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*Hydrology Component*

# INFLUENCE OF BUILT STRUCTURES ON TONLE SAP HYDROLOGY AND RELATED PARAMETERS


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## CONTENTS

## EXECUTIVE SUMMARY

A set of tools and analyses has been applied to assess the impacts of built structures on Tonle Sap hydrology, hydrodynamics, sediments, water quality and conditions for fish. Three scales of impacts have been studied: (i) upstream basin-wide development impacts, (ii) Tonle Sap catchment development impacts, and (iii) local scale individual structures.

Four scenarios have been studied. The (i) baseline scenario represents the current development level of the Mekong Basin. Two additional basin-wide scenarios have been studied: (ii) upstream tributaries' intensive irrigation and hydropower dam development, and (iii) mainstream dams + upstream tributaries' intensive development as in (ii). For the Tonle Sap scale (iv) the impact of catchment irrigation and hydropower dam development has been modeled.

The different tools and methodologies used in the study include:

- Hydrological, hydrodynamic, sediment and water quality field measurements
- Laboratory experiments for fishing gears
- Hydrological water balance studies
- Tonle Sap Lake, River and floodplain three-dimensional hydrodynamic, sediment and water quality model
- Stung Chinit irrigation system three-dimensional hydraulic, hydrodynamic, sediment and water quality model
- Model applications for floodplain structures including roads and irrigation reservoirs
- Water resources allocation model for irrigation and hydropower.

### NATURAL VARIABILITY AND BUILT STRUCTURE IMPACTS

The human impact is relatively small compared with the high natural variability of the floods. Fish have adapted to the varying conditions and consequently, at least to a degree, are resistant to the human impacts. However, dry years can be critical because built structure impacts are most pronounced then and fish are most vulnerable to additional stress.

### BASIN-WIDE DEVELOPMENT IMPACTS

The upstream development impacts can be summarized as:

- Increased dry season water levels that will probably permanently inundate and destroy the lake edge flooded forest that functions as an important habitat and buffer between the Tonle Sap Lake and its floodplain
- Decreased sediment input and consequently impacts on primary productivity
- Delay of flooding and accompanied adverse impact on larvae drift and floodplain habitat oxygen conditions
- Decreased flood season flooded area and volume resulting in less primary production and habitat for fish.

The cumulative impact of the individual impacts may result is serious consequences for Cambodia's fisheries.

### TONLE SAP CATCHMENT DEVELOPMENT IMPACTS

Implementation of the planned Tonle Sap catchment large-scale dam development plans would result in impacts similar to those in the basin-wide intensive development scenario. The impact on maximum water levels would be similar, but the floods would be delayed longer. Also, the sediment input into the lake would be diminished.

Local developments will considerably strengthen the impacts of upstream developments because both act in a similar way.

**STUNG CHINIT RESERVOIR**

- The conditions in the reservoir are favorable for fish – good oxygen conditions and sedimentation for primary productivity. However, the structure hinders natural fish migration.
- Positive influence on oxygen concentrations of the river, values increasing by approximately 20% downstream of the structure.
- Slight flushing effect of the reservoir during the flood season, total nutrient and suspended sediment concentrations have to some extent increased and visibility value decreased downstream of the structure.
- Drainage water from irrigation canals is slightly loading the river downstream.
- Data on the full hydrological cycle is required to see total changes in nutrient and sediment dynamics.
- Generalizations about the impacts of other reservoirs should be cautious because local hydrological, water quality, soil and land use conditions influence the impacts.

**FISHING GEARS**

- Slight opposing influence of bamboo fences on flow velocity can be observed when velocity is higher than 10 cm $s^{-1}$
- Opposing influence of nylon nets is slight and appears only when velocity is higher than 20 cm $s^{-1}$
- Flow velocities in the Tonle Sap Lake on the Prek Toal area were principally under 10 $cm.s^{-1}$ in August 2006 and January 2007; consequently, the hydrological and hydrodynamic impacts are small.

**PRIVATE IRRIGATION RESERVOIRS ON THE FLOODPLAIN**

- The reservoirs trap only a small portion of the flood waters and have a small impact on the large-scale hydrology.
- No major changes in water quality inside and outside of the reservoir.
- Significant changes in water quality can bee seen only in the values of chemical oxygen demand. Oxygen demand is increased because of trapped organic matter, sediment and the detritus of biomass production in the reservoir.

**FLOODPLAIN ROADS**

- In general, roads do not have a major impact on hydrology as long as enough bridges and other openings are built.
- In certain places roads may block main flood flow routes that supply fresh water, sediments and larvae/fish to the floodplain. It is important to understand the hydrodynamic behavior of the floodplain before road construction.

**SUMMARY OF THE IMPACTS AND RECOMMENDATIONS**

The large-scale basin and catchment irrigation and hydropower dams have the most significant impact on the Tonle Sap's hydrological and related conditions. However, the cumulative impact of a large number of small structures can be significant and should be clarified.

If intensive basin-wide and local development is realized, the impacts could be critical for the Tonle Sap fisheries. It is recommended that precautionary principles are applied in basin and catchment development until solid knowledge is accumulated on these impacts.

# I INTRODUCTION

## I.1 STUDY AREA AND BACKGROUND

### Importance of the Tonle Sap

1. The Tonle Sap Lake and floodplains in Cambodia contain the largest continuous areas of natural wetland habitats remaining in the Mekong system, while being the largest permanent freshwater body in Southeast Asia. Tonle Sap is a crucially important source for food and livelihoods in Cambodia. More than one million people live in the immediate surroundings of the Tonle Sap Lake and wetlands. These are the poorest people in Cambodia, and they are highly dependent on agriculture and fisheries. Tonle Sap fisheries provide 60% of the animal protein in Cambodia. The lake also operates as a natural reservoir for the Lower Mekong Basin, offering flood protection and contributing significantly to the dry season flow to the Mekong Delta.

### Tonle Sap ecosystem

2. The Tonle Sap is among the most productive freshwater ecosystems in the world (e.g. Bonheur, 2001; Lamberts, 2001; van Zalinge *et al*., 2003). Its high productivity depends on the flood pulse from the Mekong which transfers terrestrial primary products into the aquatic phase during flooding (e.g. Lamberts, 2001). For many of the Mekong fish species, the floodplain of the lake, and particularly the riparian flooded forest and shrublands, offers good conditions for feeding, breeding and rearing their young (Poulsen *et al*., 2002).

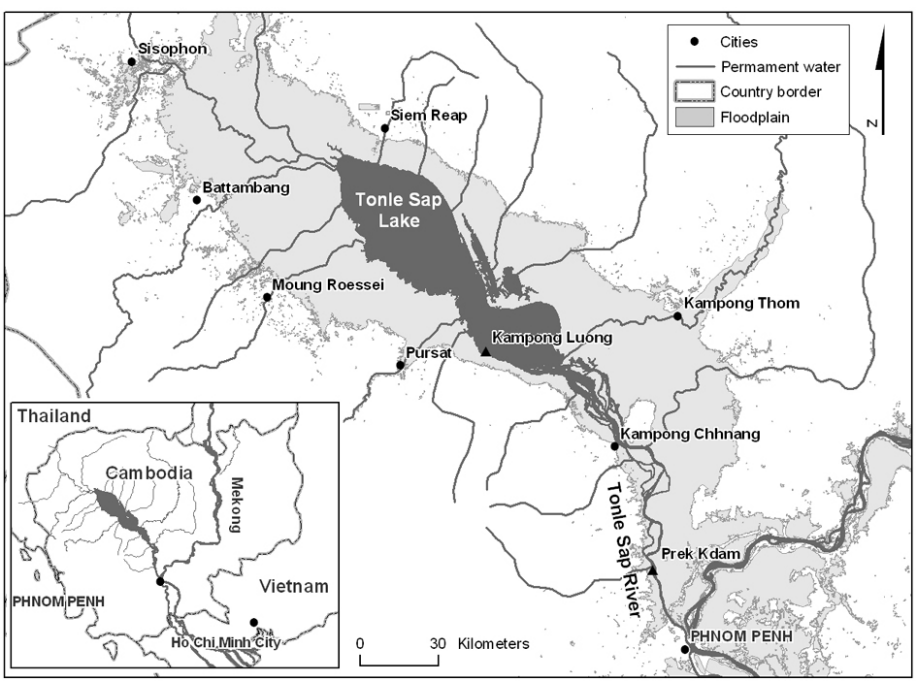



Figure 1. Tonle Sap Lake and its floodplains.

3. The basic hydrological and limnological processes, such as sediment transport and dissolved oxygen levels, are now relatively well documented (e.g. Bonheur, 2001; Carbonnel and Guiscafre, 1963; Koponen *et al*., 2004; Kummu *et al*., 2005; Lamberts, 2001; Penny *et al*., 2005; Sarkkula *et al*., 2004; Sarkkula *et al*., 2003; Tsukawaki, 1997;

van Zalinge *et al*., 2003; WUP-FIN, 2003), but the status and dynamics of biological productivity within the lake are not well studied. This is a major shortcoming in the understanding of the lake's ecological system (Kummu *et al*, 2006). Nonetheless, what is well identified about the Tonle Sap ecosystem is the concept of flood pulse (Lamberts, 2001). The concept was developed in Amazon Basin by Junk (1997), and should be utilized in Tonle Sap studies.

**Flood pulse**

4. On floodplains, the fluctuation of water level over time is the principal factor that causes the biota to adapt and produce characteristic community structures (Junk, 1997). Ecosystems that experience fluctuations between terrestrial and aquatic conditions are called pulsing ecosystems, and fall within the domain of the flood pulse concept. Junk's (1997) flood pulse concept has been widely accepted as describing highly productive floodplain environments and the ecology of pulsing systems. This information can be applied in basins with similar characteristics, such as the Lower Mekong Basin that, like the Lower Amazon, experiences large water level variation and one flood pulse per year. The importance of the flood pulse concept has been recognised by many authors working on the Mekong River/Tonle Sap system (see, for example, Bonheur and Lane, 2002; Fox, 2004; Lamberts, 2001; Poulsen *et al*., 2002; Sverdrup-Jensen, 2002).

# II METHODS, TOOLS AND STUDY LOCATIONS

## II.1 FIELD STUDIES

### II.1.1 Introduction

5. Hydrological field measurements support the validation of the Tonle Sap hydrodynamics and water quality model and the assessment of the influence of built structures. The field measurements were performed at the irrigation system on the Stung Chinit River, fishing lot area in Prek Toal and private irrigation reservoir on the floodplain in Stung Staung district. Measurements consisted of flow velocity and direction, discharge, water level and water quality analyses at the study sites. The period of field activities coincided with the annual hydrological cycle from August 2006 to January 2007.

### II.1.2 Stung Chinit

6. The goal of field measurements at the Stung Chinit irrigation system was collecting hydrological and water quality data for model calibration, assessing how the structure is changing discharges and water quality and what kind of new habitat the reservoir and canal network is creating for the fish population. Measurements were performed every second week from August 2006 to January 2007.

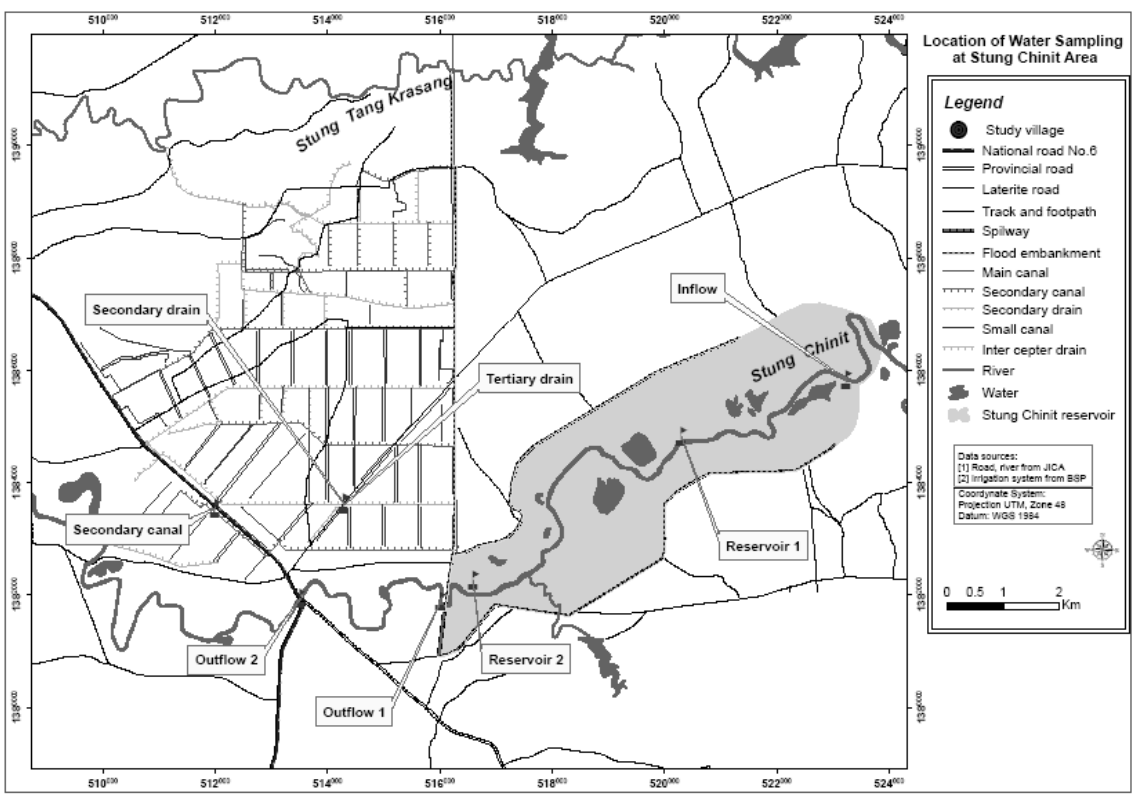



Figure 2. Measurement locations in the Stung Chinit irrigation scheme.

7. Hydrological measurements consisted of discharge and water level measurements. Discharge into the reservoir upstream of the reservoir and discharge from the reservoir right after the dam and next to the national road bridge were measured by an ADCP-device (Acoustic Doppler Current Profiler) (Figure 2.). Water levels were recorded in the reservoir next to the fish pass, downstream under the national road bridge and temporarily upstream at the discharge measurement location.

Figure 3. Discharge measurements by ADCP in Stung Chinit River.

8. Water quality measurements were carried out by water sampling in the locations where discharges were measured to find out possible changes in the river water quality caused by the structure. In addition to the river water analyses, samples were taken from the reservoir and from the irrigation canals. Water quality of the reservoir was sampled in the middle and near the outlet of the reservoir. Water quality in the irrigation canals was sampled in the secondary and tertiary drainage canals and in the secondary irrigation canal (Figure 3.). All water samples were analysed in the water quality laboratory of the Ministry of Water Resources and Meteorology in Phnom Penh. Analysed parameters were DO (dissolved oxygen), COD (chemical oxygen demand), TSS (total suspended solids), TDS (total dissolved solids), pH, conductivity, alkalinity, TOT-N (total nitrogen), NO3 (nitrate), NH4 (ammonium), TOT-P (total phosphorus) and PO4 (phosphate).

### II.1.3 Prek Toal

9. Fieldwork in the Prek Toal area aimed at finding out the impacts of fishing gears on the lake's hydrology. The major impacts of fishing gears on the flow fields of the lake are caused by thick bamboo fences which are used on fishing lot fence systems. The fences are assembled with bamboo mats attached to wooden poles placed at a distance of 50 to 70 cm from each other. The distance between the bamboo slats is 10 to 15 mm (Deap et. al. 2003). The impacts of bamboo fences on flow velocity and direction were studied by field measurements and laboratory experiments. The lake flow field without fences was studied by point measurements in the Prek Toal area in August 2006. Measurements were carried out by recording current meter (RCM9). Measurements were repeated in January 2007 when bamboo fences were installed on the lake.

Figure 4. Laboratory experiment in the fixed bed flume.

10. Laboratory experiments were performed in the laboratory of hydraulics in the Asian Institute of Technology (AIT) in Bangkok. Bamboo fences were installed to a fixed bed flume where flow velocity and discharge were controlled by setting the power of pumps. Water level was kept at approximately the same level in each measurement in the flume by setting the level of the tail gate at the end of the flume. The experiment was carried out with seven different flow velocities from 5 cm $s^{-1}$ to a maximum velocity of 68 cm $s^{-1}$. Three different pieces of bamboo fence were installed on the flume one by one for measurement at each flow velocity. Water level was recorded on both sides of the fence to find out the possible trapping effect of the fence. In addition to bamboo fence measurements the experiment was carried out with a piece of nylon net (net size 5 mm), which is replacing fences on the lake. Bamboo fences last only two years on the lake while cheaper nylon net lasts three years longer. Bamboo fences have therefore replaced nylon nets at several locations.

Figure 5. Bamboo fence on the lake, flow velocity and direction measurement by Acoustic Doppler Current Profiler.

11. In addition to the laboratory measurements, the impacts of bamboo fences were studied on the lake in the Prek Toal area. Flow velocity was measured by an Acoustic Doppler Current Profiler (ADCP, Figure 5.) on both sides of the bamboo fence of Fishing Lot No. 2 at the end of January 2007. Cross sections were measured at a distances of 2 m, 10 m, 50 m and 100 m of the fence both inside and outside of the fenced area.

### II.1.4 Private irrigation reservoir in Stung Staung District

Figure 6. Irrigation reservoir on the flood plain in Stung Staung District in dry and wet season.

12. Development of the Tonle Sap floodplain is most dramatically shown in the building up of huge private irrigation reservoirs. Reservoir banks are simply made by heaping up soil (Figure 6) to a sufficient height to trap rising floods. The height of embankments varies normally between 1.5 and 3 meters. When the flood level decreases and the area nearby the reservoir dries, the water in the reservoir is used to irrigate surrounding rice fields. Almost 40 reservoirs can be found in the Kampong Thom area. To study the impacts of private irrigation reservoirs, one of the reservoirs in Stung Staung district was chosen (Figure 6). The field measurement results indicate reservoir impacts on the floodplain hydrology and water quality. Water quality was measured by water sampling inside and outside of the reservoir (Figure 7.) when (i) the flood level was high, (ii) the water level was decreasing and the floodplain on the north side of the reservoir was already dry and (iii) all surrounding areas were dry and rice growing was started. Water samples were analysed in the water quality laboratory of the Ministry of Water Resources and Meteorology in Phnom Penh. Analysed parameters were DO, COD, TSS, TDS, pH, conductivity, alkalinity, TOT-N, NO3, NH4, TOT-P and PO4. In addition to the water sampling, water level was measured daily inside and outside of the reservoir by the reservoir staff.


Figure 7. Sampling locations at the private irrigation reservoir in Stung Stoung district.

## II.2 MODELS

### II.2.1 Modeling requirements

13. Modeling is a powerful tool to integrate heterogeneous data, fill in spatial and temporal data gaps, study dynamic processes and illustrate natural processes. In many cases, modeling is also the only practical tool to assess impacts of planned developments in a systematic and quantitative way. In the Tonle Sap built structures case, models have been used to study the different types of structures and impacts from the basin-wide to the very local scale. A 3D hydrodynamic and water quality model has been used. Three dimensionality means that both the horizontal and vertical differences in the water properties are modeled. The Tonle Sap system and reservoirs are highly three dimensional. That is, their properties vary significantly in both horizontal and vertical directions, so the use of a 3D model is necessary. As an example conditions in the lake proper and the floodplain are totally different, floodplain flow and mixing being just a fraction of the corresponding properties in the lake proper. In the floodplain, in the vertical direction the flow, sediment and oxygen conditions are quite different on the surface and near the bottom.

