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MODELLING SEDIMENT TRANSPORTATION IN TONLE SAP LAKE FOR IMPACT ASSESSMENT

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ABSTRACT

The Tonle Sap Lake in Cambodia is the largest permanent freshwater body in Southeast Asia. Cambodian floodplains, including Tonle Sap floodplain, contain the most extensive wetland habitats in the Mekong system. Mekong Upstream developments, such as the construction of dams may lead to significant trapping of sediments and nutrients and reduce the productivity of the Tonle Sap system. The 3D EIA hydrodynamic and water quality models have been set up for Tonle Sap for simulating water levels and currents, inundation of the floodplain, suspended sediment transport and sedimentation, and dissolved oxygen to understand the ecosystem processes and the possible changes in it due to the upstream development. The model simulations can be used to assess the impacts of development scenarios and support sustainable resource management in lake and its floodplain.

1 INTRODUCTION

The ecosystem of the Tonle Sap Lake is driven by the monsoon floods of the Mekong River, one of the largest rivers in the world. In wet season the lake grows fourfold and the water level rises 6-10 meters. This unique pulsing system makes the Tonle Sap one of the most productive freshwater ecosystem in the world.

A dominant feature of the Tonle Sap system is that the sediment flux to the Tonle Sap Lake in the flood season (June-September) is many times larger than the outflow flux in the dry season (October-May). This means that the Tonle Sap Lake and floodplain ecosystem is retaining more than 80 % of the sediments it receives from the Mekong River and tributaries and utilizing this material in the ecosystem processes. The Mekong River is responsible for the main part (ca. 70%) of the annual 7 million tons sediment load to Tonle Sap system (WUP-FIN, 2003).

It is hypothesized that sediments carried by the Mekong waters to the Tonle Sap Lake bring in the essential nutrients that feed into the lake's food webs (WUP-FIN, 2003). The higher the flood the more sediments and nutrients imported (van Zalinge et al., 2003). Upstream developments in Mekong such as dam construction have already led to significant trapping of sediments and nutrients (Kummu et al., 2004) and may reduce the fertility of the Tonle Sap system. Significant changes in the flood regime may influence the productivity of ecosystem.

The EIA 3D model system has been set up for the lake during the "Modelling of the Flow Regime and Water Quality of the Tonle Sap" (MRCS/WUP-FIN) project to assess and evaluate the impacts of physical and environmental changes in the Tonle Sap Lake in relation to the whole Mekong basin, as well as more locally in Cambodia. The aim has been to assist in maintaining sustainable conditions of Tonle Sap system.

2 TONLE SAP LAKE

The Tonle Sap River connects the Tonle Sap Lake to the Mekong River and joins it at Chaktomuk junction near Phnom Penh, after which the river immediately splits into the smaller Bassac River and the larger Mekong River (Figure 1). The area is globally unique and the lake has an extraordinary hydrological system. In the wet season, the Tonle Sap River changes its direction and flows to the Tonle Sap Lake instead of from the lake because of the flooding of the Mekong River. The lake functions as a natural flood water reservoir for the Mekong system and thus, is very important source of water for the Mekong delta during the dry season.

