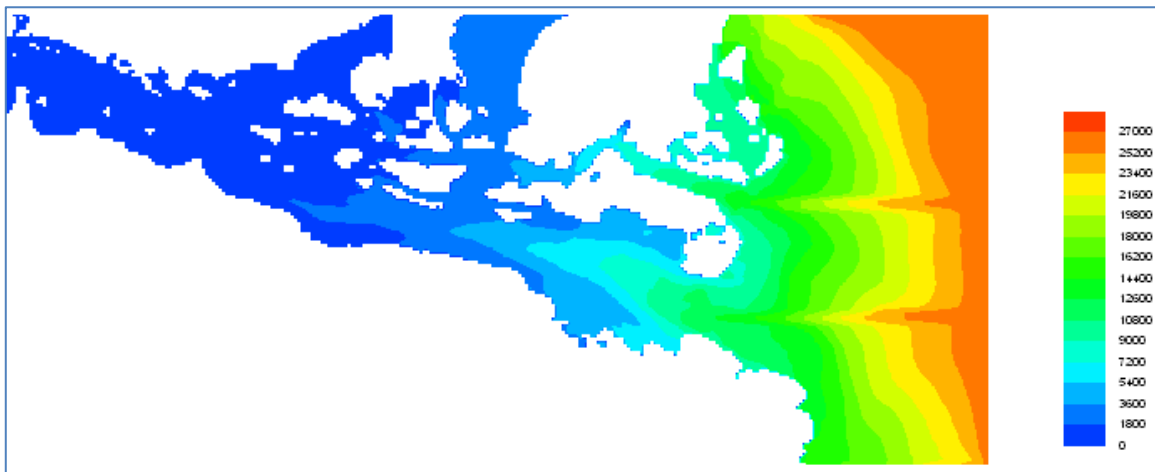


c)

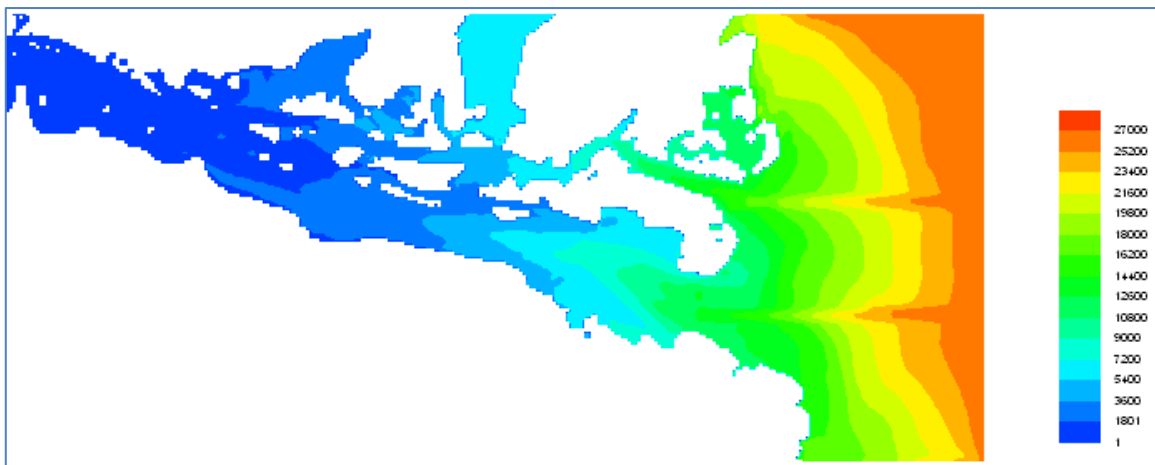
Figure 35. Average salinity concentration on the surface layer in April 2000 (mg/l) a) baseline 2000; b) sea water level rise; c) dredging scenario



a)



b)



c)

Figure 36. Average salinity concentration on the bottom layer in April 2000 (mg/l) baseline 2000; b) sea water level rise; c) dredging scenario

## 1.5. Summary of the salinity intrusion scenarios

Four scenarios were run for the Tieu River mouth application. They were baseline, sea level rise, dredging and flow regime change. Salinity was examined in My Tho for each scenario. The model results show the rather surprising sensitivity of the saline intrusion to even relatively small flow regime changes and dredging. On the other hand a moderate sea level rise would not have a dramatic effect on the saline intrusion.

The results of the scenario runs are presented in Table 1. Figure 151 illustrates sea level rise impact compared to the dredging scenario. Observer the different scales in the figures.

Table 1. Results of the scenario runs. Numbers show salinity in mg/l in My Tho.

	avg	std	min	max	median
<b>Baseline</b>	182.5	158.4	3.4	785.5	137.8
<b>Sea_lev +0.25</b>	241.1	202.8	3.4	1064.0	183.8
<b>Dredging</b>	380.3	318.6	3.5	1791.0	306.3
<b>Base (march)</b>	13.1	22.0	0.0	145.2	3.5
<b>FR3 (march)</b>	1.3	2.8	0.0	26.8	0.2

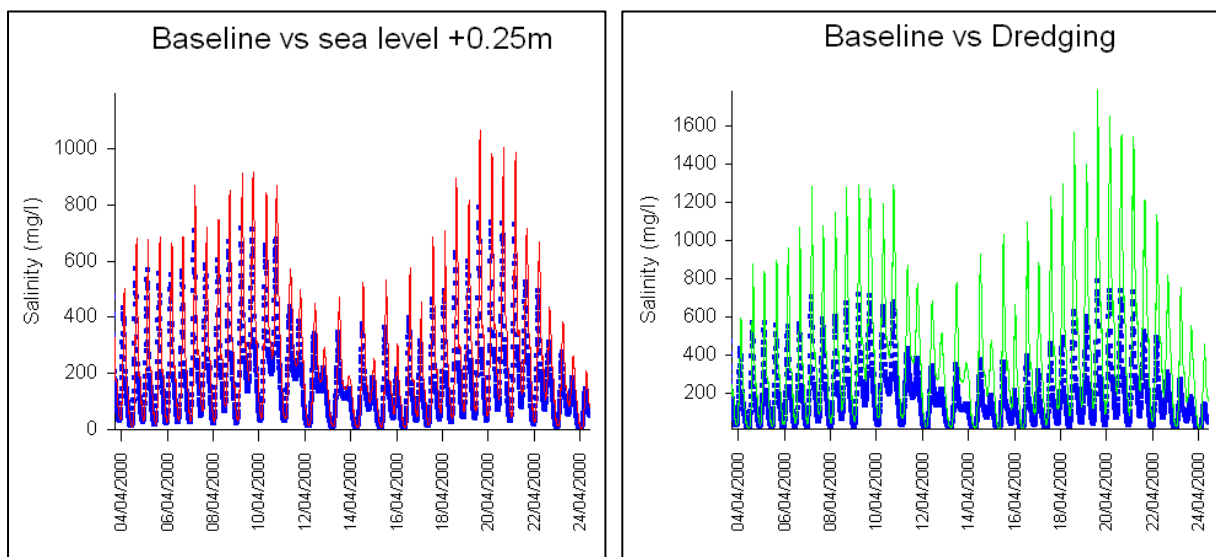


Figure 37. Simulated salinity in My Tho for the sea level rise (left) and dredging (right) scenarios. Baseline shown with blue colour. Observer different scales in the figures.