### II.2.2 Overview of the EIA 3D hydrodynamic model

14. The EIA 3D hydrodynamic and water quality floodplain/lake/river model utilized in the study is probably the only existing 3D flood model in the world, at least on the level of a practical tool. It has been developed based on a previous 3D lake and sea model. The EIA 3D model was developed by the Environmental Impact Assessment Center of Finland Ltd (EIA Ltd.). The development work started 1974 when EIA Ltd. was still part of the Technical Research Centre of Finland. The model has been applied under the Cambodian National Mekong Committee (CNMC) and Mekong River Commission Secretariat (MRCS) to the Tonle Sap since 2001 (WUP-FIN, 2003).

15. The EIA 3D model system is a fully three-dimensional model based on rectangular grid representation. The system accommodates meteorological, hydrological, topographic, land use and infrastructure characteristics of the area under study. The modelling platform includes data processing, model control, GIS, database control, model data products and visualization. The model is able to describe the three-dimensional characteristics of the flooding, flow, water quality, erosion and sedimentation in the lakes, reservoirs, river channels and floodplains. The EIA 3D model system structure is presented in Figure 8.

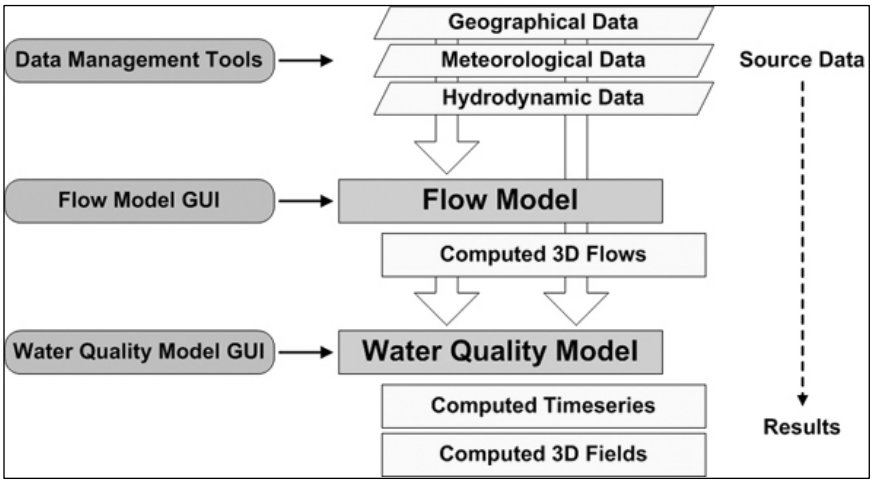



Figure 8. Schematic EIA model structure. GUI = Graphical User Interface.

### II.2.3 Hydrodynamic model equations

16. Computed flows are determined by the following factors:
    1. wind force,
    2. atmospheric pressure at the surface,
    3. conservation and incompressibility of water,
    4. internal friction (viscosity),
    5. transport of velocity differences with water currents (advection),
    6. Coriolis force caused by the earth's rotation,
    7. density differences and water level gradients (hydrostatic pressure),
    8. bottom friction,
    9. vegetation impacts on friction and wind stress.

17. The motion of a fluid particle on the surface of the earth is governed by the Navier-Stokes equation of motion (the force balance equation) /1/

$$\frac{\partial u}{\partial t} = fv - \frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\nu_{hor}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{hor}\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_{ver}\frac{\partial u}{\partial z}\right) - \mathbf{u}\cdot\nabla u \qquad (1)$$

$$\frac{\partial v}{\partial t} = -fu - \frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(\nu_{hor}\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{hor}\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_{ver}\frac{\partial v}{\partial z}\right) - \mathbf{u}\cdot\nabla v \qquad (2)$$

$$\frac{\partial p}{\partial z} = -g\rho \qquad (3)$$

$$\nabla\cdot\mathbf{u} = 0 \qquad (4)$$

**u** = velocity vector, m/s
**u**, v = horizontal velocity components, m/s
t = time, s
p = pressure, Pa
f = Coriolis coefficient
$\rho_0$ = average density of water, kg/m$^3$
$\rho$ = density of water, kg/m$^3$
g = 9.81 m/s$^2$
$\nu_{hor}, \nu_{ver}$ = horizontal and vertical eddy momentum viscosity, m$^2$/s
$\nabla$ = gradient operator, m$^{-1}$

The forces included are (from left to right) local acceleration, advective (or convective) accelerations, pressure gradient, gravitation, Coriolis force and molecular viscosity.

Equation (4) is the continuity equation (mass conservation equation). /3/ The vertical viscosity can either be calculated by a turbulence model such as k-ε or given. In the Tonle Sap models a constant vertical viscosity of 35 cm$^2$/s is used.

### II.2.4 Hydrodynamic model input and output data

18. Model input data consists of:
    1. bathymetric data for the model grid, either as shorelines, point depth data and depth isolines, or as a digital elevation model,
    2. wind measurements from the modelled area for wind forcing computation, wind speed (m/s) and direction (degrees) with a 3 – 6 h or better time resolution,
    3. boundary flows ($m^3/s$) including rivers and open boundaries (daily or more frequent values),
    4. flow and/or water level measurements for model calibration, flow is often measured in cm/s for every ten minutes, for surface height the time resolution depends on the modelled area and may vary from 10 minutes to one day,
    5. land use (vegetation types).

19. The land use types affect both the hydrodynamic and water quality parameters. In the hydrodynamic model the effect comes from three sources:
    - wind fetch
    - wind shielding
    - vegetation stress (friction).

    Average vegetation height, cover and friction are given for each land use type. These in turn determine wind and flow friction in different depth zones. Wind friction is diminished proportional to the vegetation cover above the water level. Vegetation flow friction affects flow only in the layers that are lower than the vegetation height.

20. Model outputs include:
    1. water depth (DEPS, DEPZ)
    2. water elevation (SURF)
    3. flow velocity components (U, V)
    4. flood duration (FLDU-files)
    5. flood arrival time (FLAR-files).

### II.2.5 Sediment model

21. The governing equation for the *i*th fraction of suspended solids includes advection, dispersion, settling and erosion by re-suspension. It retains the conventional form of the general transport equation as follows:

$$\frac{\partial c_i}{\partial t} + u\frac{\partial c_i}{\partial x} + v\frac{\partial c_i}{\partial y} + w\frac{\partial c_i}{\partial z} = D_h\frac{\partial^2 c_i}{\partial x^2} + D_h\frac{\partial^2 c_i}{\partial y^2} + D_v\frac{\partial^2 c_i}{\partial z^2} - k_{s,i}c_i + S_{e,i}. \quad (5)$$

| | |
|---|---|
| $c_i$ | concentration of a substance, units/m$^3$ |
| $t$ | time, 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 |
| $k_{s,i}$ | settling coefficient cm/d |
| $S_{e,i}$ | net upward suspended sediment flux, depends on critical shear bottom stress or velocity. |

A 7 cm/d settling velocity has been used for the Tonle Sap sediment model. It is based on grain size measurements and model calibration. A 12 cm/d settling velocity is used for the Stung Chinit model in order to accommodate large grain size sediments.

The model input values include initial and boundary sediment concentrations. They are obtained from measurements.

### II.2.6 Oxygen model

22. Dissolved oxygen concentrations are governed by sediment oxygen demand, BOD (biochemical oxygen demand) and aeration. The equation for oxygen without transport and diffusion (these are the same as in equation 5) is:

$$\frac{\partial c}{\partial t} = -k_1 BOD + k_2(c_s - c) \quad (6)$$

Here $k_1$ is the BOD rate, $k_2$ aeration rate and $c_s$ oxygen saturation value. In the bottom layer the effect of the bottom sediment oxygen demand is added to the equation.

23. In addition, BOD7 (biological oxygen demand) is one of the calculation parameters. It has not been used so far because of the amount of time required for BOD load modelling. Instead bottom sediment oxygen demand (SOD) is used.

24. The aeration and bottom sediment oxygen demand values are given for each land use class. It is obvious that the vegetation cover and land use type have a strong effect on aeration and the decaying biological material on the ground. The degradable biological material in the water phase (BOD) is transported around and consumes oxygen at a rate that is not assumed to be strongly land use dependent. The values for the SOD vary between 0.05 and 1.4 mg/m$^2$/d depending on the land use (vegetation) type. Similarly the aeration coefficient varies between 1 and 10 cm/d.

## II.3 TONLE SAP 3D MODEL SET-UP

### II.3.1 Model grid

25. The model covers a 261 km x 196 km = 51 000 km$^2$ area. During the highest flood about 15'000 km$^2$ of this area is flooded. The model area includes the main tributaries and the Tonle Sap River from Prek Kdam to the lake (Figure 9).

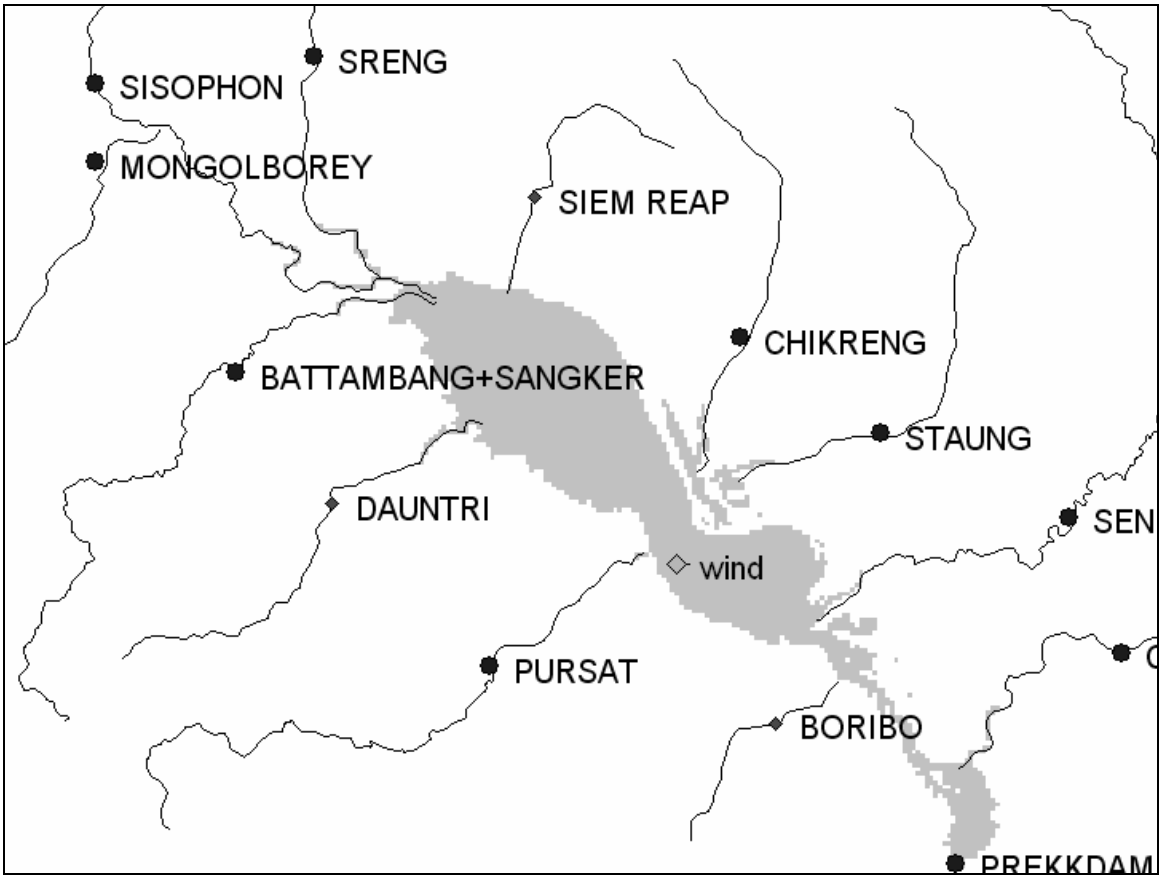



Figure 9. The 3D model application area for Tonle Sap Lake and its floodplain.

26. The basic grid size is 1 km and the number of grid cells on the horizontal plane 261 x 196 = 51 156. On the vertical plane there are 14 layers which are 1 m thick to 12 m depth. Below that grid thickness is 1.5 and 2.5 m. Near the bottom the layer thickness varies depending on the total depth. Altogether there are 716 184 3D grid points. Part of the Tonle Sap model grid is shown in Figure 10.

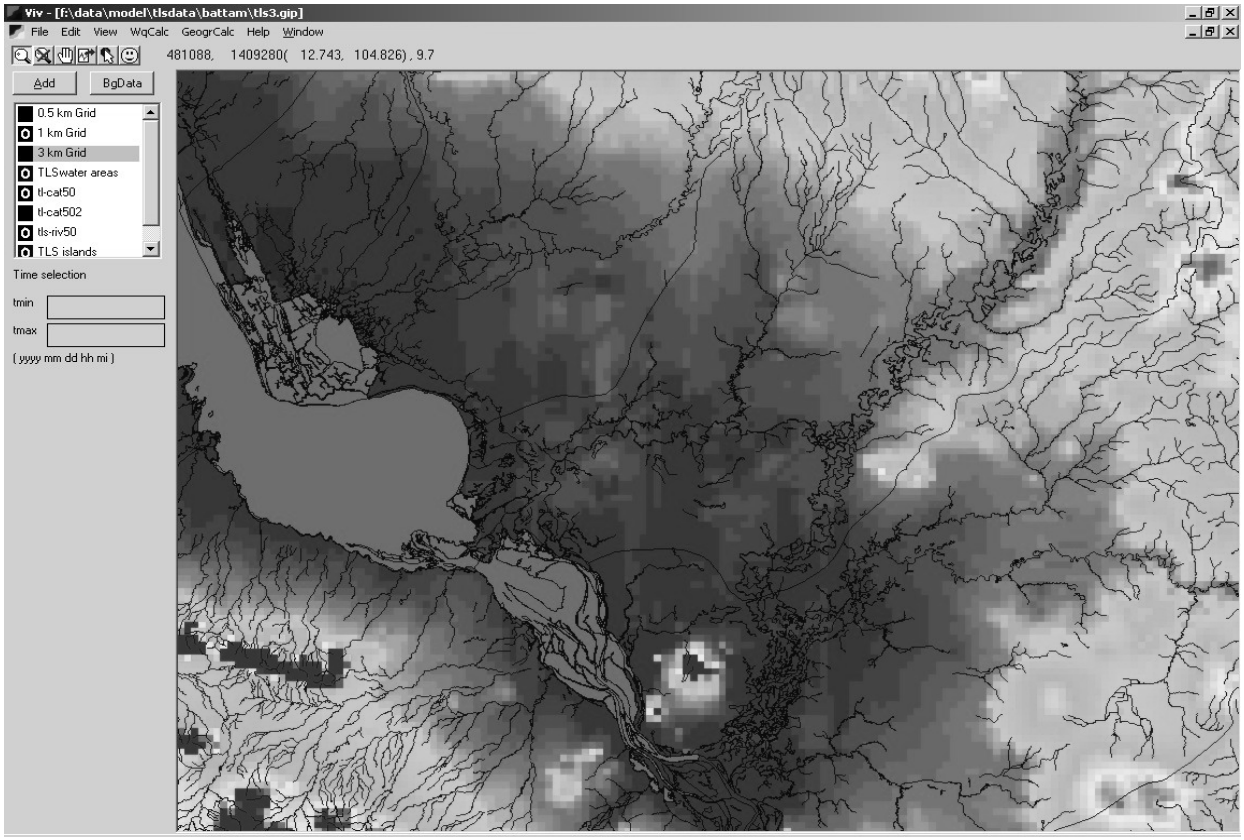



Figure 10. Tonle Sap model grid. Colors show elevations of the grid cells.

### II.3.2 Topographic and land use data

27. The floodplain topography is based on the Certeza survey from 1964. It includes first and second order leveling around the lake, 1400 linear km of profile surveys and photogrammetry. The data has been compared to other topographic data, satellite data and recent surveys. The comparisons indicate that the Certeza data is accurate enough for modelling purposes. The data has been further checked and supplemented with MRCS/CNMC topographic survey data consisting of 22 survey lines totaling 470 km.

28. The lake proper and the Tonle Sap River topography are based on the MRCS Hydrographic Atlas survey of 1999. The data has been transformed to the same reference system as the floodplain topography (Ha Tien MSL - Mean Sea Level).

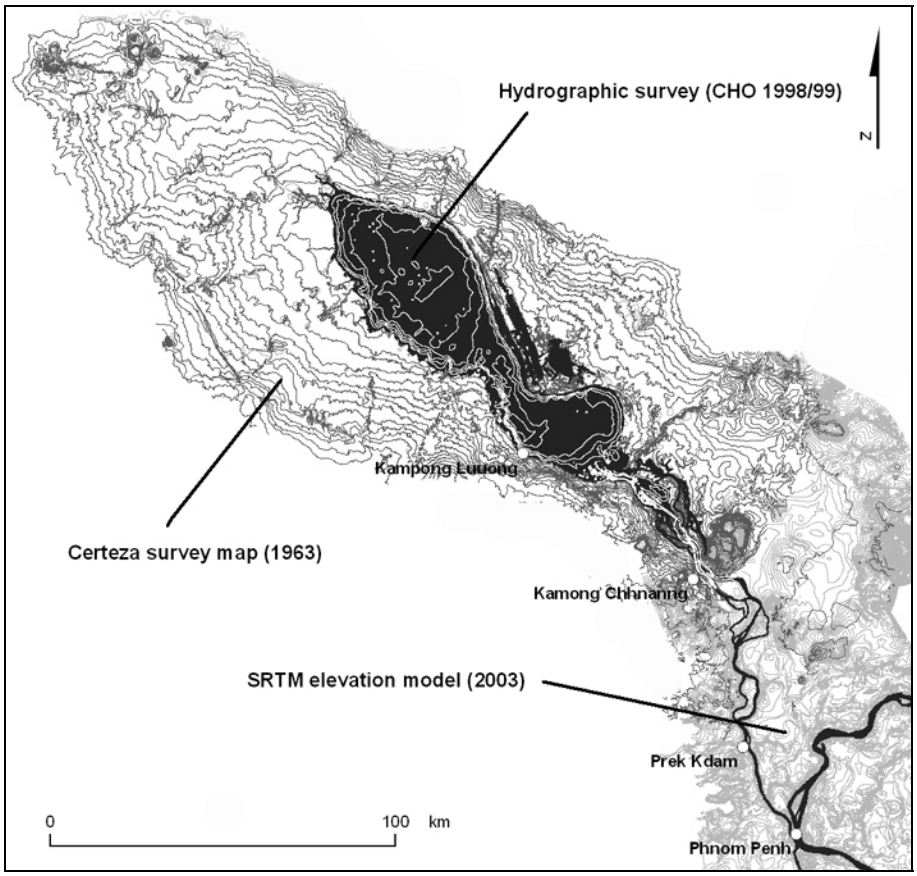



Figure 11. Tonle Sap topographic data.

29. The land use data is based on the JICA Reconnaissance Survey. In the model the 59 original classes have been aggregated to 8 model classes. For instance “shrubland” and “abandoned field covered by shrub” are combined. Only the main classes are used, that is:
    1. agricultural land
    2. grassland
    3. shrubland
    4. forest
    5. water
    6. soil and rock.