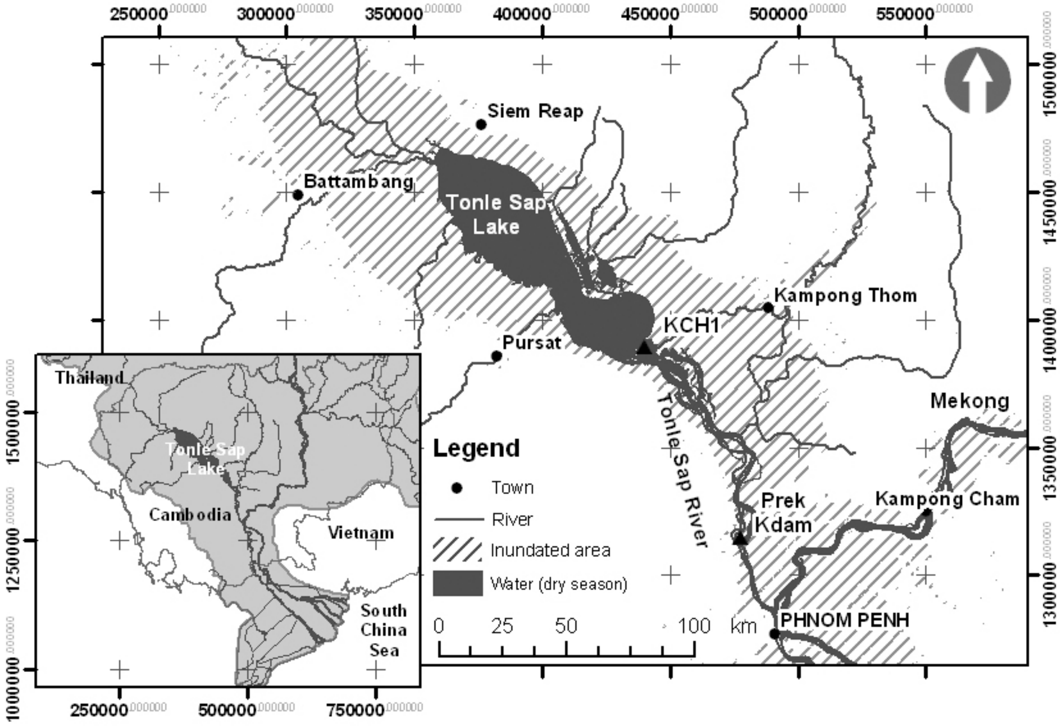


Figure 1: Location of Tonle Sap Lake (left) and the lake and floodplain in more detailed (right). Also the locations of KCH1 and Prek Kdam measurement stations are presented.

The area of the lake varies between dry and wet season from 2500 km^2 up to about 15 000 km^2 while the depth of the lake increases from less than one meter up to 7 - 9 m. During the wet season, the volume of the lake increases from about 1.3 km^3 up to 60-80 km^3 depending of the flood intensity. The bottom of the lake lies approximately 0.5-0.7 m above the mean sea level. Hence, during the year the surface of the lake varies between 1.3 m and 10.3 m above the mean sea level, respectively (WUP-FIN, 2003).

In the last two decades, the flood pulse concept has been widely accepted as the key factor for highly productive floodplains. Thorough studies made in the Amazon Basin (Junk, 1997) offer a lot of useful information on pulsing system processes for basins similar to the Mekong. The sediment transported by the floods into the lake basin contributes an important phosphorus source for flood lake ecosystems (Sarkkula et al., 2004; Sarkkula et al., 2003).

The lake provides about 60 % of Cambodia's total supply of protein. The Tonle Sap ecosystem is believed to be one of the most productive inland waters and one of the most fish-abundant lakes in the world. Flooded forests and shrubs offer shelter and breeding grounds for fish and other aquatic animals (Bonheur, 2001). The annual flood also creates good conditions to cultivate floating and recession rice. Hence, the Tonle Sap Lake is a crucially important source for food and living in Cambodia.

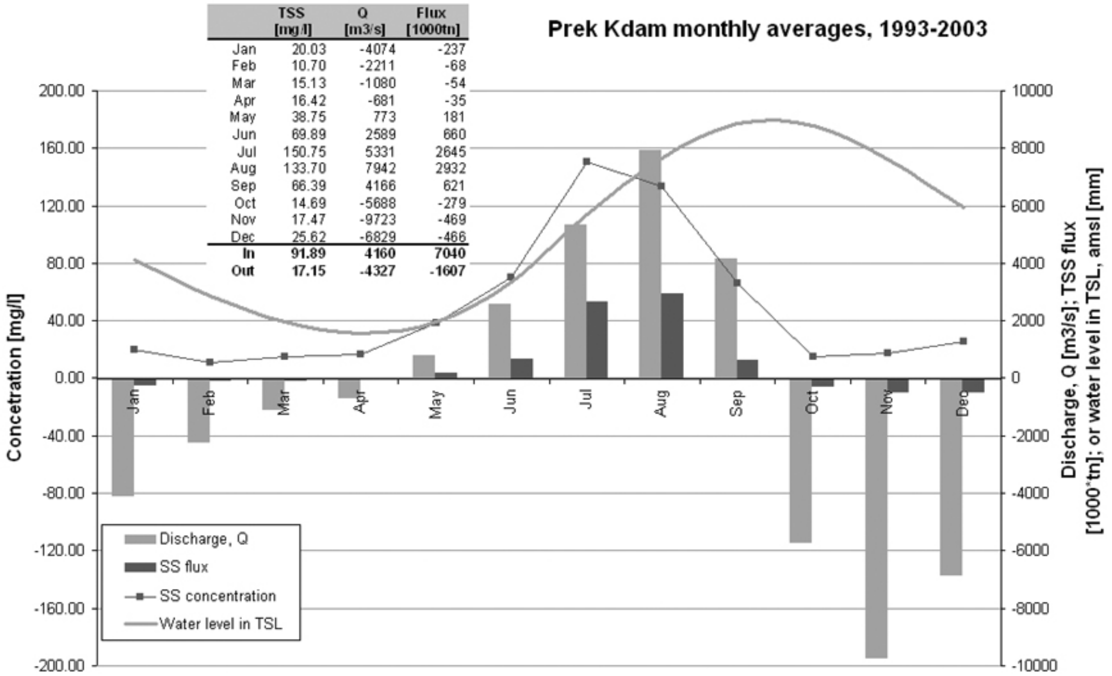
Any disturbance of the ecosystem may have disastrous impacts on the livelihoods of the whole country.

3 SEDIMENT FLUXES

Suspended sediment (SS) flux from Mekong River during the flood season dominates the sediment transportation dynamics of the Tonle Sap System. The Mekong River is responsible for the main part (ca. 70%) of the sediment load to Tonle Sap.

The average suspended sediment flux into the Tonle Sap Lake is 7 million tons (MT) while the outflow flux is only 1.6 MT. Thus, more than 80 % of the sediments the system receives from the Mekong River and the tributaries remains in the lake and floodplain.

Figure 2 shows the monthly average SS fluxes and concentrations (1993-2003) of Prek Kdam (location in Figure 1). The positive and negative values in the figure correspond to fluxes into the Tonle Sap Lake (TSL) and out from the lake, respectively. The water level of the lake and discharge in and out of the lake are presented in Figure 2.



	TSS [mg/l]	Q [m3/s]	Flux [1000tn]
Jan	20.03	-4074	-237
Feb	10.70	-2211	-68
Mar	15.13	-1080	-54
Apr	16.42	-681	-35
May	38.75	773	181
Jun	69.89	2589	660
Jul	150.75	5331	2645
Aug	133.70	7942	2932
Sep	66.39	4166	621
Oct	14.69	-5688	-279
Nov	17.47	-9723	-469
Dec	25.62	-6829	-466
In	**91.89**	**4160**	**7040**
Out	**17.15**	**-4327**	**-1607**

Figure 2: Monthly average flows, sediment fluxes and sediment concentrations in Prek Kdam (1993-2003). Positive = inflow to the Tonle Sap Lake and negative values = outflow.

From Figure 3 it can be seen that the inflow to the lake contains much higher SS concentration compared to the outflow rates. Also, the SS concentration of the outflow does not depend the discharge as strongly as the SS concentration during the inflow.

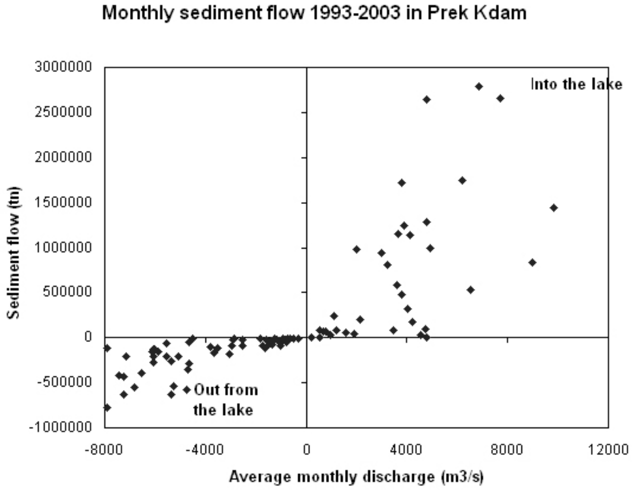


Figure 3: Monthly SS flux in the Tonle Sap River, Prek Kdam, 1993 – 2003 plotted as a function of monthly average flow. Positive values correspond to flux into the Tonle Sap Lake and vice versa. Year 1998 and 1999 data not complete.

4 EIA 3D HYDRODYNAMIC MODEL

The models applied for the Tonle Sap Lake were 3-dimensional (3D) EIA[1] Hydrodynamic Model for the detailed water level, current, floodplain inundation, and sedimentation studies, and 3D EIA Water Quality Model for calculating the transport and processes of a selected set of water quality indicators and hazardous materials (Koponen et al., 2004). The models have been developed by Technical Research Centre of Finland and EIA Ltd. (Environmental Impact Assessment Centre of Finland) during the last 20 years.

4.1 Model characteristics

The flow model can be classified as a 3-dimensional baroclinic z-level model (e.g. Virtanen et al., 1998) and is based on the standard Navier-Stokes equations in a rectangular grid (Koponen et al., 2003).

The complicated hydrodynamic and sedimentological characteristics of the Tonle Sap Lake system necessitate use of a versatile enough model. The EIA 3D model can solve basically any dynamic or static flow and sediment situation. With the EIA model it is possible to calculate 2D solutions as well, although usually 3D solutions are more

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[1] Name of the model comes from the name of the developer company, Environmental impact assessment centre of Finland, EIA Ltd.

appropriate for erosion, sediment transport, and oxygen concentration studies (Koponen et al., 2003). Reasonable simulation times are reached by using appropriate algorithms (e.g. time splitting and implicit solvers) and model resolutions. The model also has a geographic information system (GIS) user interface.

Figure 4 presents the EIA 3D model structure.