### II.3.3 Boundary conditions

30. Lake *wind measurements* are used. They have been conducted by the MRCSW WUP-FIN project. Phnom Penh airport winds are quite different, and have not been used.

31. *Discharges* are provided on the model boundaries:
    - 12 tributaries shown in Figure 9
    - Prek Kdam

32. The discharges in tributaries are based on the latest rating curves and hydrological model (MRCS/SWAT) results. The Tonle Sap River and overland flow have been correlated to the available Mekong, Tonle Sap River and Lake water levels and discharges.

33. *Oxygen and sediment* measurements are used for the model boundary values and for model calibration and validation. For each discharge boundary there are also oxygen and sediment boundaries. Oxygen concentrations are based on the monthly averages of the available measurements. Sediment concentrations in tributaries are based on the CNMC and MRC measurements. Sediment concentrations in Prek Kdam are based on the MRC Water Quality Monitor Network data.

### II.3.4 Model calibration and validation results

34. The measured and modelled water levels are shown in Figure 12. The simulation was conducted from June 1996 to November 2004. The match is surprisingly good considering that the Prek Kdam and overland flows have been estimated based on one point water level measurements and a second order lake volume model.

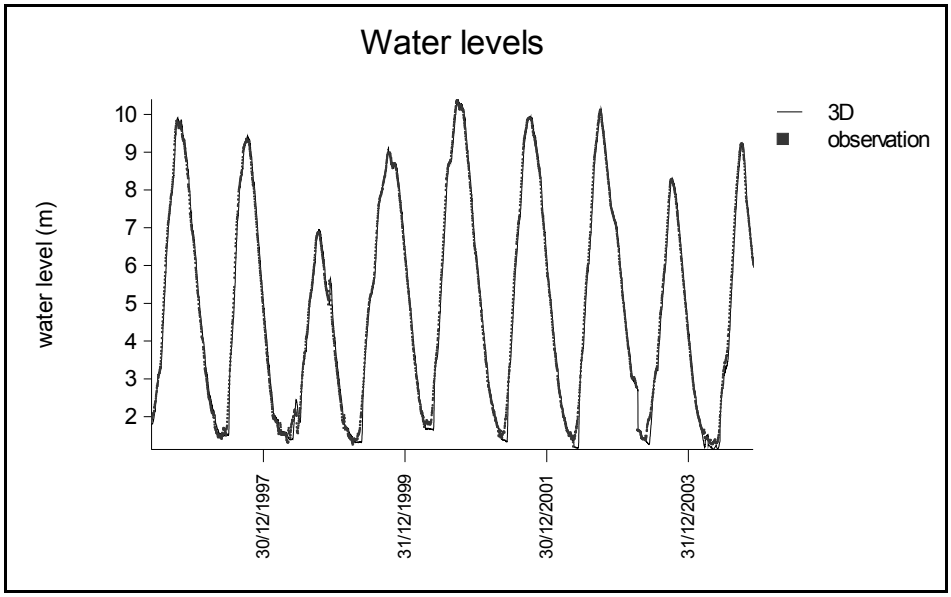



Figure 12. Measured (red dots) and WUP-FIN model calculated water levels at the Tonle Sap (Kampong Luong).

35. The total suspended sediment (TSS) results from Kampong Chhnang (KCH1) station are presented in Figure 13. For the validation, the time period between May 2001 and May 2002 was used. Because of the limited measurement data, only surface suspended sediment (SS) concentrations (0-1 m below the water surface) were used. 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 are higher than the calculated. During the receding flood (October-January) the computed values are higher than the observed ones. This may be due to high sediment resuspension rates in the lake during low water level.

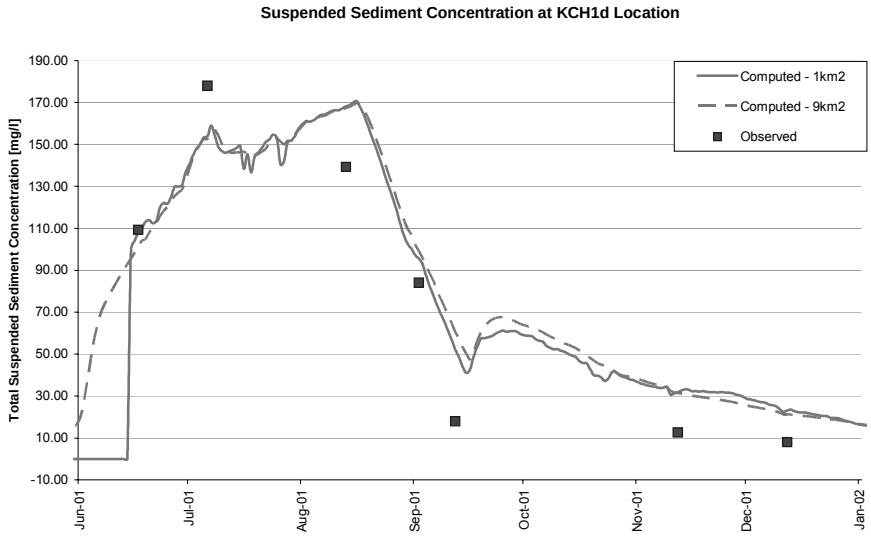



Figure 13: TSS concentration comparison between observed and computed values at KCH1.

Simulated sedimentation (Figure 14) corresponds well with the natural levees that can be seen in the Tonle Sap near the lake proper edge. The simulated net sedimentation is nearly zero in the lake proper, which has been confirmed by field measurements.

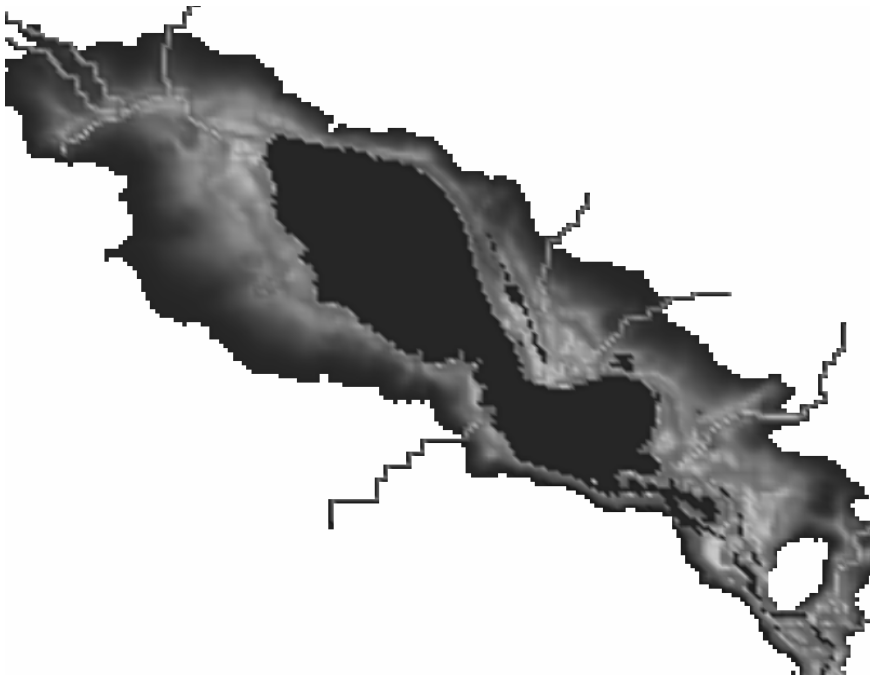


Figure 14. Calculated net sedimentation between May 1. – Sept. 13, 2001.

36. According to measurements the characteristic feature of the floodplains is the large-scale anoxia. The model reproduces this phenomenon well. Figure 15a illustrates typical measured oxygen distributions in two cross-sections from the western floodplains and from the middle of the lake. The measured distribution of surface oxygen can be compared with the simulated values as shown in Figure 15b. In the floodplain the model also produces anoxia near the bottom.

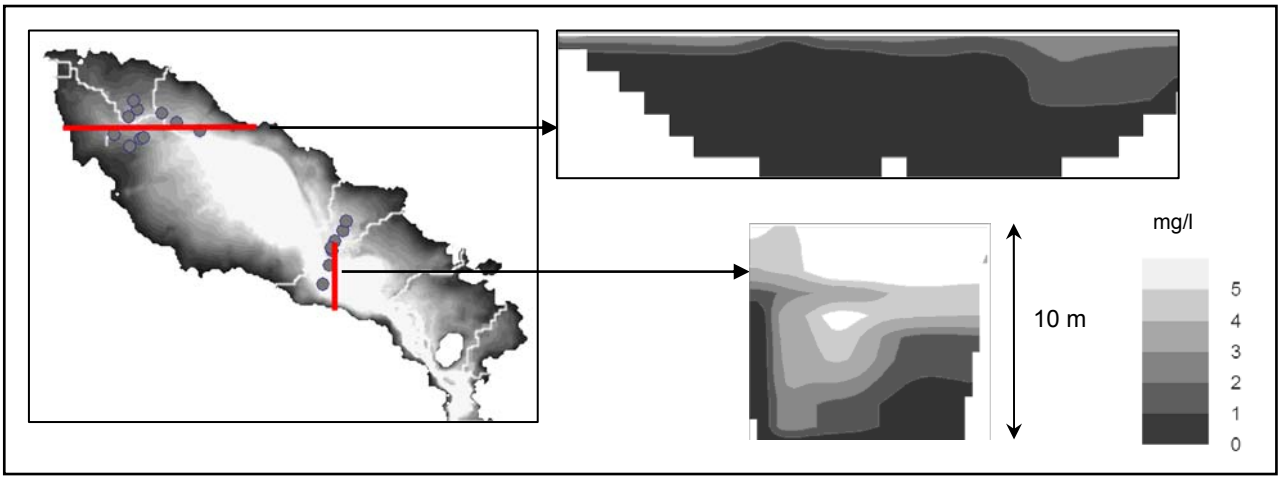



Figure 15a. Two water quality measurement cross-sections and sampling sites. Floodplain water depths are shown on the left hand side (1 m intervals). Measured October 2002 oxygen cross-sections shown on the right hand side from the north and middle of the lake.

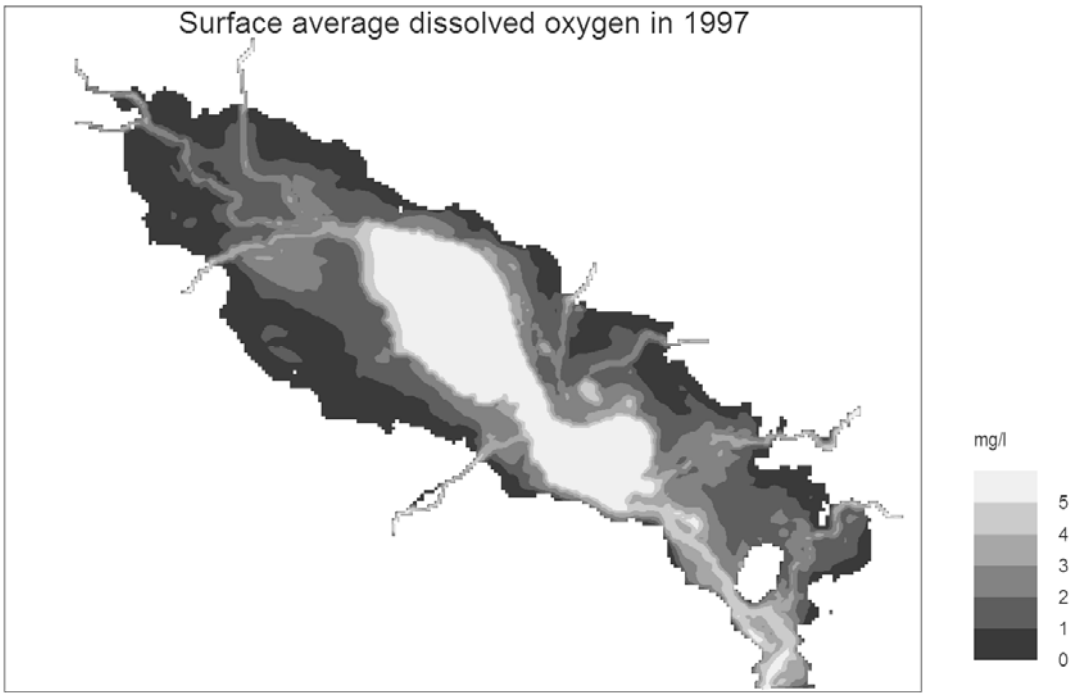



Figure 15b. Modelled time average of the surface oxygen.

## II.4 STUNG CHINIT 3D RESERVOIR MODEL

37. Stung Chinit is an irrigation system that was developed by an ADB project. The model application area can be seen in Figure 2. Corresponding model implementation is presented in Figure 16. The model grid size is 50 m. The narrow channels are described with a smaller grid size.

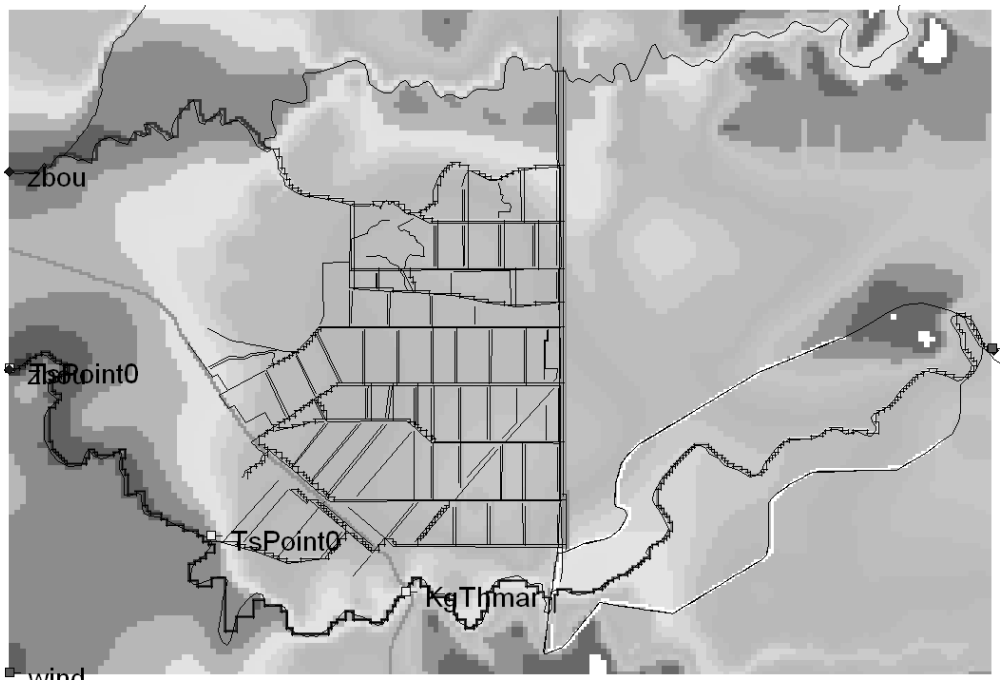



Figure 16. Stung Chinit model implementation area showing the reservoir on the right hand side, river and the irrigation channel system. Colors signify elevations (red lower, blue higher).

38. An alternative *nested* model has been applied to the area (Figure 17). It consists of 1000, 50 and 25 m grids that are combined together. The 25 m grid covers the irrigation channel system. The model has not been used in the final simulations because it requires more computation time. Also, the focus has been on the impacts of the reservoir and not on the functioning of the irrigation channel system.

39. The upstream boundary discharge has been obtained from a rating curve relating measured water levels to discharge. For the downstream a flow rating curve was developed. The reservoir spillway description proved to be a difficult part of the implementation. It was found that utilization of a hydraulic weir description gave stable results. A broad crested weir formula that is solved iteratively has been applied. The sediment and oxygen upstream boundary values have been estimated from available measurements.

40. The model has been used to simulate flow, reservoir fill-up, and sediment and oxygen levels. Similar model parameter values have been used as with the Tonle Sap model.


Figure 17. Stung Chinit nested model implementation. Grid sizes are 1000, 50 and 25 m. The finest grid covers the irrigation channel network.

## II.5 DEFINITION OF THE MODEL SCENARIOS

41. The model scenarios represent possible future basin-wide and Tonle Sap catchment developments. Intensive scenarios have been selected in order to see more clearly the impacts on the Tonle Sap system. The scenarios assume specific increases in hydropower and irrigation structures. The actual future development depends on economic and political factors and cannot be predicted. The scenarios give an indication of the nature and order of the magnitude of possible impacts on the Tonle Sap but are not intended to predict precisely what will happen in the future.

### II.5.1 Basin-wide scenarios

42. Three basin-wide scenarios have been used in the study.

    1. **Baseline**: development of the basin is on the current level.
    2. **Intensive Development**: 55 $km^3$ of hydropower and irrigation dams in the Chinese Mekong mainstream and in the upstream Mekong tributaries are constructed.
    3. **Mainstream Dams**: dams in the Intensive Development scenario + 85 $km^3$ of mainstream dams in Lao PDR, Thailand and Cambodia (High Luang Prabang, Sayabouri, Pa Mong, Upper Thakhek, Ban Koum, Stung Treng, Sambor) are constructed.

43. The Baseline scenario is obtained from measured Tonle Sap in- and outflows. The development level changes slightly between years, but in practice the development

changes have been minor compared to the total flow volumes. Because of this the development level can be assumed to stay nearly on the same level between years.

44. The Intensive Development scenario represents possible future intensive development of the Mekong water resources (Table 1 and Norplan and EcoLao, 2004). The projected storage capacity for the year 2025 is 55 $km^3$. China and Lao PDR will clearly dominate in the hydropower capacity and storage volume and will account for about 83% of the total Mekong capacity.

45. Chinese dam cascade details for 8 dams are presented in Table 2. Plans exist for a total of 14 dams. The existing Lao PDR storage capacity is dominated by the Nam Ngum 1 reservoir with an active storage capacity of 4.7 $km^3$. At the moment the total Upper Mekong Basin hydropower capacity is 2850 MW and the Lower Basin 1800 MW.

Table 1. Existing and predicted active storage volume ($km^3$) in the Mekong Basin. (Norplan and EcoLao, 2004).

| | China | Lao PDR | Thailand | Cambodia | Vietnam | Total |
|---|---|---|---|---|---|---|
| 2004 | 0.62 | 5.19 | 5.53 | N/A | 0.89 | 12.24 |
| 2010 | 10.52 | 12.95 | 5.53 | N/A | 0.92 | 29.92 |
| 2025 | 23.19 | 22.61 | 5.53 | N/A | 3.59 | 54.92 |

Table 2. Characteristics of the Chinese Mekong dam cascade (Norplan and EcoLao, 2004).

| No. | Project | Year of commissioning | Installed capacity (MW) | Active storage ($km^3$) |
|---|---|---|---|---|
| 1 | Manwan | 1993-96 | 1500 | 0.26 |
| 2 | Dachaoshan | 2001-2004 | 1350 | 0.37 |
| 3 | Xiaowan | 2010-14 | 4200 | 9.9 |
| 4 | Gonguoqiao | 2012 | 750 | 0.12 |
| 5 | Jinghong | 2013 | 1500 | 0.25 |
| 6 | Nuozhadu | 2014 | 5500 | 12.3 |
| 7 | Mengsong | Before 2025 | 600 | - |
| 8 | Ganlanba | Before 2025 | 150 | - |

46. The Mainstream Dams (MS) scenario is based on the Indicative Basin Plan of the Mekong Committee in 1970. It is not very probable that the MS scenario will be realized because of the environmental and socioeconomic impacts and political complications. However, these plans are still discussed and have even been presented recently in the Thai media. Because of this it is relevant to study the possible impact of these dams.