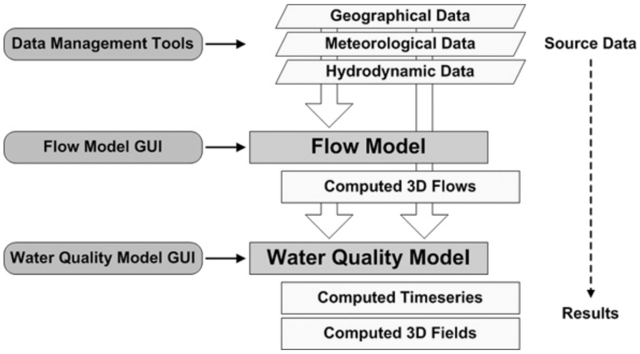


Figure 4: EIA 3D model structure.

3D Water Quality Model has been coupled with the flow model, as shown in Figure 4, for simulating the transport and processes of selected set of water quality indicators and hazardous materials. Water quality is modelled with simulated water flow, which is used to compute the dispersion of nutrients and other substances from given sources. In addition, the modelled substances may diffuse, sediment, re-suspend, decay and react with each other.

For Tonle Sap model application the 1.0 km grid size was used. Landuse map for the floodplain was used to describe the impact of the vegetation on the friction and wind.

4.2 Sediment transportation modelling

The governing equation for the ith fraction including advection, dispersion, bed erosion by re-suspension, and deposition retains the conventional form of the general transport equation as follows:

$$\frac{\partial c_i}{\partial t} + u\frac{\partial c_i}{\partial x} + v\frac{\partial c_i}{\partial y} + w\frac{\partial c_i}{\partial z} - w_s\frac{\partial c_i}{\partial z} = D_h\frac{\partial^2 c_i}{\partial x^2} + D_h\frac{\partial^2 c_i}{\partial y^2} + D_v\frac{\partial^2 c_i}{\partial z^2} + S_{e,i} - S_{d,i}. \tag{1}$$

c_i	concentration of a substance, [units/m^3]
t	time, [s]
x,y,z	coordinate directions, [m/s]
u,v,w	known water flow velocity components, [m/s]
D_h	horizontal concentration diffusivity, [m^2/s]
D_v	vertical concentration diffusivity, [m^2/s]
$S_{e,i}$	net upward suspended sediment flux
$S_{d,i}$	net downward suspended sediment flux

Although, the model is able to deal with multi-fraction sediment classes, both cohesive and non-cohesive. In Tonle Sap model application so far only one cohesive sediment class has been utilised having the settling velocity of 0.07 m/day. This is based on the water samples taken from the lake.

The key to the realistic description of the processes is the proper formulation and parameterisation of the erosion and deposition terms. As source terms, the following formulae among others were adopted:

$$\frac{\partial C_i}{\partial t} = K_{e,i}\left(\tau_b - \tau_{cr,i}\right) = \frac{S_{e,i}}{h} \quad . \tag{2}$$

$$\frac{\partial C_i}{\partial t} = \left(1 - \frac{\tau_b}{\tau_{cr,i}}\right)\frac{2w_{s,i}}{h}C_i = \frac{S_{d,i}}{h} \quad . \tag{3}$$

τ_b	bed shear stress [N/m^2]
$\tau_{cr,i}$	critical bottom shear stress [N/m^2]
$w_{s,i}$	settling velocity for the ith non-cohesive sediment fraction [m/s]
$K_{e,i}$	erosion coefficient [-]
h	unit height [m]

It was assumed, however, that both processes might occur simultaneously, the sum of which gives then the instantaneous state of the suspended sediment balance. In equilibrium, it is written as follows:

$$C_{eq,i} = \frac{K_{e,i}h\left(\tau_b - \tau_{cr,i}\right)}{2w_{s,i}\left(1 - \frac{\tau_b}{\tau_{cr,i}}\right)} \tag{4}$$

Once the time variation of the concentration is known the local bed change can be calculated based on the sediment particle density and bulk porosity by

$$\frac{\partial z_{0,i}}{\partial t} = \frac{\partial C_i}{\partial t}\frac{h}{\rho_{s,i}\left(1 - p_{b,i}\right)} \tag{5}$$

$\rho_{s,i}$	sediment density [kg/m^3]
$p_{b,i}$	bulk porosity [-]

and the total rate of change can be obtained by summing all the fractions treated separately. The mathematical model outlined above was solved numerically by appropriate finite difference method on the grid identical to the one used in the flow model. Erosion and settling were parameterised based on the result of the water quality sample analyses. The model can be used for predicting bed changes for longer scenarios as well.

Finally, we underline the importance of reasonable approximation of the bottom shear stress distribution, as a driving force of the fluxes there. In shallow waters, the main factors are the wind-induced waves and the resulting wave- induced shear stress at the bottom. In the present model the so-called SPM (Shore Protection Manual) shallow water wave formulae proved acceptable, providing the significant wave height in terms of the wind speed, fetch and local depth (e.g. Kang et al., 1982).

4.3 Tonle Sap Lake from modelling point of view

The Tonle Sap area poses extraordinary challenges for the lake and floodplain modelling. The area is characterized by large spatial coverage; long distances of numerous tributaries; complicated and dynamic hydraulic system of lakes, rivers, floodplains and ponds; high variability of land use and vegetation types; highly variable flow regimes and wide main channel surrounded by flood banks and tributaries.

One of the main problems is the complicated hydrodynamic characteristics of the area. The lake is 25 km wide during the dry season and over 75 km wide during the peak flood. Thus, it cannot be expected that the flow is homogenous across the main basin and the flood banks. When the lake areas are shallow, the flow characteristics can be 2D whereas in the smaller tributaries they are at least approximately 1D. In deeper water depths in the lakes, rivers, and floodplains, the flow will have 3D characteristics

In the system, the problems created by the extensive and heterogeneous data are solved by the use of standard GIS tools for data management and processing. The basic DEM, tributaries shapes and land use data have already been in GIS form, and it has been enhanced with the other available data. The complicated hydrodynamic characteristics have been solved by selecting a versatile enough model.

Usually 3D solutions are calculated but in the future, it will be possible to convert them into 2D solutions, although erosion and sediment transport studies necessitate 3D solutions. Reasonable simulation times are reached by using appropriate algorithms (e.g. time splitting and implicit solvers) and model resolutions. For special analysis of details of floodplain dynamics, finer resolution (20 – 200 m grid cell size) can be used than for the rest of the lake (1000 m grid size or its multiplications).

5 MODEL VALIDATION

To validate the sediment module of the model the modelled suspended sediment concentrations were compared to the observed field measurements in various sites. Here only the results from KCH1 station (location in Figure 1) is presented (Figure 5). For the validation, the time period between 5/2001 and 5/2002 was used. Because of the limited measurement data, only surface SS concentrations (0-1 m below the water surface) were used.

To understand the impact of the grid resolutions on the sediment transportation, two different grid resolutions were used: 1 km^2 and 9 km^2. When comparing the observed SS concentrations with the calculated ones, the correlation is good during the flood period (July-September) except the very high peak when the observed values is higher than the calculated. During the receiving flood (October-January) the computed values are higher than the observed ones.

The results of the validation process from other stations are well correlated. However, more work with the sediment transportation parameters validation is necessary. Also, at present only one sediment fraction class was used in the modelling. Multi-fraction sediment classes would give more reliable results with additional field work.

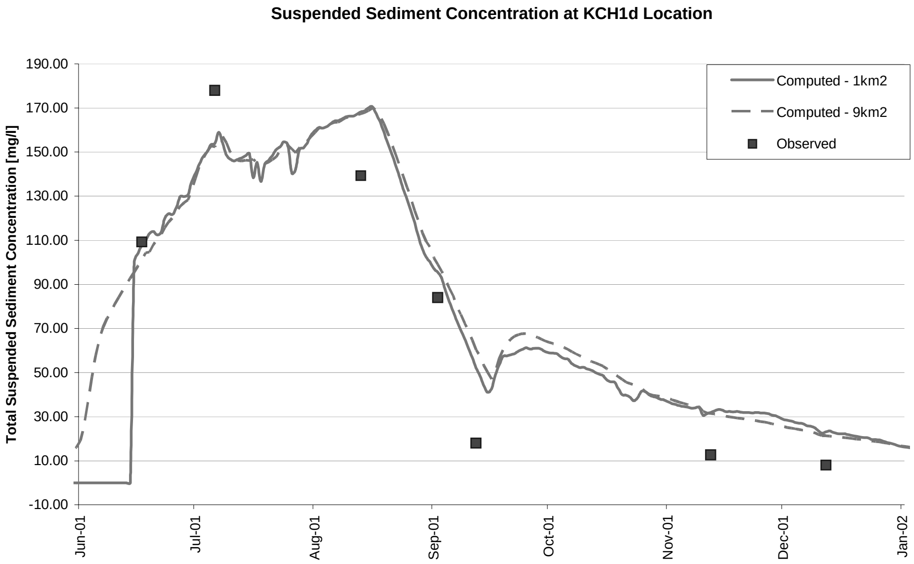


Figure 5: TSS concentration comparison between observed and computed values at KCH1.