### II.5.2 Tonle Sap watershed scenarios

47. The net storage capacities for hydropower and irrigation development have been obtained from the Lower Mekong Water Resources Inventory (WATCO, 1984). The planned total net storage is 5.5 $km^3$ in the upper reaches of the Tonle Sap tributaries. The division of the storage between the sub-basins is presented in Table 3 and location of the storages and accompanying irrigation areas in Figure 18.

Table 3. The division of the Tonle Sap hydropower and irrigation storage between the sub-basins (source: Tonle Sap Built Structures database)

| Sub-basin | Net storage capacity million m3 |
|---|---|
| Sen | 2900 |
| Staung | 550 |
| Chikreng | 160 |
| Mongkol Borey | 115 |
| Sreng | 610 |
| Chinit | 390 |
| Pursat | 860 |
| **Total** | **5585** |

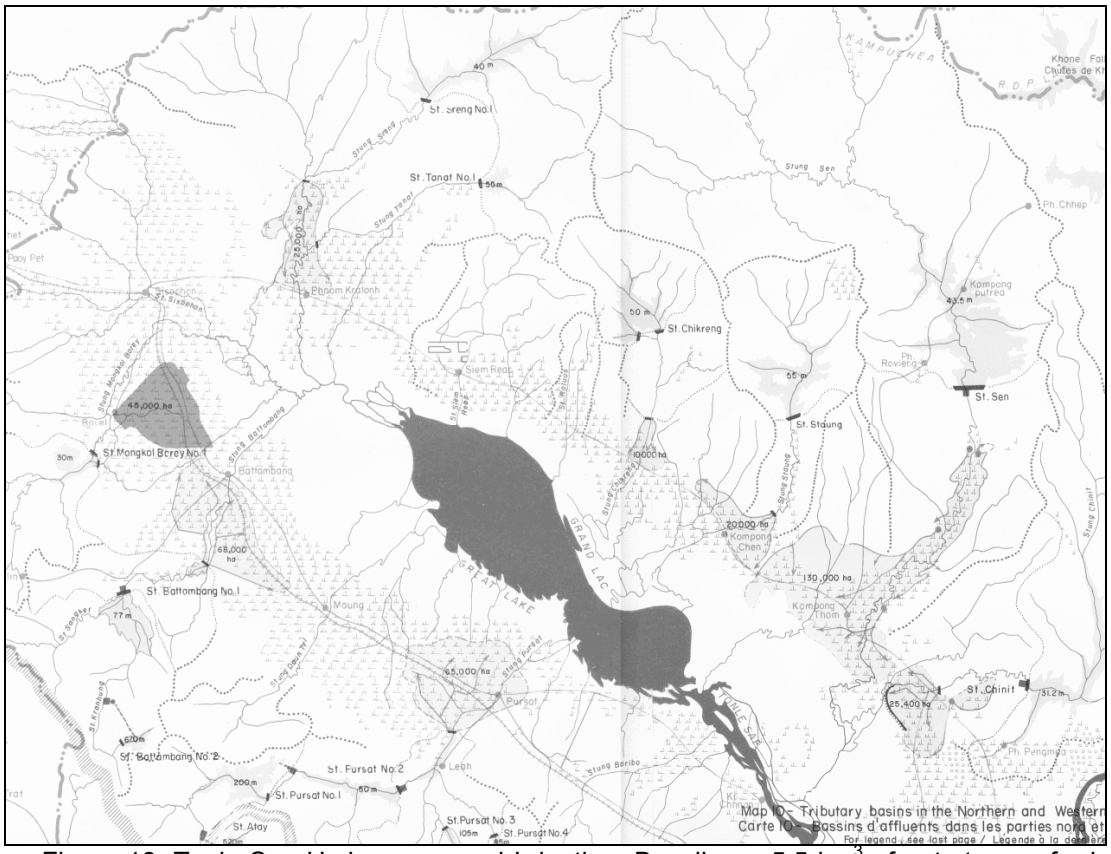



Figure 18. Tonle Sap Hydropower and Irrigation: Baseline + 5.5 km$^3$ of net storage for hydropower and irrigation in the upper reaches of the Tonle Sap tributaries. Presented in Lower Mekong Water Resources Inventory (WATCO, 1984).

48. Although at the moment there are no major hydropower or irrigation dams in the Tonle Sap, developments are going to be realized in the near future. The China Daily reported on February 17th 2007 that Chinese companies have signed several agreements with Cambodian government officials to build a hydropower plant in Battambang province. The plant will cost USD 190 million. Its power generation capacity will be 53 MW. The plant will be quite small compared to the Chinese dams described in Table 2, but could have a significant impact locally.

# III BASIN-WIDE TONLE SAP SCALE RESULTS

## III.1 TONLE SAP HYDROLOGICAL CHARACTERISTICS

49. The area of the lake varies between the dry and wet season from around 2,500 $km^2$ up to about 15,000 $km^2$, while the water level of the lake increases from less than 1.4 m to 6.8-10.3 m above the mean sea level (amsl) in Ha Tien datum, depending on the year. The bottom of the lake is approximately 0.5 - 0.7 m amsl. During the wet season, the volume of the lake increases from about 1.3 $km^3$ during the dry season up to 75 $km^3$, depending on the flood intensity. The summary of the available data is presented in Table 4 and Figure 19. Here the year represents the flood cycle which begins in May of the year in question.

Table 4. Summary of the hydrological data in Tonle Sap Lake during the years 1997-2003.

| | Water level [m] | | Lake area [km2] | | Lake volume [km3] | |
|---|---|---|---|---|---|---|
| | max | min | max | min | max | min |
| **max** | 10.36 | 1.48 | 15278 | 2402 | 76.05 | 1.83 |
| **min** | 6.86 | 1.19 | 9637 | 2061 | 33.00 | 1.35 |
| **average** | 9.11 | 1.34 | 13218 | 2237 | 59.56 | 1.59 |

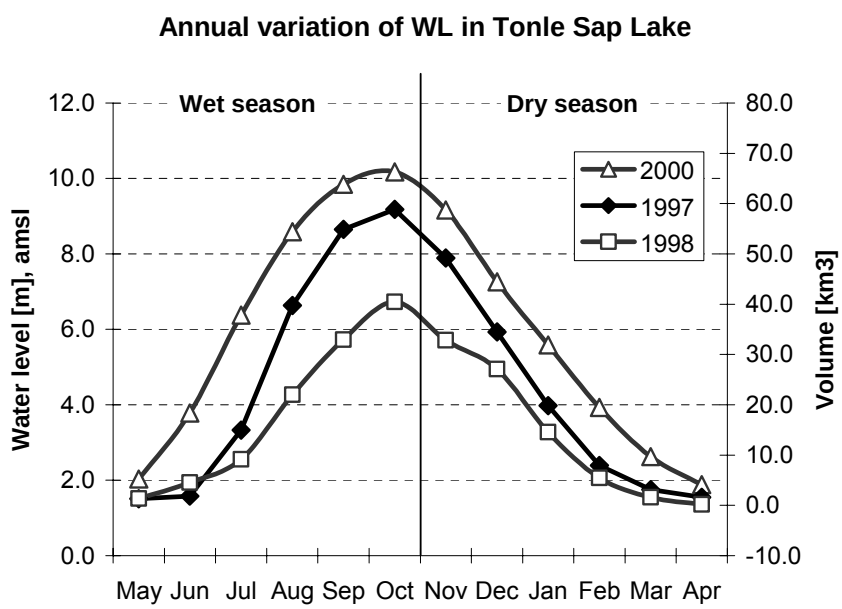



Figure 19. Annual variation of water level in the Tonle Sap Lake. Years 1997, 1998, and 2000 represent average flood, dry year, and high flood, respectively. Water levels are above the mean sea level in Ha Tien, Vietnam. Bottom of the lake lies about 0.7 m above the mean sea level.

50. The Tonle Sap Lake and its sub-catchments with the main tributaries are presented in Figure 20. Also, the locations of the Prek Kdam measurement station, where the discharge into and out of the lake to/from the Mekong is measured, and Kampong Luong, where the lake's water level is measured, are presented.

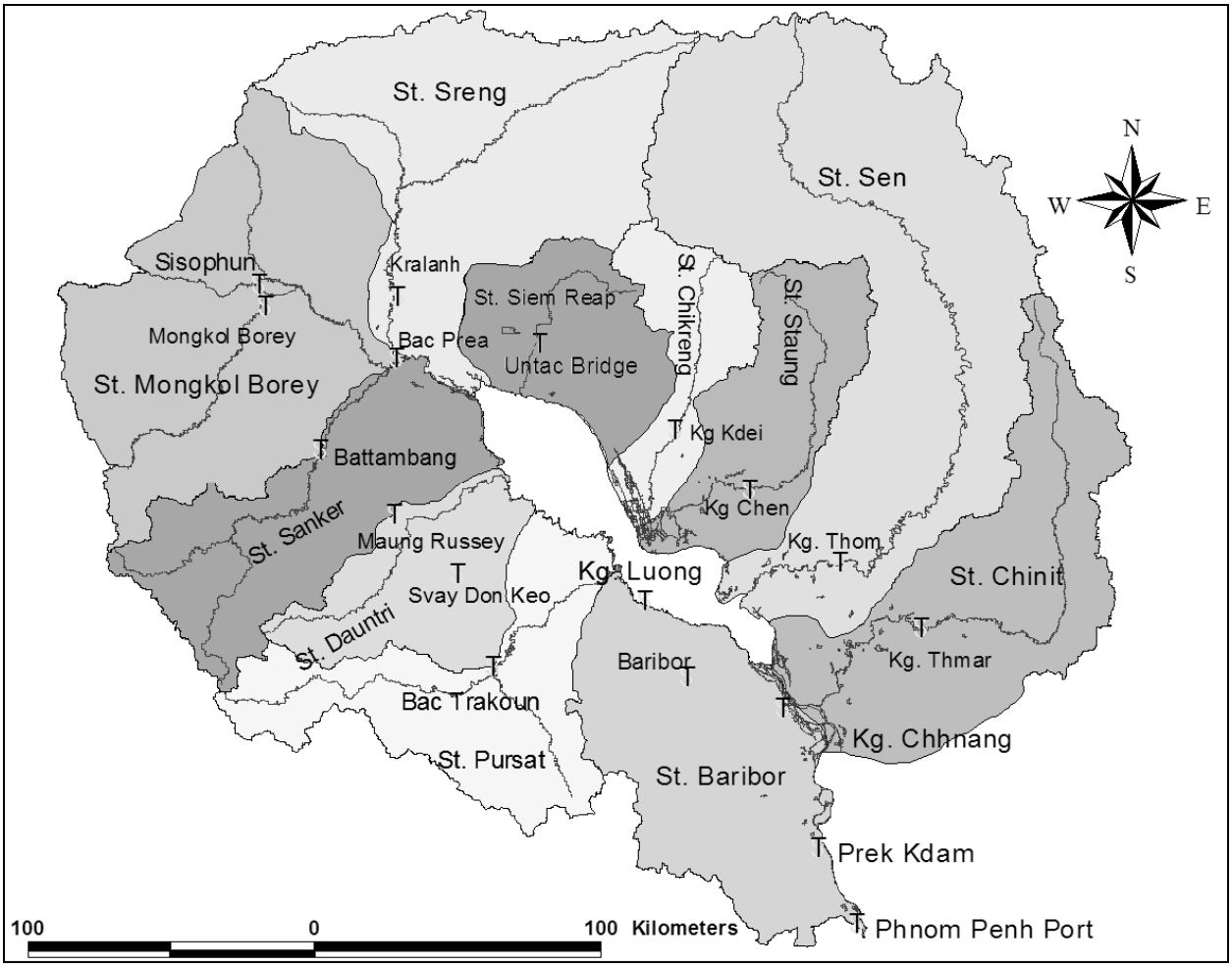



Figure 20. Tonle Sap Basin and its sub-catchments with the main rivers.

51. The following data have been used for the water balance calculations (numbers located in Figure 21):

1. Water level of the lake at Kampong Luong ($WL_{KL}$) and water level of the Tonle Sap River at Prek Kdam ($WL_{PK}$) and Phnom Penh Port ($WL_{PP}$)
2. Inflow into and out of the lake through the Tonle Sap River at Prek Kdam - $Q_{TSR}$
3. Overland flow from the Mekong to the Tonle Sap through floodplains – $Q_{OVR}$
4. Inflow from the 12 main tributaries - $Q_{TRIB}$
5. Rainfall data around the lake from two stations - $Q_{PREC}$
6. Evaporation from two stations – $Q_{EVAP}$

52. Figure 21 illustrates the location of different components of the water balance study.

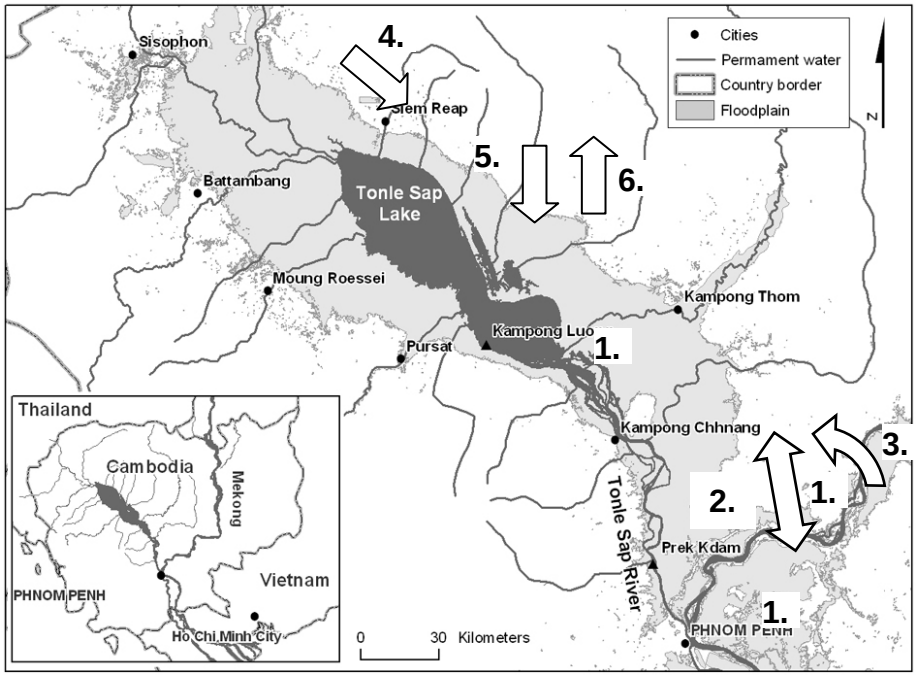



Figure 21. Illustration of the water balance calculation elements' locations.

53. Due to the flooding, the discharge can be measured only from the part upstream from the floodplain. In Table 5 the total area and observed area for each tributary is presented. The total area of the catchment, without the dry season lake area, is 83,011 km$^2$ from which 54.4% or 48,684 km$^2$ was observed by the measurements. The total area of the Tonle Sap Basin including the dry season lake, as presented in Figure 20, is 85,786 km$^2$. This is around 10.8% of the total area of Mekong Basin (Mekong River Commission, 2003).

Table 5. Total catchment and observed area. Observe that Sisophun and Mongkol Borey are separated here whereas in Figure 20 they are combined.

| Data available | Area km² | Observed area km² | % | Not observed km² |
|---|---|---|---|---|
| Chinit | 8236 | 4130 | 50.1% | 4106 |
| Sen | 16359 | 14000 | 85.6% | 2359 |
| Staung | 4357 | 1895 | 43.5% | 2462 |
| Chikreng | 2714 | 1920 | 70.7% | 794 |
| Siem Reap | 3619 | 670 | 18.5% | 2949 |
| Sreng | 9986 | 8175 | 81.9% | 1811 |
| Sisophun | 4310 | 4310 | 100.0% | 0 |
| MKBorey | 10565 | 4170 | 39.5% | 6395 |
| Sangker/Battambang | 6052 | 3230 | 53.4% | 2822 |
| Dauntri | 3695 | 835 | 22.6% | 2860 |
| Pursat | 5965 | 4480 | 75.1% | 1485 |
| Baribor | 7153 | 869 | 12.1% | 6284 |
| **Catchment** | **83011** | **48684** | **54.4%** | **34327** |
| **Dry season lake** | **2774** | | | |
| **Catch.+lake** | **85785** | | | |

54. The monsoon climate has two main seasons in Southeast Asia:
    - Wet season from May to October
    - Dry season from November to April.

55. Around 87% of the precipitation occurs during the 6 month rainy season as can be seen from Table 6 and Figure 22. The annual average precipitation in Siem Reap was 1494 mm during the years 1997-2004 while in Prek Kdam it was 1079 mm. The average, used in this study for rainfall, was 1287 mm (Table 6).

Table 6. Monthly average precipitation at Siem Reap (SR) and Prek Kdam stations.

| | SR | Prek Kdam | AVG |
|---|---|---|---|
| Jan | 0.7 | 15.8 | 8.2 |
| Feb | 4.6 | 1.1 | 2.8 |
| Mar | 20.8 | 17.2 | 19.0 |
| Apr | 62.9 | 40.2 | 51.6 |
| May | 164.7 | 112.8 | 138.7 |
| Jun | 245.7 | 140.1 | 192.9 |
| Jul | 234.2 | 139.1 | 186.7 |
| Aug | 205.9 | 134.2 | 170.1 |
| Sep | 272.1 | 183.4 | 227.7 |
| Oct | 210.4 | 192.6 | 201.5 |
| Nov | 65.4 | 85.2 | 75.3 |
| Dec | 7.0 | 17.8 | 12.4 |
| Annual prec | 1494.4 | 1079.4 | 1286.9 |

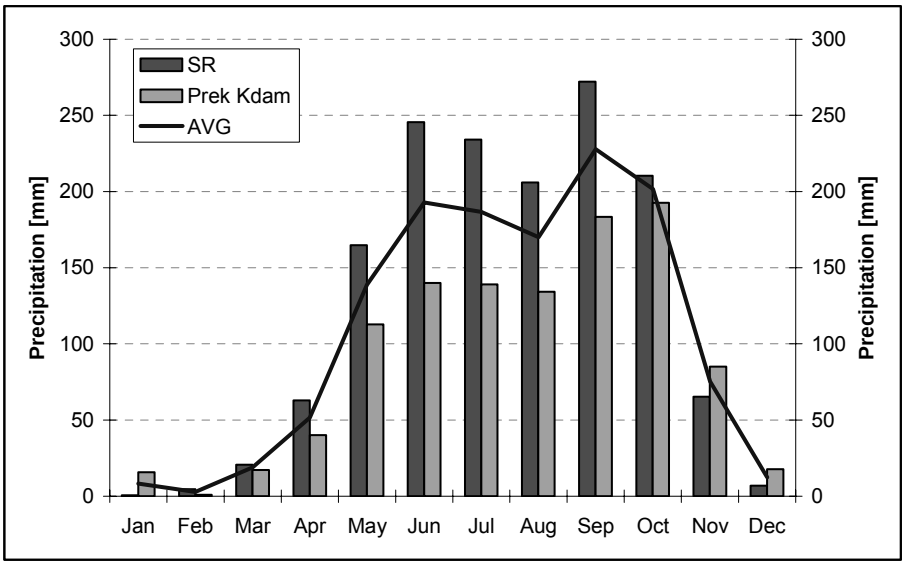



Figure 22. Monthly average precipitation at Siem Reap (SR) and Prek Kdam stations.

56. Overland flow from the Mekong through the floodplains is an important element in the Tonle Sap hydrology (Figure 24). However, based on the modelling done by the MRCS WUP-JICA study (CTI Engineering, 2004), the overland flow was reduced significantly after the national road construction. This happened due to the damming effect of the road and other embankments on the floodplain which link the Mekong River mainstream and Tonle Sap Lake floodplains.

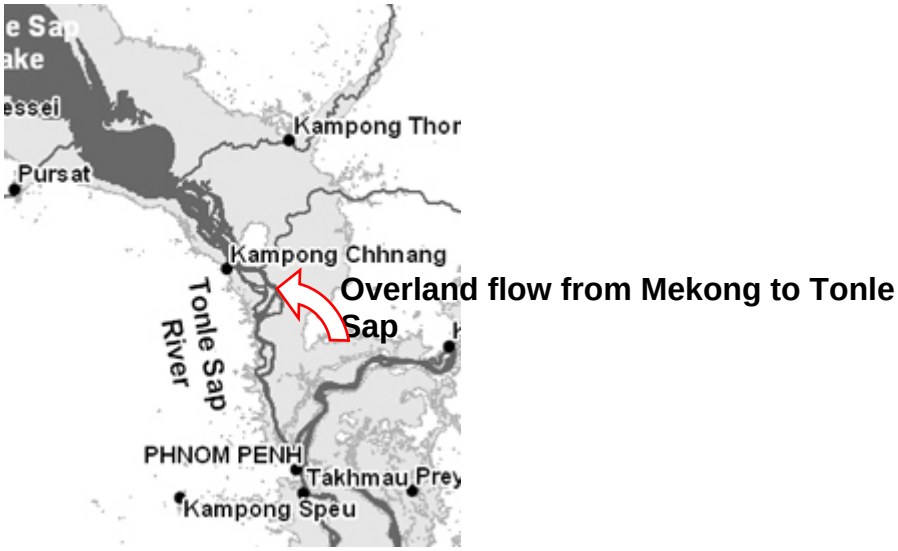



Figure 23. Overland flow from Mekong mainstream to Tonle Sap.

57. Basing the calculations on rating curves or monitoring the overflow continuously is almost impossible . Thus, to be able to include the overland flow in the water balance study the accurate hydrodynamic model should be applied. However, this is not available yet and the overland flow was calculated based on the difference between the calculated flow volume of the tributaries and Tonle Sap River and the measured volume.

58. The average overland flow into the lake was 4.4 $km^3$ during 1997 – 2003, while the average overland flow from the lake was only 0.7 $km^3$.

59. The Tonle Sap water balance is summarized in Table 7. The total inflow to the Tonle Sap varies from 44.1 $km^3$ (1998) to 106.5 $km^3$ (2000), the average being 79.0 $km^3$. Of the inflow, around 87% ends up to Mekong through the Tonle Sap River, 1% through overland flow while 12% evaporates directly from the lake.

Table 7. Summary of the inflow and outflow in $km^3$. Mekong part includes both, flow in Tonle Sap River and overland flow.

| | In-Flow | | | | Outflow | | | Balance | |
|---|---|---|---|---|---|---|---|---|---|
| | Tribs km3 | Mekong km3 | Prec km3 | TOTAL km3 | Mekong km3 | Evap km3 | TOTAL km3 | km3 | |
| **1997** | 23.1 | 47.3 | 8.5 | 78.9 | 64.2 | 8.7 | 72.9 | 6.0 | |
| **1998** | 12.6 | 24.8 | 6.7 | 44.1 | 36.8 | 6.7 | 43.5 | 0.6 | |
| **1999** | 27.4 | 41.0 | 11.3 | 79.8 | 72.9 | 10.5 | 83.3 | -3.6 | |
| **2000** | 39.7 | 51.8 | 15.0 | 106.5 | 93.3 | 11.5 | 104.8 | 1.8 | |
| **2001** | 27.1 | 52.9 | 12.4 | 92.5 | 83.0 | 10.5 | 93.5 | -1.0 | |
| **2002** | 21.7 | 56.8 | 11.3 | 89.8 | 84.3 | 10.0 | 94.3 | -4.5 | |
| **2003** | 15.2 | 38.5 | 7.9 | 61.6 | 50.4 | 7.5 | 57.9 | 3.7 | |
| **avg** | **23.8** | **44.7** | **10.4** | **79.0** | **69.3** | **9.3** | **78.6** | **3.0** | from absolute |
| **% of total** | **29.7%** | **57.0%** | **13.3%** | | **87.8%** | **12.2%** | | **3.8%** | values |

60. In Figure 24 the annual water balances have been presented. The inflows are precipitation, tributary flows and flow from the Mekong. The outflows are evaporation and flow to the Mekong.

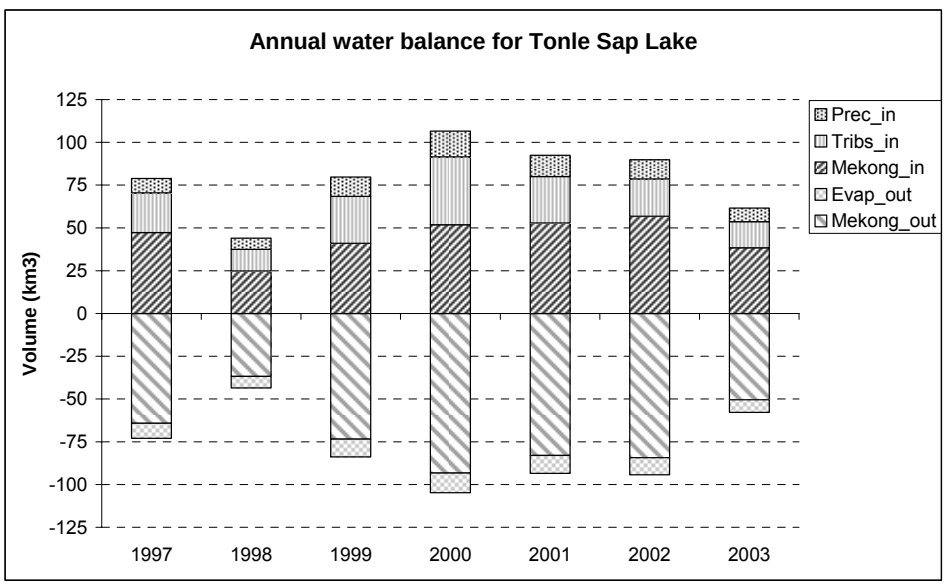



Figure 24. Annual water balances for Tonle Sap Lake (1997-2003). Positive values are flows into the lake and negative ones out of the lake.

61. In Figure 25 and Table 8 the monthly average water balances have been presented. The Tonle Sap fills up in May – September and dries out in October – April.

Table 8. Summary of the inflow and outflow in $km^3$. Mekong part includes both, flow in Tonle Sap River and overland flow.

| | Inflow | | | Outflow | |
|---|---|---|---|---|---|
| | Tributaries | Mekong | Precipitation | Mekong2 | Evaporation |
| Jan | 0.4 | 0.0 | 0.1 | -9.4 | -0.8 |
| Feb | 0.3 | 0.0 | 0.0 | -4.1 | -0.6 |
| Mar | 0.3 | 0.0 | 0.1 | -2.2 | -0.5 |
| Apr | 0.4 | 0.0 | 0.1 | -1.2 | -0.4 |
| May | 0.8 | 0.9 | 0.3 | -0.7 | -0.3 |
| Jun | 1.3 | 5.6 | 0.7 | -0.2 | -0.4 |
| Jul | 2.2 | 11.2 | 1.1 | -0.1 | -0.7 |
| Aug | 3.6 | 15.5 | 1.5 | -0.3 | -0.9 |
| Sep | 4.7 | 10.2 | 2.8 | -1.5 | -1.1 |
| Oct | 6.0 | 1.3 | 2.7 | -17.3 | -1.2 |
| Nov | 2.3 | 0.0 | 0.8 | -18.9 | -1.3 |
| Dec | 0.7 | 0.0 | 0.1 | -14.7 | -1.2 |

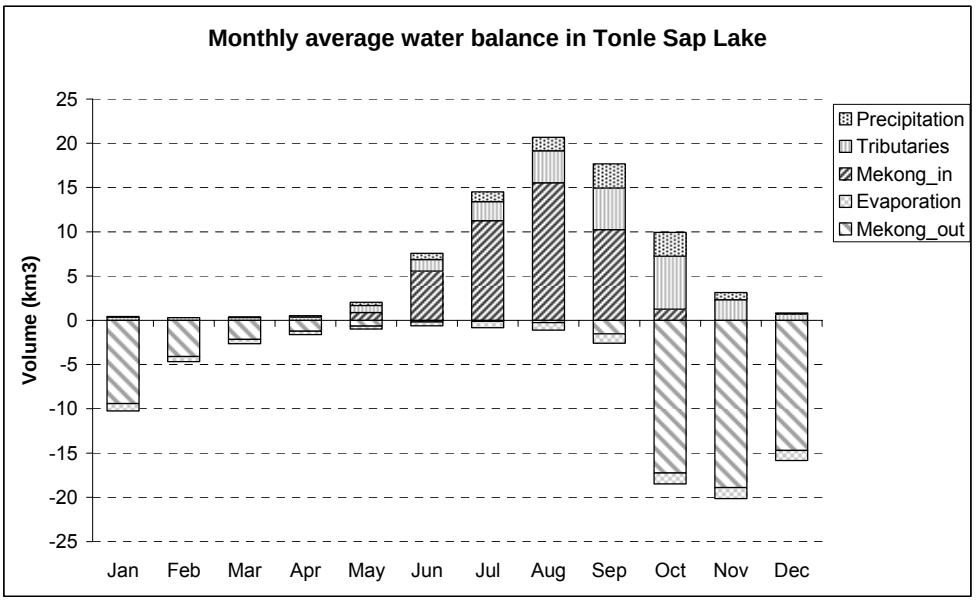



Figure 25. Monthly Tonle Sap water balances.

## III.2 MEKONG SCALE BUILT STRUCTURE IMPACTS

### III.2.1 Human impact compared with natural variability

62. The conditions in the Tonle Sap are very variable. The total inflow to Tonle Sap varies from 44.1 $km^3$ (1998) to 106.5 $km^3$ (2000), average being 79.0 $km^3$. The maximum lake volume varies between 30 and over 70 $km^3$ (see Figure 27). The maximum area varies between 10,000 and 15,000 $km^2$ and maximum lake height between 7 to 10 m.

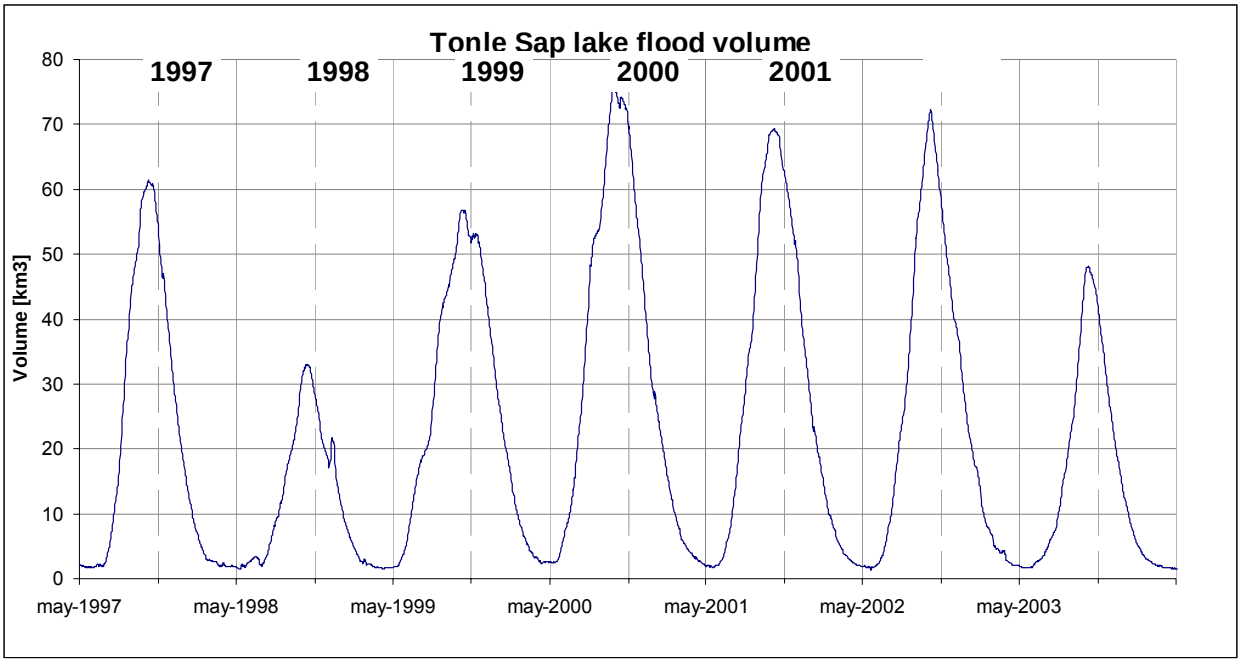



Figure 26. Yearly variation of the Tonle Sap Lake volume

63. The magnitude of the natural variability can be compared with the human impact on the Tonle Sap flow. The change of inflow for the Intensive Development Scenarios is about 4.5 $km^3$ and for the Mainstream Dams about 11 $km^3$. These are about 10% and 25% of the dry year (1998) total inflows respectively. In a wet year (2000) the percentages fall to 4% and 10% of the total inflow.

64. The computed impact of the development scenarios is shown in Figure 27 (for a definition of the scenarios see Chapter II.5). The figure presents the current water level (solid line) compared with the Tonle Sap hydropower and irrigation dam (grey line), Basin-wide Intensive (tightly dotted line) and Mainstream Dams Development scenarios. The scenarios change the dry season water level, flood timing and maximum flood height. The changes are most pronounced in the dry year (1998), and because of this in consequent chapters the results are mostly presented from the year 1998.

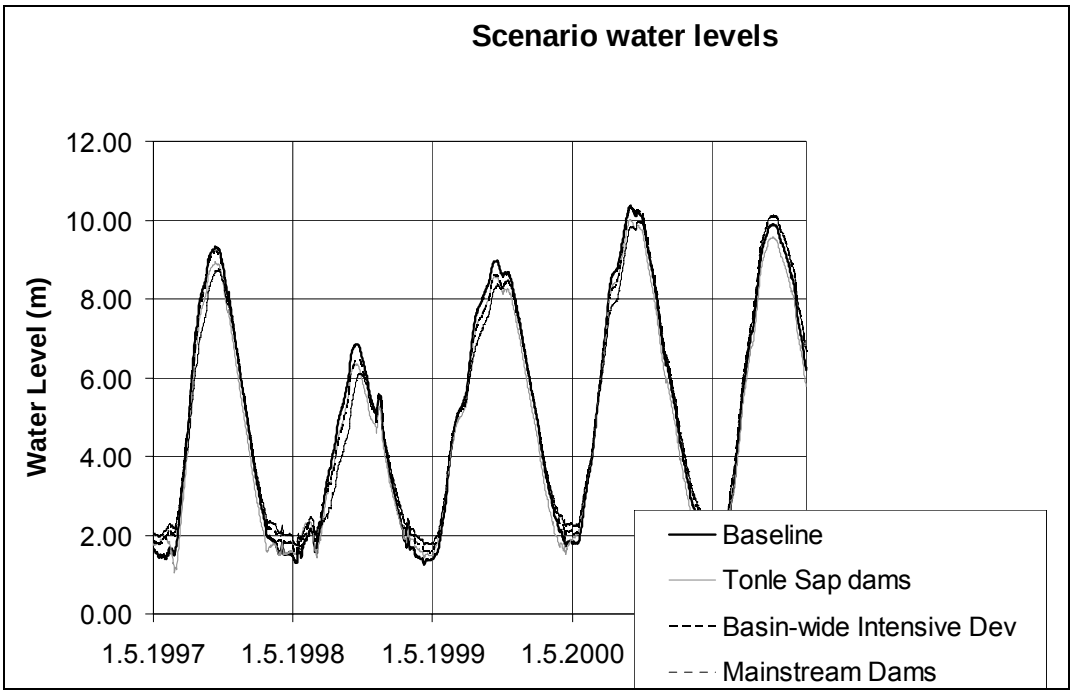



Figure 27. Natural water level variation between years (solid black line) compared with the scenario water levels (gray and dotted lines).

65. Upstream developments cause changes in the Mekong water levels and consequently in the Tonle Sap River flow. The estimated flow changes in the Intensive Development scenarios are based on the basin-wide MRCS model results. The flow changes have been added to the measured in- and outflows. For the Mainstream Dam scenario it is assumed that the flow into the lake changes proportional to the mainstream flow change. The outflows are adjusted to get 20 cm and 40 cm dry season lake water level rises respectively in the Intensive and Mainstream cases. As is discussed below, the actual dry season water level rise is uncertain. Here the lower end of the water level rise is used.

### III.2.2 Upstream development impacts

66. In general, development of upstream water resources can have a major impact on the Tonle Sap fisheries. This follows from the fact that the Tonle Sap is strongly influenced by the Mekong. Around 57% of the Tonle Sap water originates from the Mekong either through the Tonle Sap River (52%) or overland flow (5%) while tributaries share is around 30% and precipitation 13%. Not only the Mekong strongly impacts the Tonle Sap, but some of the Tonle Sap fish migrate upstream the Mekong. Obviously, Mekong conditions have a direct impact on these types of fish.

67. As seen in Figure 27, the impact of the upstream dams is most pronounced during dry years. This results from the fact that during dry years the storage capacity of the dams is greatest relative to the flow. The impacts are aggravated by the fact that the fisheries are most stressed during dry years and consequently more vulnerable to adverse flow changes.

68. Figure 28 presents the calculated water levels in 1998 for the Baseline, Intensive Development and Mainstream Dams scenarios. Increasing upstream water storage for hydropower and agriculture lowers the maximal flood height and depth and consequently the flooded area. Although a straightforward relationship between Tonle Sap fisheries productivity and inundated area has been cast into question with recent years' catch data, it is clear that a decreasing flood means less primary production and fish habitat. The decrease of the maximum flood height for the Basin-wide Intensive Development scenario is about 0.5 m and corresponding flooded area about 10% during the dry year (1998). The loss of inundation happens in the very high areas that are flooded in any case for a short period of time. In addition, they are estimated to be nutrient poor and oxygen depleted habitats. A more serious problem is the decreased flood depth and volume over the lower reaches of the floodplain.

69. As seen from Figure 29, increasing upstream water storage delays and shortens the flooding, which impacts fish migration, habitats and fish growth. The delay and shortening depends on the floodplain elevation zone (compare Figure 29a), year (wet/ dry/ average), intensity of the upstream developments and reservoir operation. The largest impacts are encountered during the dry years when the storage capacity is relatively large compared to the natural flows.