6 RESULTS

6.1 Modelling results

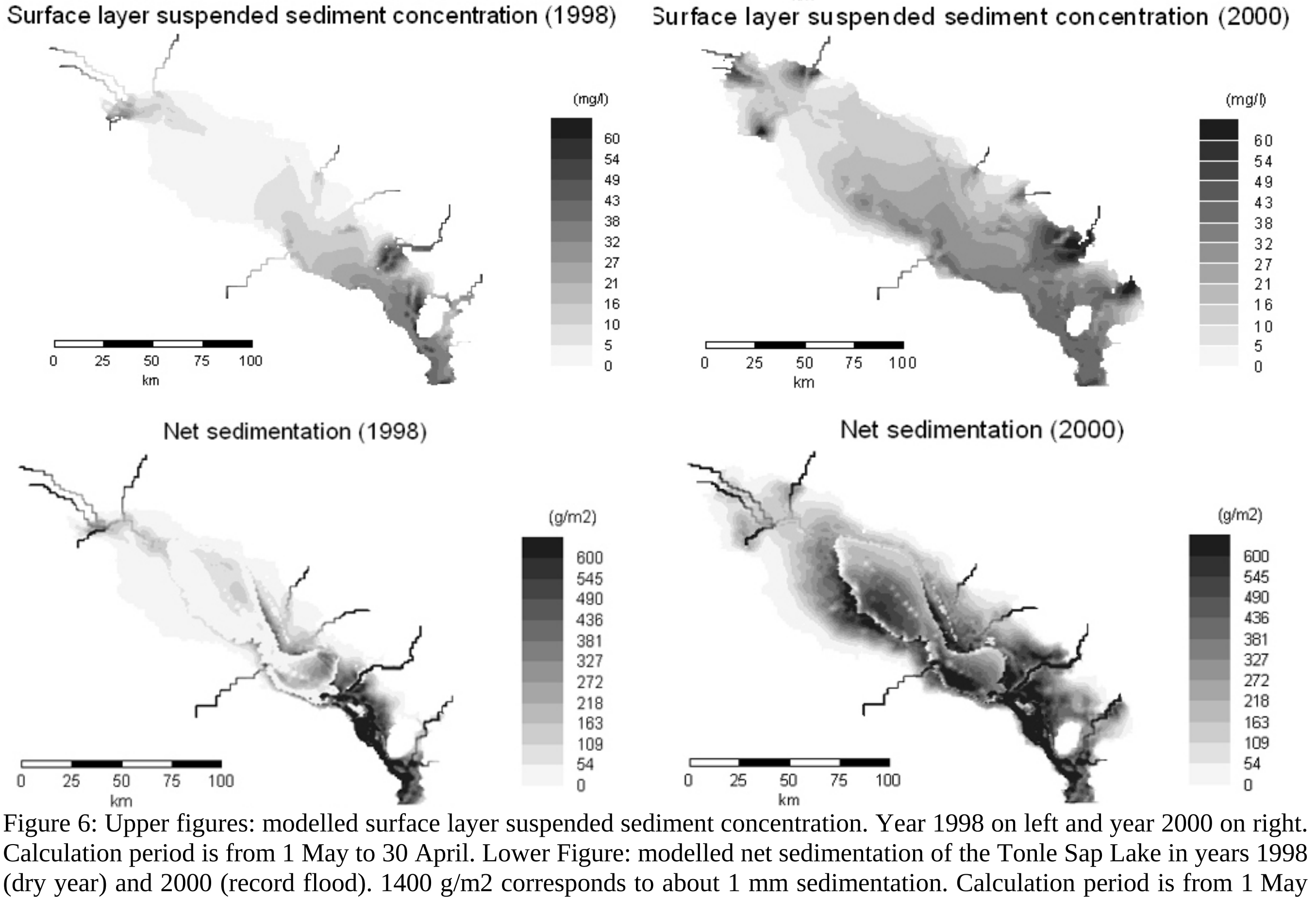
Figure 6 shows the modelled suspended sediment concentrations in two extreme years: very dry year 1998 and record flood year 2000. One modelled year means here the period from 1 May to 30 April.

The high natural variability of the hydrological conditions is strongly reflected in the sedimentation pattern. In a dry year with low sediment input very limited amount of Mekong sediments reach the lake area and its surroundings. A high flood year means also wide spreading of sediments around Tonle Sap Lake.

An interesting indication by the model is that the agricultural lands in the upper parts of the wetland do not seem to receive natural fertilization by the Mekong sediments, the sediments being trapped by the habitats close to the lake by the flooded forest and shrubland. The sediment trap results correlate very well with that. More detailed analysis of the sedimentation in different zones of the lake has been made in Keskinen et al. (2005) in this same proceedings.

The sediments deposited temporarily in the lake proper are easily resuspended by wind and wave induced currents especially in the dry season when the lake is about one meter deep, as well as by the currents induced by Mekong flood waters in the beginning of the flood season. Thus, the modelled net sedimentation rates in the lake proper may have some errors because those are momentary net sedimentation rates and depending very much on the last days' wind conditions. According to the previous studies and field measurements the sedimentation in lake proper is close to 0.1 mm/year. In most part of the lake the model results correlate rather well with this net sedimentation rate.

All the two-dimensional results presented here can be exported as a GIS layer and used in any GIS program for further analysis purposes. An analysis tool was developed to inside the model system to better understand the results of the model. This tool can be also used comprehensively for the impact analysis combined e.g. with fisheries and rice production data on the Tonle Sap System. The integration of the socio-economic, hydraulic, and hydrodynamic data and the results are presented in Keskinen et al. (2005).