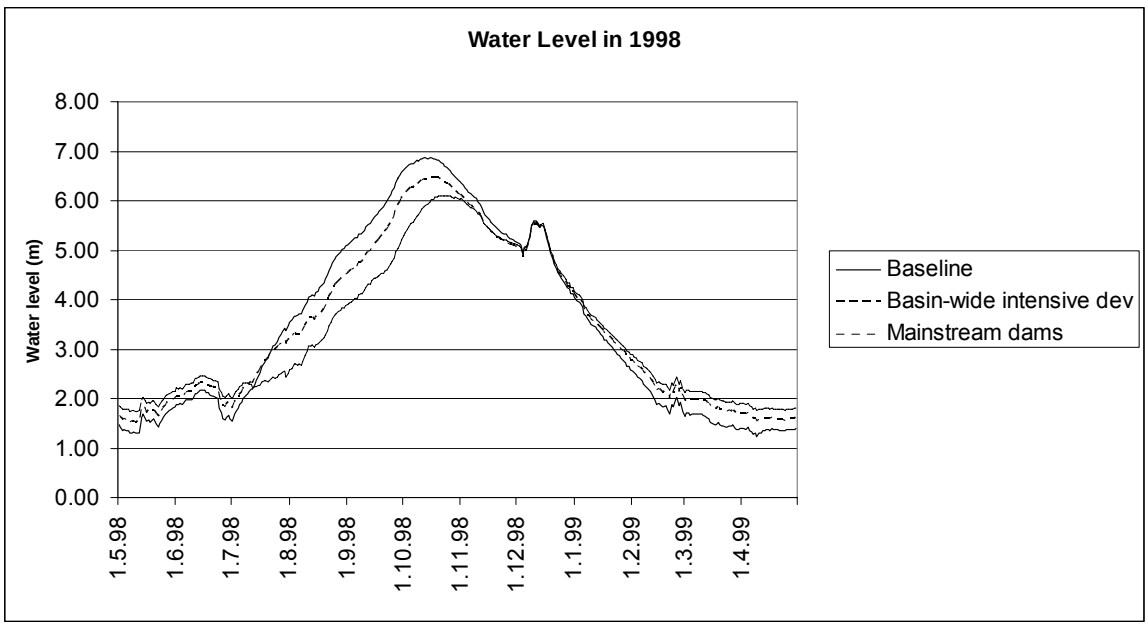



Figure 28. Lake water levels in the Baseline (uppermost line), Intensive Development (middle) and Mainstream Dams (lowest) scenarios.

70. The modelled impact of the Intensive Development scenario on the flood arrival time is presented in Figure 30a. The delay in inundation is typically one week compared to the current situation. In the Extreme Mainstream Dams Development scenario the delay can even be one month in a dry year. The flood duration is related to the flood arrival time. The shortening of the inundation is typically 1 – 2 weeks in the upper areas of the Tonle Sap floodplain (Figure 29b).

71. Because the start of the flood season happens quite regularly every year within a window of a few days, the delay in the flooding can adversely affect fish breeding. Shortening of the inundation affects the habitats on the floodplain and decreases the time fish can feed and grow on the floodplain.

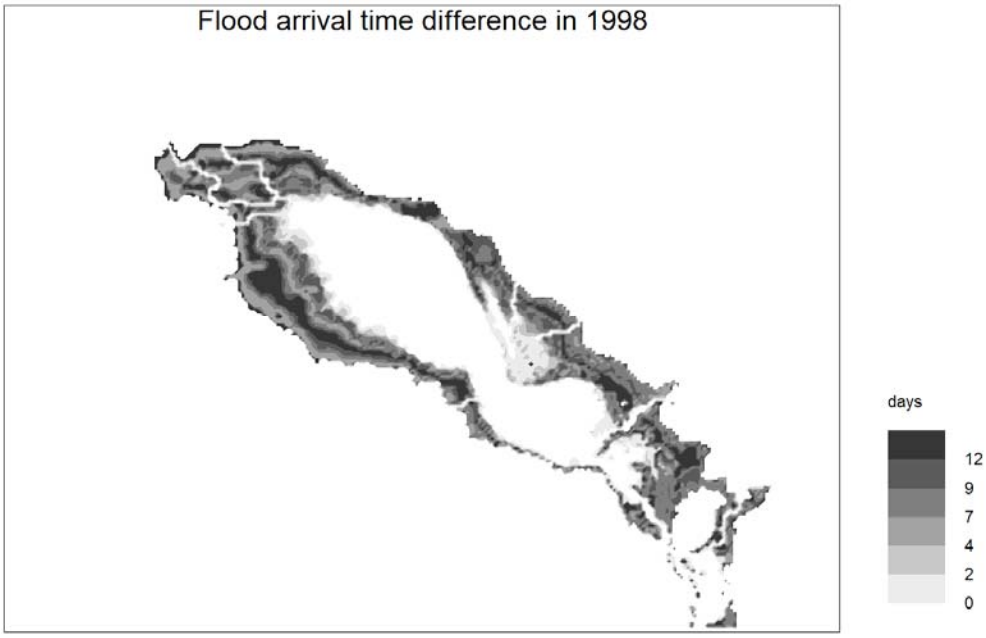



Figure 29a. The impact of Intensive Development scenario on flooding. The figure shows the arrival time difference between the Baseline and Intensive Development scenarios. In other words the values show how many days the flood is delayed because of the upstream developments.

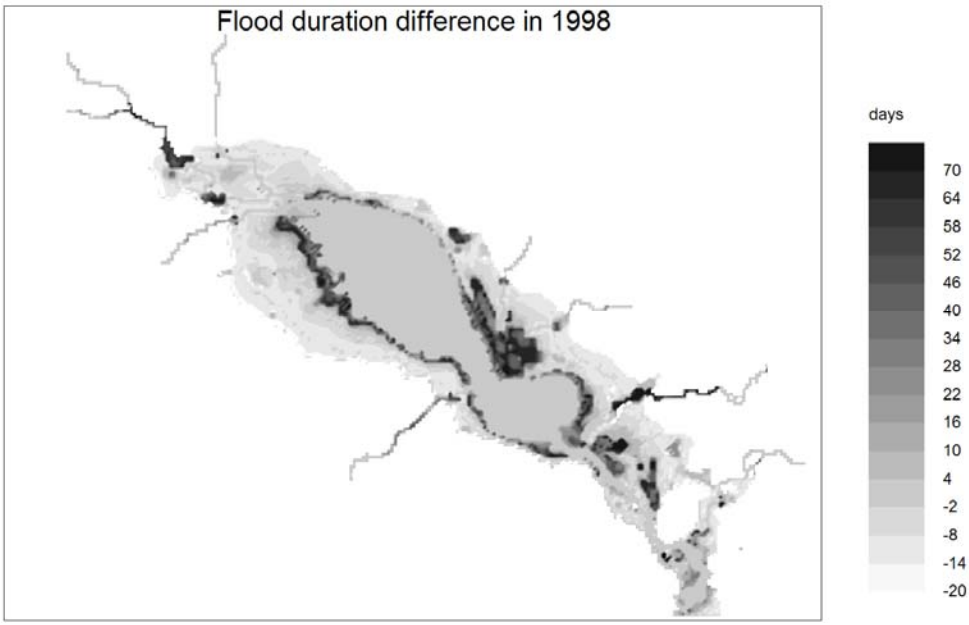



Figure 29b Impact of Intensive Development scenario on flooding. The figure shows shortening and lengthening of the flood in days because of the upstream developments. The simulation year (1998) is a dry year. The lengthening of the inundation near the lake edge is caused by raising water levels during the dry season.

72. During the dry season upstream hydropower dams release water, keeping the Mekong and Tonle Sap River and Lake water levels higher than normal. The estimates for the water level change vary between 0.15 and 0.9 m depending on the study. The studies have been based either on use of rating curves or mathematical models. In the scenario runs it is assumed that the Intensive Development scenario will raise the dry season water levels 20 cm and the Mainstream Dams 40 cm.

73. The permanent water level change impacts the flooded forest near the Lake edge (Figure 30a). The flooded forest in a very narrow fringe on the lake edge acts as a buffer protecting the floodplain against rough conditions in the lake. It is also an important habitat for fish where it can search for shelter for breeding and feeding while benefiting from the oxygen and nutrient rich lake conditions. The dry season lake edge moves to the floodplain permanently inundating the lake edge forest (Figure 31b) and destroys the forest that requires periodical dry conditions. The increase of the dry season lake area is 300 – 900 $km^2$, or 15 – 45% of the dry season lake area.

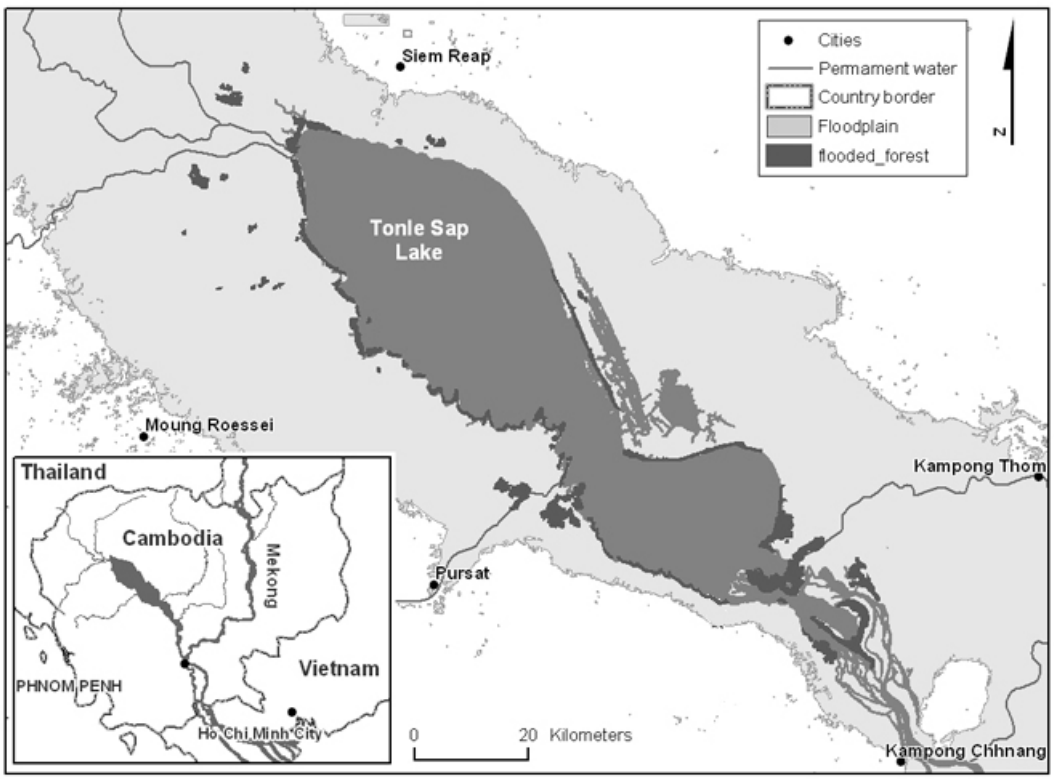



Figure 30a. Flooded forest based on JICA (1999) land use map for the Tonle Sap Lake.

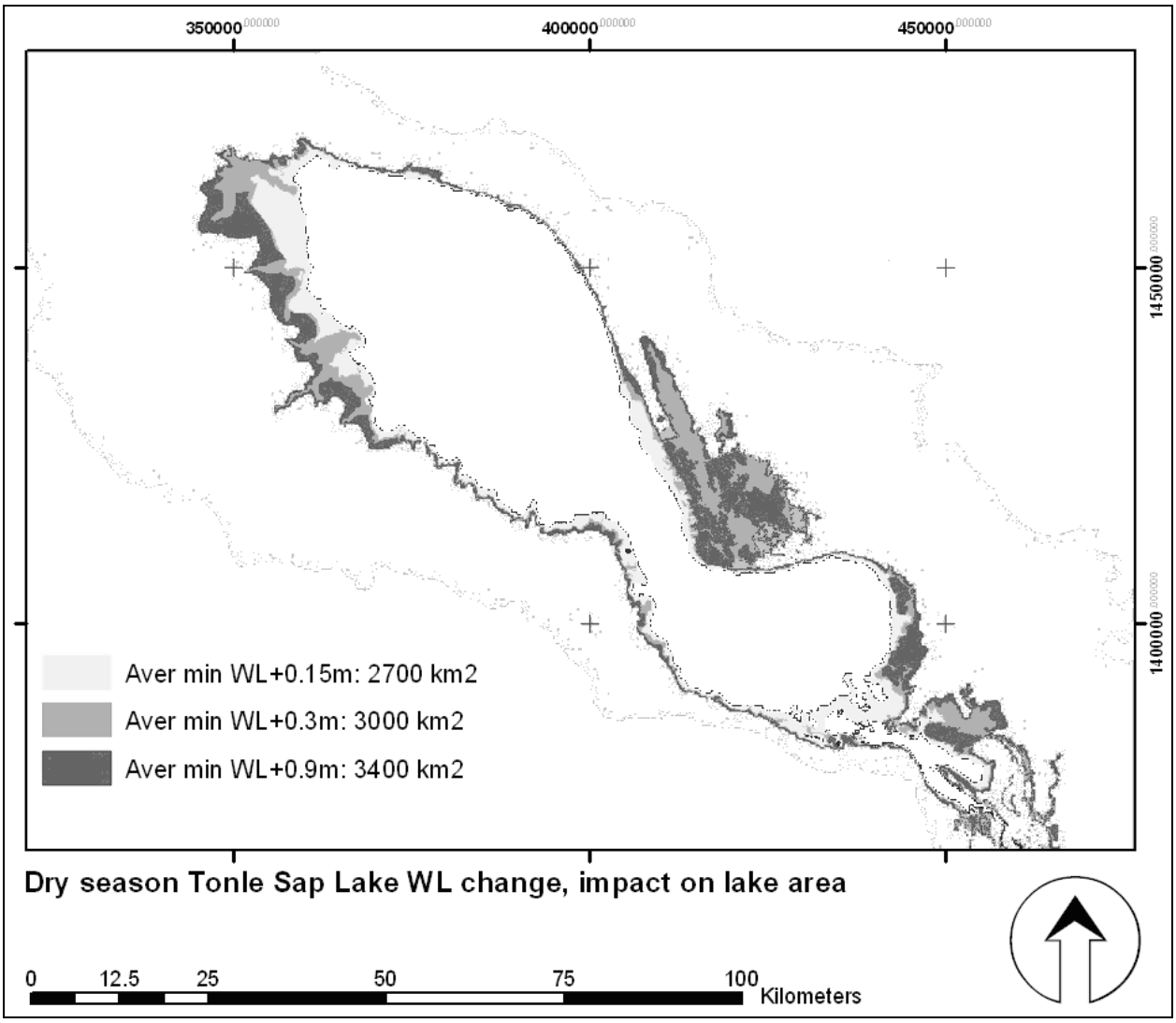



Figure 30b. Increase of the dry season lake area according to different estimates. Yellow corresponds to 15 cm water level rise, orange to 30 cm and red to 0.9 m rise.

74. Although the lake productivity is not well understood, it may be assumed that the sediments may play a key role in providing nutrients to the Tonle Sap system and thus sustaining its high productivity. About 70% of the sediment influx to the Tonle Sap originates from the Mekong (Figure 31). Thus, the changes in the amount and composition of sediment caused for instance by upstream dam development or land use changes can have a major impact on the sediment inflow and Tonle Sap productivity.

75. As an example of the upstream development impact on sedimentation, the impact of the Chinese dam cascade was studied. More than 50% of Mekong downstream suspended sediment originates from China. The planned Chinese dam cascade potentially traps nearly all of this sediment resulting in reduced sediment input and Tonle Sap productivity. Figure 32 represents the corresponding reduction in sedimentation in the Tonle Sap floodplain obtained from modeling results. *The most impacted areas shown in dark are also high fisheries productivity areas*. The hydrological year strongly affects the sediment input and

also the impact of the dams. In the figure the average hydrological year (1997) is presented. During 1998 the impact is less pronounced because the sediment input from the Mekong is smaller.

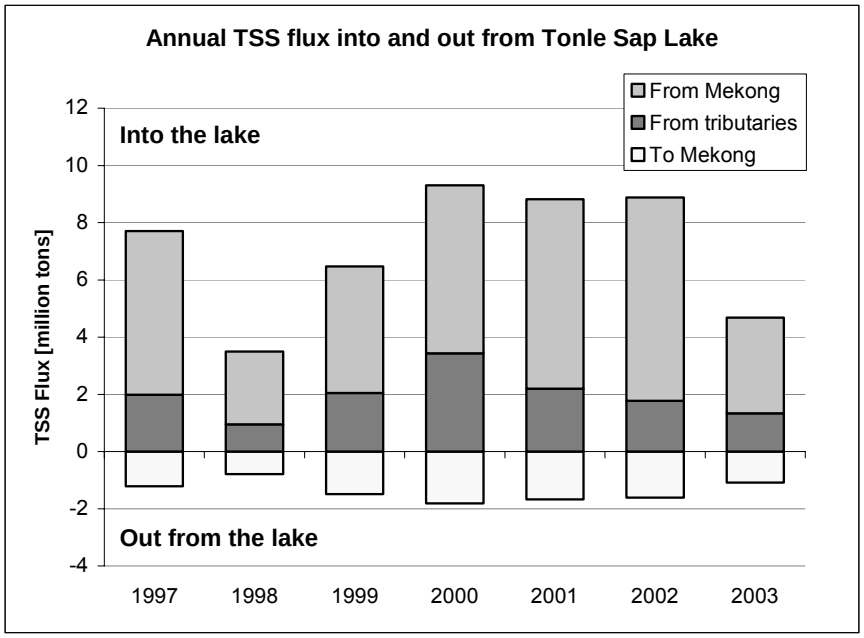



Figure 31. Annual TSS flux into and out from the Tonle Sap Lake (1997-2003). Results based on flow and TSS measurements.