Surface layer suspended sediment concentration (1998)

Surface layer suspended sediment concentration (2000)

Net sedimentation (1998)

Net sedimentation (2000)

Figure 6: Upper figures: modelled surface layer suspended sediment concentration. Year 1998 on left and year 2000 on right. Calculation period is from 1 May to 30 April. Lower Figure: modelled net sedimentation of the Tonle Sap Lake in years 1998 (dry year) and 2000 (record flood). 1400 g/m2 corresponds to about 1 mm sedimentation. Calculation period is from 1 May to 30 April.

6.2 Comparison the results with previous studies

Sedimentation studies show that net sedimentation on the Tonle Sap Lake proper has been in the range of 0.1-0.16 mm/year since the connection between Mekong River and Tonle Sap was established about 5500 years ago (Penny, 2002; Tsukawaki, 1997) as presented in Figure 7. This means an accumulation of 0.50-0.70 m thick sediment layer in the lake during that time. The net sedimentation rates modelled with 3D EIA model fit rather well with the results of Tsukawaki and Penny.

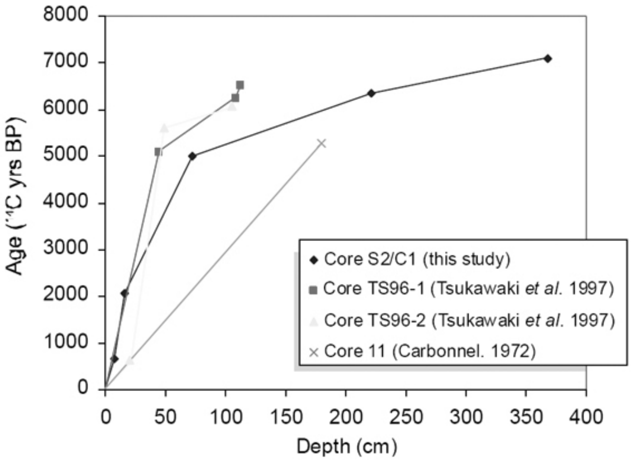


Figure 7: Plot of age against depth for all published radiocarbon age determinations for lake Tonle Sap (Penny, 2002).

A very strong belief amongst the local people and international organizations is that the lake is filling up with sediment within a few decades. This information was based on the studies made in 1960's (e.g. Carbonnel and Guiscafre, 1963; Kaosa-ard, 1995). According to the coring results of Penny and Tsukawaki and the modelled results presented here, the conclusion is that the lake will not fill up with sediments in the near future.

The TSS data, secchi depth measurements as well as the model calculations show that efficient sedimentation takes place in the flood season in the vicinity of the Tonle Sap River and the tributaries, in the delta area and in the flooded forests around the lake proper. This explains the low sedimentation rate in the lake proper after being connected with the Mekong River, although the Tonle Sap system having obviously received an increased amount of sediments after this turning point. The efficient sedimentation can be concluded from the measurement data, where clearing of the flood waters appears when they fill and inundate the vegetated zone. The effective reduction of SS concentrations and turbidity values is due to the damped wind forcing and wave activity and consequently, low flow velocities and less turbulence compared to the open lake conditions (Sarkkula et al., 2003).

7 SCENARIO MODELLING FOR IMPACT ASSESSMENT

Altogether, more than 70 million people live in the basin, of which 45 % in its lower part (Cambodia and Vietnam). Rapid economic growth, especially in countries such as China and Thailand, has increased the pressure to increase hydropower production. Thus, China has finished two hydropower dams, Manwan and Dachaoshan, in the Mekong mainstream and has six more under construction or projected for the so-called Yunnan cascade. The Manwan dam was finished in 1993; following its completion, it has had severe impacts on the sediment flux downstream in the Lower Mekong Basin, where the measured SS rates have halved from 69 to 35 MT/year (Kummu et al., 2004). Tens of smaller scale dams have been build to the tributaries in Thailand, Vietnam and Laos.

The model was run with a "dam trapping" scenario, where year 2000 flood was used but the sediment load from Mekong was halved. This could represent the worst scenario, effect of the regional developments utilizing Mekong water, such as extensive damming of tributaries and the mainstream. It can be seen that the "dam trapping" scenario would mean dramatic reduction of the net sedimentation in the Tonle Sap (Figure 8) and consequently, in the supply of sediment bound nutrients to its floodplain for maintaining its biological productivity (Sarkkula et al., 2003).