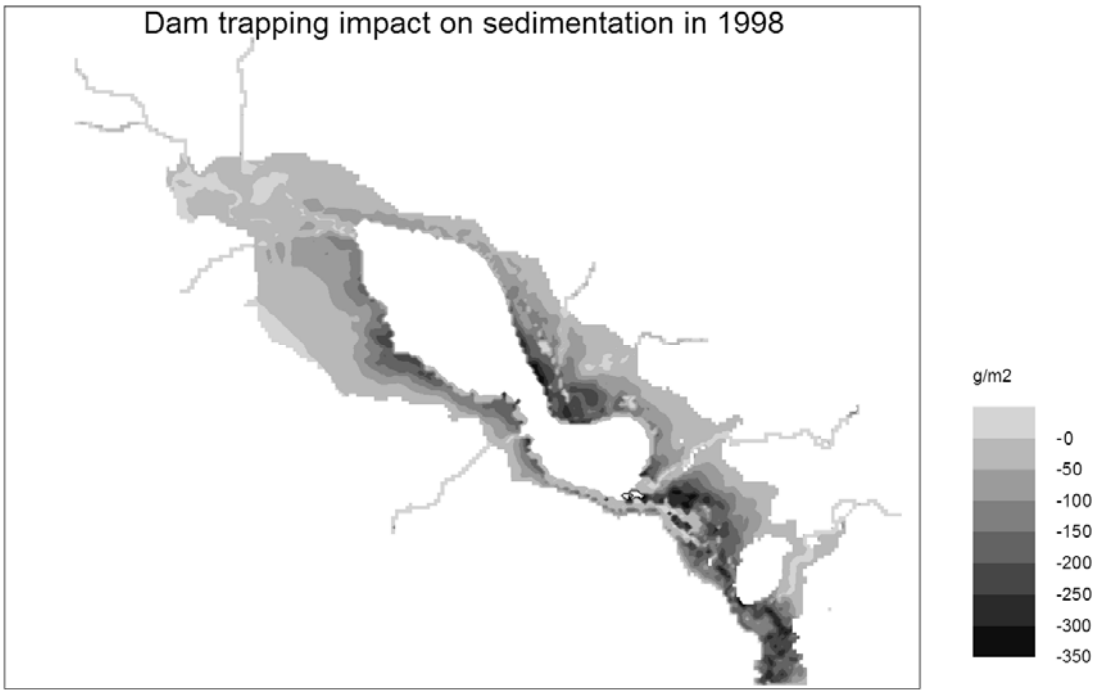
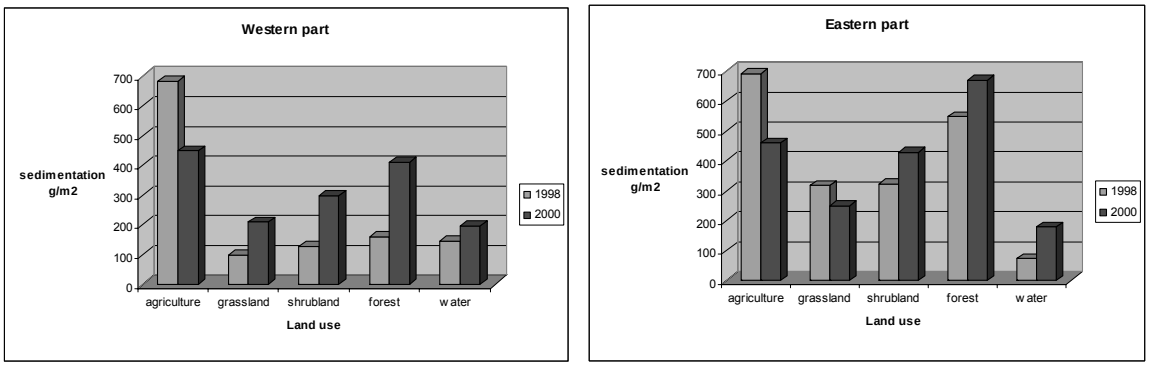



Figure 32. Modelled decrease of sedimentation due to the dam's trapping of sediments. The most impacted areas shown in blue are also high fisheries productivity areas. The average hydrological year (1997) is shown. During 1998 the impact is less pronounced because smaller Mekong sediment input.




a) b)

Figure 33. Modelled sedimentation per square meter in different hydrological years: light grey dry year (1998) and dark grey wet year (2000). On the left hand side western part of the Tonle Sap and right hand side eastern. Results are presented for different land use classes (agriculture, grassland, shrubland, forest and water). The area of the agricultural land is marginal.

76. The impact of the hydrological year on sedimentation is shown in Figure 35. The dry year (1998) is shown in light grey and the wet year (2000) in dark grey. The figure presents the average simulated sedimentation per unit area, and changes in inundated area should be taken into account in estimating the total sedimented material. The impact of the hydrological year can be seen especially on the western part of the lake (left box in the figure). During a high flood year the flood is able to carry significantly more sediment to the western part than during a dry year.

77. The sediment processes in the Mekong Basin are not very well known. The origin of the very fine sediments (average grain size 13 µm) that are most important for the Tonle Sap, has not been specifically studied. Also, the actual dam trapping capacity of the finer sediments has not been estimated. Because of this uncertainty the results presented above must be considered with caution.

78. Oxygen conditions are important for the fish. Fish species have developed strategies to cope with low oxygen conditions, but in general good oxygen conditions favor fish breeding and growth. The upstream developments can negatively impact oxygen conditions in critical breeding areas**.** The impact is caused by the flood delay especially in dry years and consequent delay of arrival of oxygen rich waters to the floodplain (Figure 36). This delay can have a negative impact on the sensitive juveniles on the floodplain. As the figure shows, the simulated oxygen values diminish by about 0.5 – 2 mg/l during August – September in the highly productive Lake Chhma area. When the oxygen values are low to start with, the reduction can be critical for the fish.

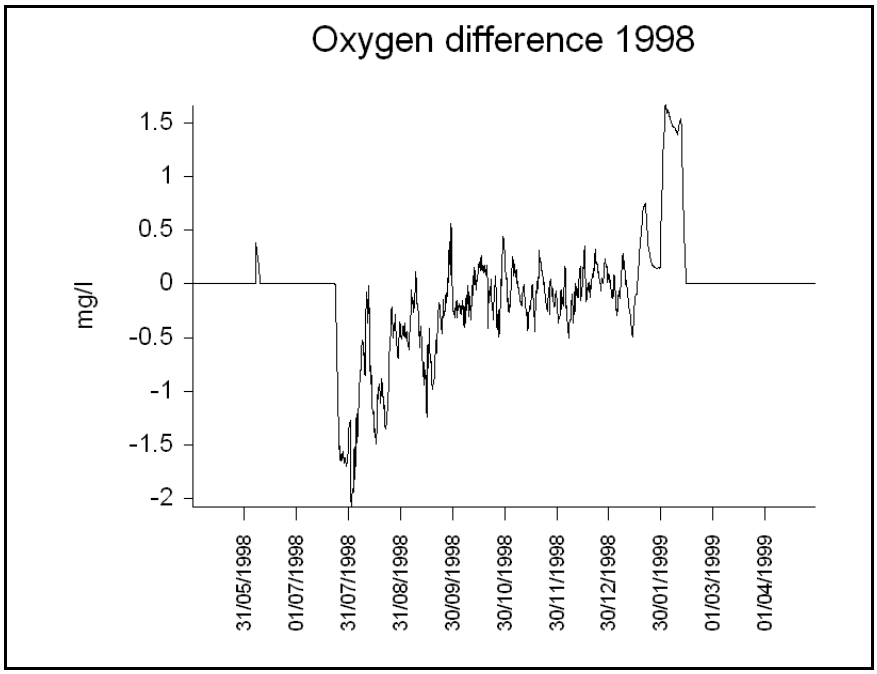



Figure 34. Modelled surface dissolved oxygen concentration difference between Baseline and Intensive Development scenario for 1998. The area is located about 5 km from the lake edge near Lake Chhma. The flat period when the time series is 0 corresponds to time when the area is dry land.

79. The changing flow regime changes water flow in the lake and the floodplain. This in turn impacts fish larvae and juvenile drift. The key process in the larvae drift is the entrance of the migratory fish larvae from the Mekong and drift to the breeding areas. Figure 35 shows the simulated fate of the Mekong larvae and juveniles in the Tonle Sap Lake. Practically all larvae end up on the northern and eastern shores. The intensive development scenario changes the drift more to the western basin. The change of the drift needs to quantified and its importance assessed by fisheries experts.

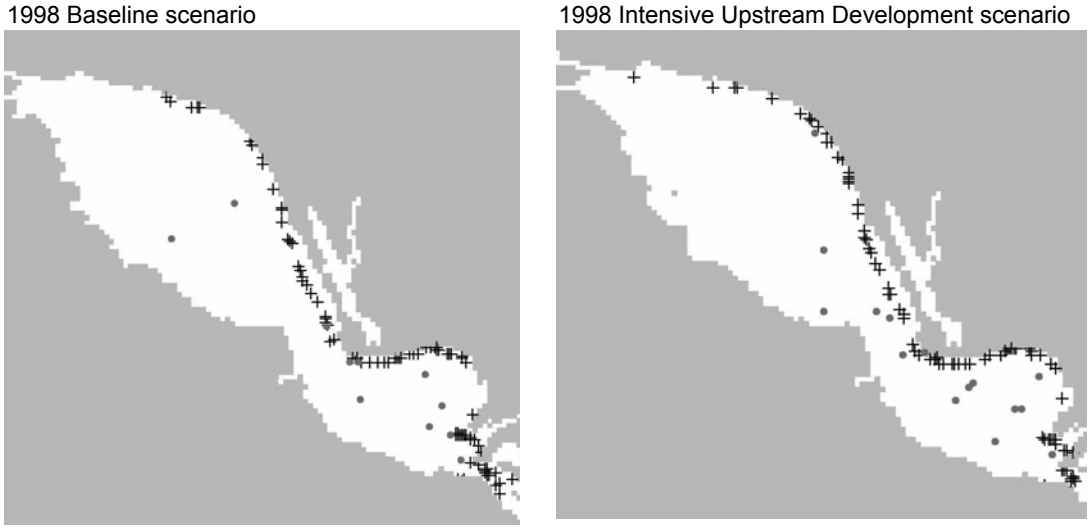



Figure 35. Simulated fish larvae drift from the Tonle Sap River during July – August 1997. Crosses indicate first point where larvae touches the flooded forest. Dots show drifting larvae. Observe lack of drift to the southern/western shore and concentration of the larvae on the eastern and Lake Chhma areas. Increased drift to the western basin in the intensive development scenario, which may result in decreased productivity in the Fishing Lot No 2.

80. Above the impacts of the development scenarios on specific Tonle Sap hydrological, sediment, water quality and fish larvae processes are discussed. Even taken individually, some of the impacts such as destruction of the riparian forest near the lake edge and decrease of sediment input to the lake could potentially have a significant impact on fisheries. When taken together impacts strengthen each other and even the smaller impacts may be important when taken together.

### III.3 TONLE SAP SCALE IMPACTS

81. The Tonle Sap development was studied based on the Lower Mekong Water Resources Inventory, WATCO 1984 (see chapter "Tonle Sap watershed scenarios"). The inventory is based on a feasibility study for hydropower and irrigation development. At the moment the watershed water resources remain largely undeveloped. The actual implementation of the plans cannot be predicted, although some hydropower dams are under consideration.

82. For the whole Tonle Sap, the combined hydropower and irrigation storage potential represents relatively a small portion of the total inflow to the Tonle Sap. The total Tonle Sap storage capacity in the WATCO Inventory is 5.5 $km^3$ (see Table 3). This can be compared to the annual total inflow to the Tonle Sap, which varies between 44 and 107 $km^3$, the average being 79 $km^3$.

83. Figure 36 presents calculated current (solid line) and Tonle Sap Dams (grey line) scenario water levels. The levels are compared with the Intensive Development scenario (dotted line). During the rising flood the Basin-wide and Tonle Sap scenarios behave quite similarly. In the Tonle Sap scenario the flood delay starts earlier, but this depends on the actual operation of the dams. Because the Basin-wide Development and Tonle Sap Dams

scenarios are close together, the results presented in the previous chapter are mostly relevant for the Tonle Sap Dams scenario.

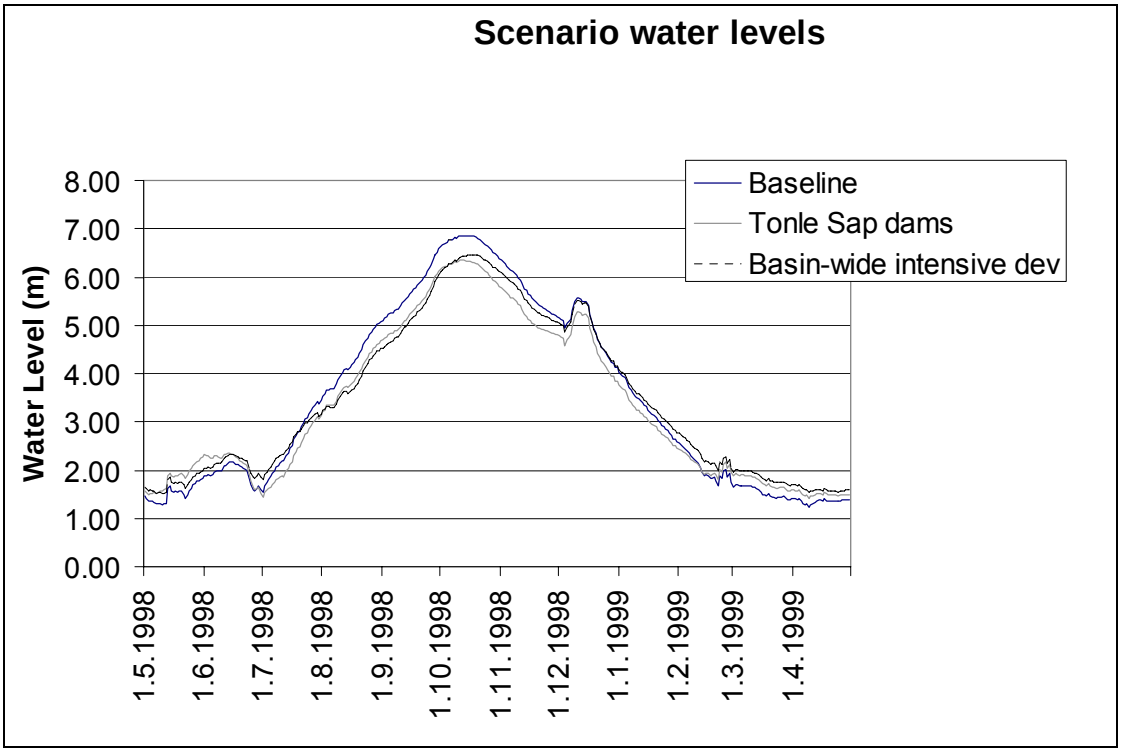



Figure 36. Impact of the potential Tonle Sap dam developments on the Lake water levels. Solid line the Base-line, dotted one Intensive Upstream Development scenario and the grey one Tonle Sap developments defined in Table 3.

*84.* The Tonle Sap dam storage behaves in similar way to the upstream dams reducing flood flow and increasing dry season flow. The total magnitude of the impact during the rising flood is similar compared to the Basin-wide Intensive Development scenario. Because of this, *the Tonle Sap hydropower and irrigation storage structures can significantly strengthen the upstream development impacts.* The total cumulative impact of the Tonle Sap Dams and Basin-wide Developments scenarios would be about the same as in the Mainstream Dams scenario during the rising flood.

*85.* The main difference between the upstream Mekong and local Tonle Sap development is that the local developments have less impact on the total inflow. Eventually stored water is released from the local storages minus the amount evaporated from the reservoirs and possible irrigation schemes.

# IV LOCAL SCALE RESULTS

## IV.1 INFLUENCE OF ROADS

86. Figure 37 presents a figure showing the calculated flow field during rising flood in Pursat province near the Pursat River. The left figure is without road and the right one with a 10 km road from the upper floodplain to the lake edge. The flow velocities are in general very small in the floodplain compared to the lake and flows can easily bypass the road on the lakeside. A road in this type of place does not impact the flooding, although it can block flow from one part of the floodplain to another.

87. A road placed on the upper left hand corner of the area shown in Figure 39 would block the flow from the river to the floodplain as long as there was not be a bridge. The flow can be important in bringing oxygen and nutrient rich water to the floodplain as well as spawn from upstream. The importance of taking into account the hydrodynamic conditions of the floodplain is highlighted in Figure 40 showing the fish-rich Lake Chhma area. The complex channel network should not be blocked in order not to cause degradation of conditions by decreased flow, oxygen, nutrient, and spawn inputs.

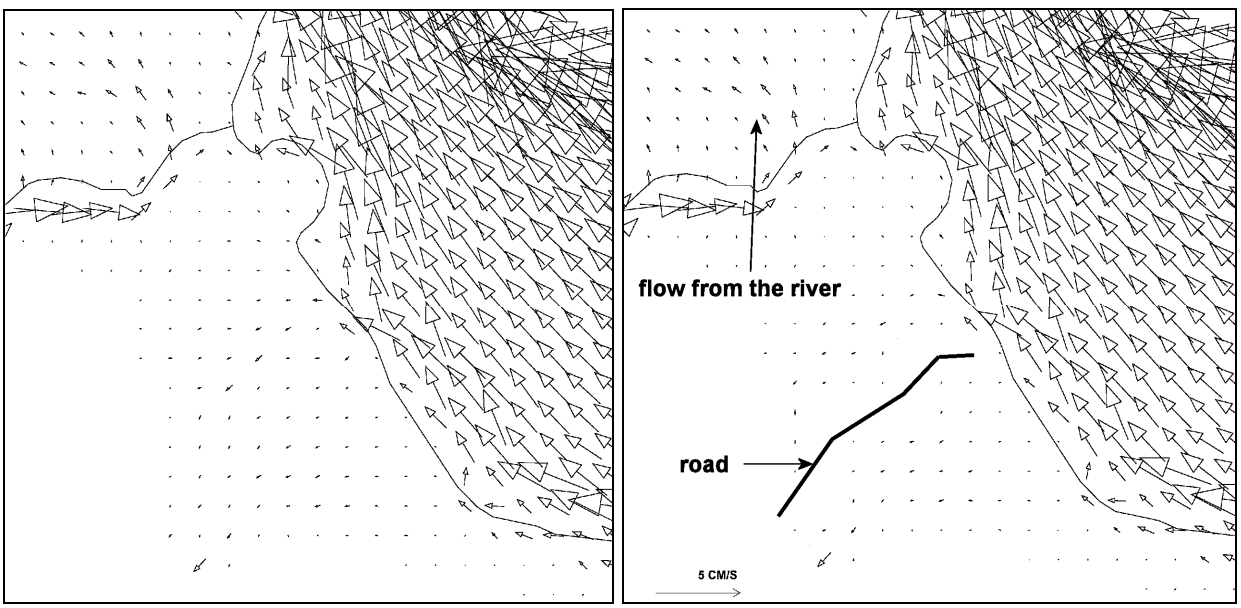



Figure 37. Impact of a road construction on floodplain flow in the Pursat province near the Pursat River. Left without a road and right with about 10 km long road. Lake flow is indicated by large arrows. Flow from the Pursat River to the floodplain indicated on the north-western corner of the figure. Observe very low floodplain flow velocities and small impact on either the floodplain or lake flow.

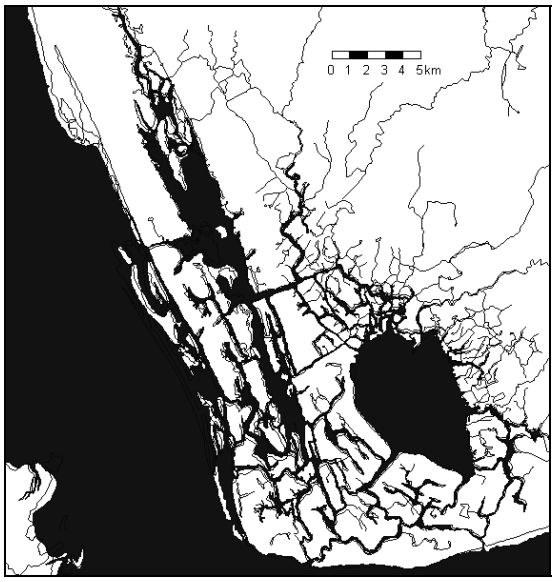



Figure 38. Lake Chhma area illustrating complex network of channels. Flows essential for the hydrological, hydrodynamic and ecological functioning of the area should not be blocked.

## IV.2 INFLUENCE OF IRRIGATION SCHEMES ON HYDROLOGY, SEDIMENTS, WATER QUALITY AND FISH

### IV.2.1 Field study based Stung Chinit impact assessment

88. As a representative reservoir, the Stung Chinit irrigation scheme was studied both by modelling and field sampling. The map of the area, set-up of the field study and the measurement points are presented in the chapter “Methods and Tools”. The main results indicating reservoir impacts are studied below.