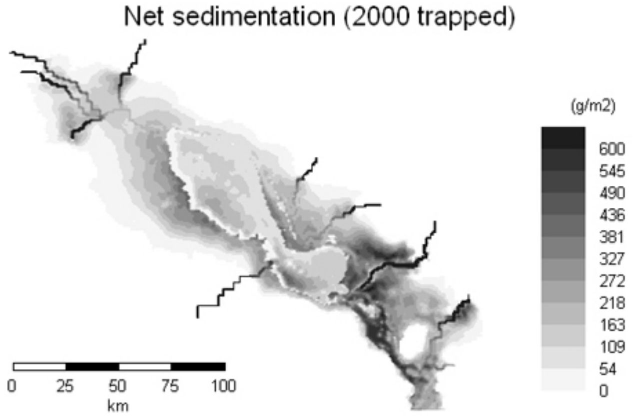


Figure 8: Net sedimentation rates on the dam trapping scenario (compare to the present net sedimentation in Figure 6).

Another threat to the Tonle Sap ecosystem is the local development and increasing pressure, because of the fast growing population, on its natural resources. For example the area of the flooded forest in the vicinity of the lake is decreasing because of illegal logging and increasing demand of the wood for fishing gears, boats, and fire wood.

The forest is crucially important for the Tonle Sap System forming a shelter for the floodplain and providing a suitable conditions for the fishes to breed.

The flooded forest may face another threat if the dam regulation in Mekong main stream and tributaries will increase the dry season flow as predicted by Adamson (2001). This would mean that the average dry season water level in the lake would rise from 1.57 m to 1.81 m above the mean sea level (DHI, 2004). If the lake level would rise as presented, part of the flooded forest would stay inundated throughout the year which would destroy that part of it.

Together the local and upstream impacts may exterminate big part of the flooded forest area. The model was run with the scenario where the flooded forest was totally removed and changed for a shrub land. The simulation result is presented in Figure 9. Comparing the scenario results to the present situation (Figure 6) it can be seen that the net sedimentation rates are higher in upper parts of the floodplain than now and also the net sedimentation in lake proper would slightly increase.

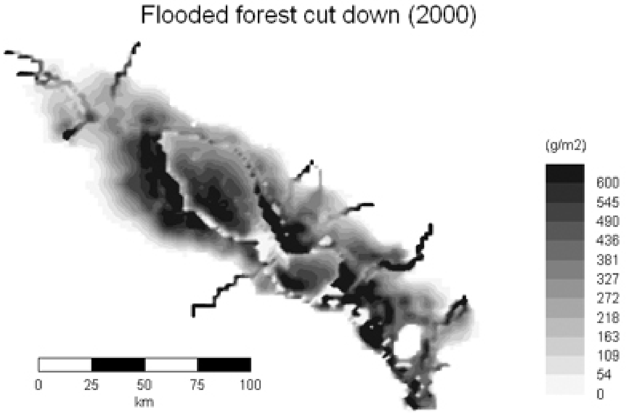


Figure 9 Net sedimentation rates on the flooded forest scenario (compare to the present net sedimentation in Figure 6)

8 CONCLUSION

A dominant feature of the Tonle Sap system is that the sediment flux to the Tonle Sap Lake in the flood season is much larger to the outflow flux in the dry season. The sediment is very important part of the aquatic-terrestrial ecosystem of the lake bringing a lot of nutrients in the lake system.

The common belief has been that the lake is filling up with the sediment but the recent studies (Penny, 2002; Tsukawaki, 1997) show that the net sedimentation in the north-western part Tonle Sap lake proper has been in average 0.1 mm/year and 0.16 mm/year in the north-eastern part from 5500 years B.P. until present. Thus, the lake is not filling up with sediments.

During the WUP-FIN Tonle Sap Modelling project 3D Flow model was set up for the lake with sediment transportation modelling. The modelled net sedimentation rates fit well with the results of Tsukawaki and Penny.

According to the model results the main sedimentation areas are in the flooded forest and flood plains in the vicinity of the lake proper and the rivers. Model results are supported by the water quality measurements, where a steep decline of suspended sediments concentrations is found when moving from lake to the flood plain and by the topographic features of the lake where a natural levee has formed on the lake edges.

It is hypothesized that sediments carried by the Mekong waters to the Tonle Sap Lake bring in the essential nutrients that feed into the lake's food webs. Upstream development, as building reservoirs or dams, may have, and has already had (Kummu et al., 2004), effect on the sediment and nutrient concentration. This would mean dramatic reduction of the net sedimentation in the Tonle Sap and consequently, in the supply of sediment bound nutrients to its floodplain for maintaining its biological productivity as shown in dam trapping scenario. This would directly has influence e.g. as reduced fish catches and thus, people around the lake and whole Cambodia.

Another development scenario was run where the flooded forest on the vicinity of lake proper was removed describing the possible impacts on the local and upstream development which may destroy big areas of the forest. Removing of the flooded forest had impact on the sediment dynamic in the system and thus, might change the ecosystem of the lake.

These two scenarios run with the model show that the model is capable tool to assist impact assessment when looking the local or upstream impacts on the lake. However, more research urgently needs to be done to better understand the nutrient cycle of the lake and the impacts of the upstream and local developments on it.

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