89. Inflow to the Stung Chinit irrigation reservoir and outflow from the reservoir were approximately the same on the measurement days (Figure 39.). Main structure impacts on the flow (inflow versus outflow) are not present. Small differences can be observed, and can be attributed to rainfall pulses, lake water level oscillations caused e.g. by wind, backwater effects and operation of the irrigation system.

90. Figure 39 illustrates the abrupt change in hydrological conditions during the flood and dry seasons. In November the flow is about a fifth of that in October. In January the flow is less than 10% of the peak flood flow. The balance between the in- and outflows did not change during the observation period.

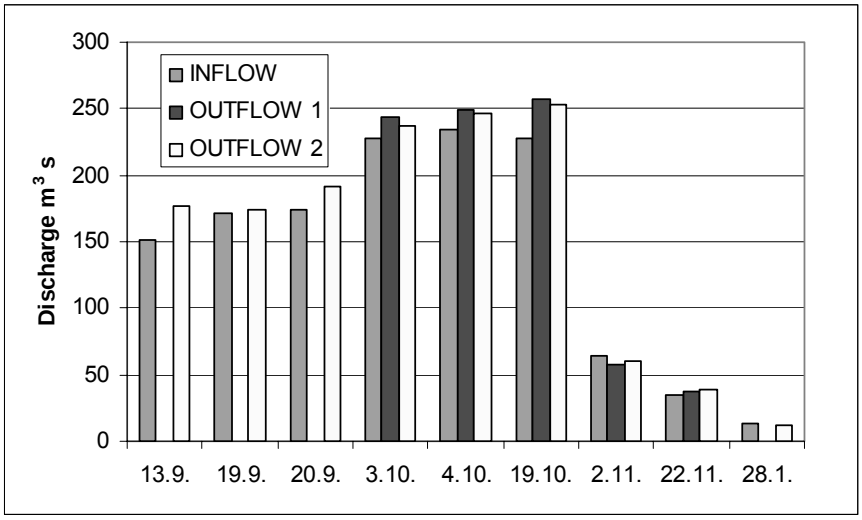



Figure 39. Measured Stung Chinit reservoir impact on flow in September – January 2007. The blue bars show measured inflow (discharge) and red and yellow ones outflow measured in different downstream locations (compare to Figure 2).

91. The Stung Chinit irrigation system positively affects the downstream oxygen conditions. Oxygen concentration in the river increases after flowing over the spillway and through the sluice gate of the dam (Figure 42, outflow oxygen concentrations). The concentration of outflowing water is approximately 20% higher than the concentration of the river water entering the reservoir. This is because of the spillway and sluice gate aerate the through-flowing water effectively.

92. In the reservoir oxygen concentration decreases to some extent because of decay of organic material. Slow flow velocities in the reservoir and the biomass production of the reservoir increase the amount of sedimented organic matter on the bottom. Decay of this material as well as of the inundated terrestrial organic material consumes oxygen. Oxygen concentration decreases in deeper water layers if flow and waves are not able to mix stratified water layers (Figure 42, reservoir profiles). Decreased oxygen concentrations occur especially in the sheltered deep water areas where flow velocities are low, but open areas can also stratify during calm periods. Decreased oxygen concentrations on the bottom layer may have negative impact on some oxygen sensitive fish species and it also increases nutrient concentrations due to anoxic processes. Low oxygen concentrations in the reservoir occur in any case locally. The overall impact of the reservoir is to increase the oxygen concentrations of the outflowing river water. In addition, the surface oxygen concentrations remain good in the reservoir.

93. The oxygen values can be compared with different flow conditions in November and January. In January the flow is less than half of the November flow. The outflowing water is well oxygenated in the whole water column. In January the dissolved oxygen concentration is about 1 mg/l higher because the water temperature is lower and oxygen concentration higher. Surprisingly, the reservoir oxygen conditions are not appreciably affected by the through-flow and the reservoir is rather well oxygenated even near the bottom both in November and January.

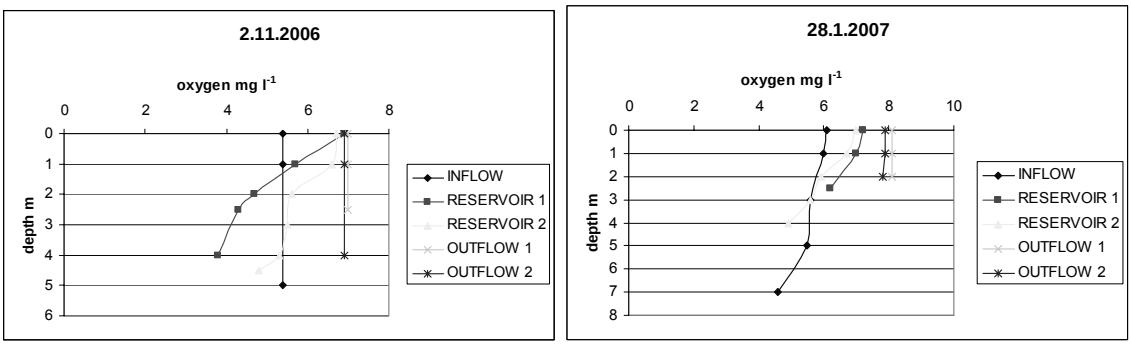



Figure 40. Oxygen profiles in the sampling locations 2.11.2006 and 28.1.2007.

94. The overall tendency of the reservoir is to slightly increase total suspended sediment concentrations (Figure 43.). Values of inflowing water vary between 15 - 37 mg $l^{-1}$ and values of outflowing water between 11 - 45 mg $l^{-1}$. Visibility, measured as Secchi depth, has a correspondingly decreasing trend in the influence area of the structure. The visibility decreases more or less steadily from upstream to downstream (Figure 44.). The increased value of total suspended sediment concentration and decreased visibility downstream of the structure can be caused by phytoplankton production in the reservoir and resuspension. Erosion of the riverbank downstream of the dam may also explain the changes in the values.

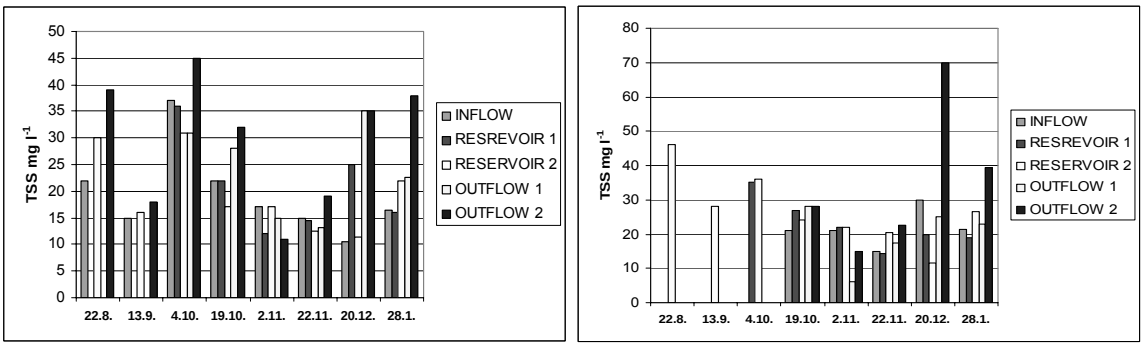



Figure 41. Total suspended sediment concentration one meter under the water surface (on the left) and one meter above the bottom (on the right).

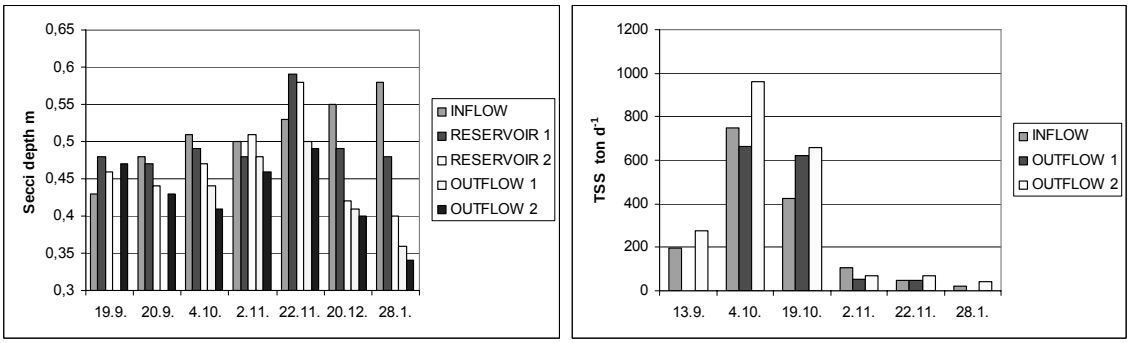



Figure 42. Secchi depths at the sampling locations (on the left) and total suspended sediment mass balance in the river (on the right).

95. A significant reservoir impact on the river nutrient dynamics cannot be observed. Total nitrogen and phosphorus concentrations of inflowing, reservoir and outflowing water vary without a very clear trend (Figure 45.). There is anyway a weak average trend in concentration and nutrient mass balance (Figure 46.) results. During the flood season nutrients are released from the reservoir, during the flood peak trapped in the reservoir, and with smaller discharges the balance is approximately stable.

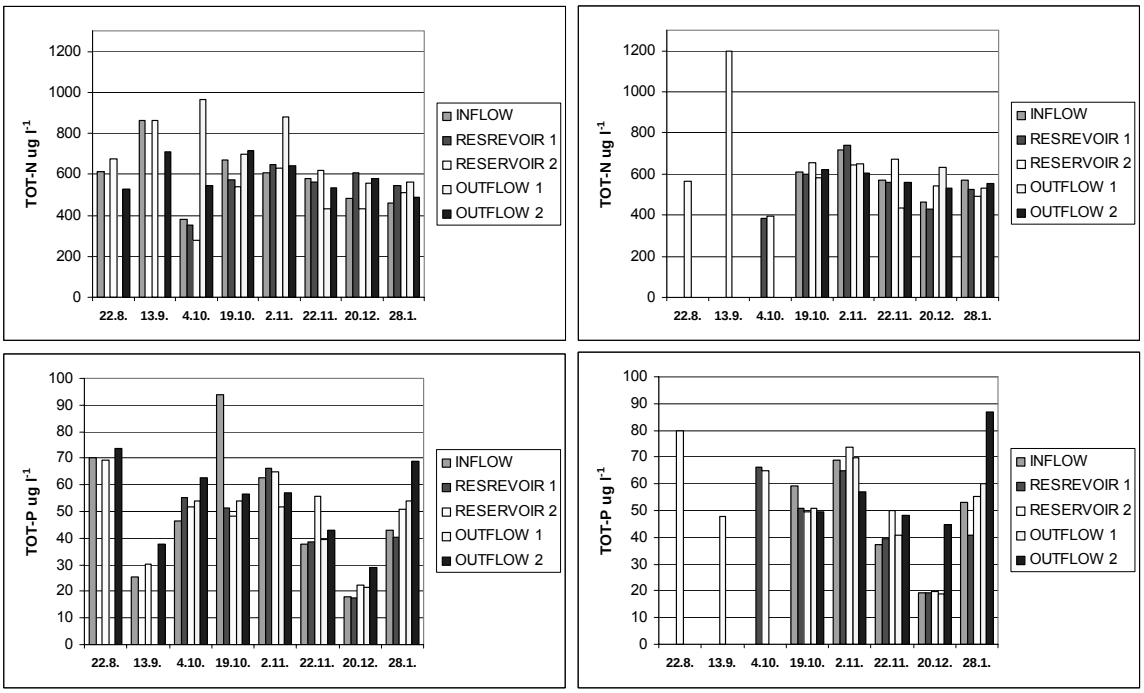



Figure 43. Total nitrogen and phosphorus concentrations one meter under the water surface (on the left) and one meter above the bottom (on the right) at the sampling locations.

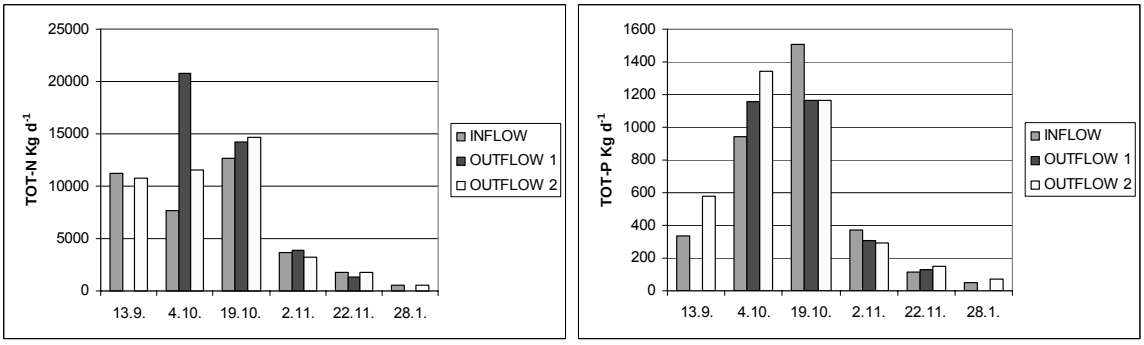



Figure 44. Total nitrogen (on the left) and total phosphorus (on the right) mass balance in the river.

96. Comparing suspended sediment, total nitrogen and total phosphorus concentrations at different times with radically different flows shows that they do not depend on flow in a straightforward way. However, it is important to note that the fluxes are much smaller in the dry season (November and January) than in the flood season because of the much smaller flows (Figure 44).

97. In general, the water quality characteristics of the river water are not significantly impacted by the reservoir. Proportions of phosphorus and nitrogen fractions stay stable or vary inconsistently in the influence area. Also, other measured parameters do not indicate any significant changes in the river water quality. Minimum, maximum and average values of other water quality parameters are listed in Table 9.

Table 9. Chemical oxygen demand, pH, alkalinity and conductivity values.

| | | CODM mg $l^{-1}$ | pH | ALK+ mgCa | Cond. mS $m^{-1}$ |
|---|---|---|---|---|---|
| INFLOW | min | 1,4 | 5,9 | 7,5 | 2,4 |
| | aver. | 2,7 | 6,7 | 11,6 | 3,0 |
| | max | 6,2 | 8,0 | 19,2 | 4,1 |
| RESERVOIR 1 | min | 1,5 | 6,1 | 9,8 | 2,5 |
| | aver. | 2,8 | 6,7 | 11,9 | 2,8 |
| | max | 4,5 | 7,9 | 15,2 | 3,2 |
| RESERVOIR 2 | min | 1,4 | 5,7 | 8,1 | 2,5 |
| | aver. | 3,1 | 6,4 | 12,0 | 2,9 |
| | max | 8,4 | 7,9 | 17,6 | 3,2 |
| OUTFLOW 1 | min | 1,1 | 6,1 | 8,5 | 2,6 |
| | aver. | 2,5 | 6,6 | 12,0 | 3,0 |
| | max | 3,9 | 7,8 | 17,2 | 3,9 |
| OUTFLOW 2 | min | 1,8 | 6,0 | 9,0 | 2,6 |
| | aver. | 3,1 | 6,5 | 12,0 | 3,0 |
| | max | 8,5 | 7,9 | 17,7 | 3,5 |

98. The irrigation canal network maintains water balance in the rice fields and at the same time offers, together with the reservoir, a new habitat for fish. When irrigation is active the discharges of the canals are relatively high. Nutrients and total suspended sediments are released from rice fields and canals during that period. Concentrations of total nitrogen, phosphorus and suspended sediments increase in the irrigation and drainage canals compared to the values in the reservoir (Figure 45). High peaks in the nutrient concentration values indicate the impact of fertilizers. Water flowing back into the river via drainage canals has a loading effect downstream of the river. However, the loading effect of the system is small due to the small through-flow.

99. Connectivity of the canal network depends on the operational status of the irrigation system. When irrigation is active the canal flows are relatively high and the canals are connected with each other. When irrigation is passive the canal flows decrease and many of the canals dry up. During the measurement period irrigation was active until 20.12. At that time the secondary irrigation canal was dry and discharges of tertiary and secondary drainage canals were so small that canals were not connected. All the canals were dry by 28.1. During the passive irrigation phase the connectivity of the canals breaks reducing fish movement and the suitability of the habitat for fish.

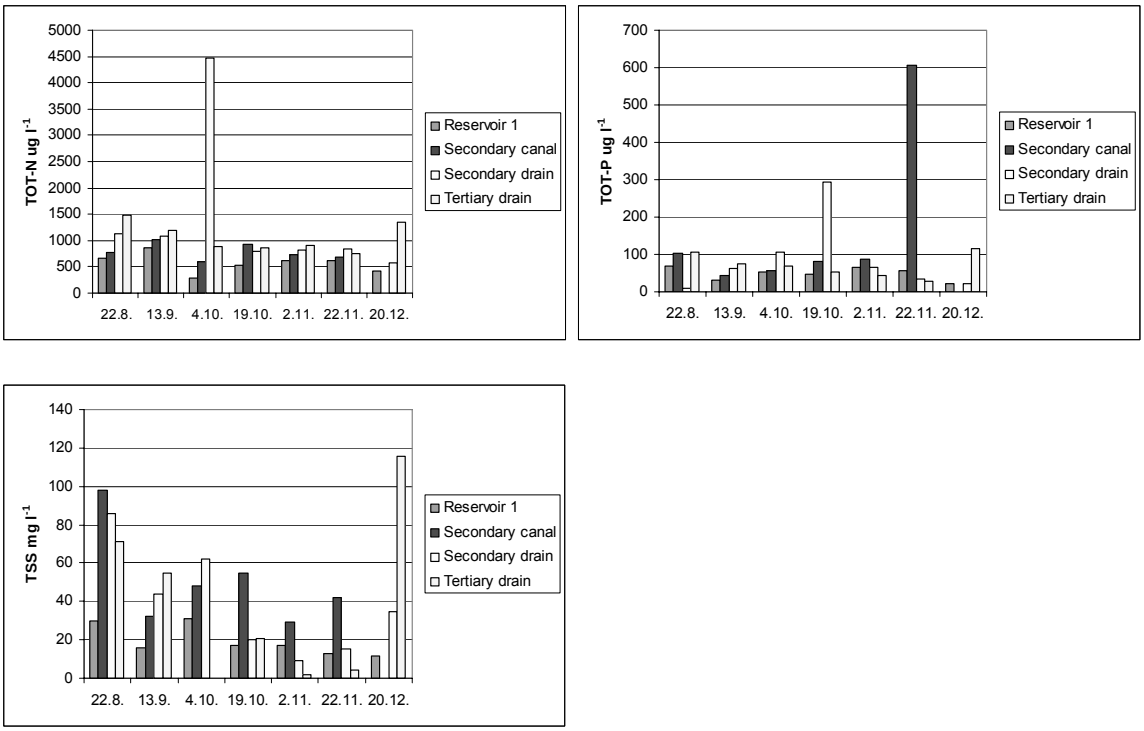



Figure 45. Total nitrogen (above on the left), total phosphorus (above on the right) and total suspended sediment concentrations in the irrigation canals.

100. Oxygen conditions are good in the irrigation canals and chemical oxygen demand is equivalent to the values of the reservoir (Table 10). Significant changes can be seen in the drainage water pH, alkalinity and conductivity. The values are smaller compared to the values in the reservoir.

Table 10. Oxygen, chemical oxygen demand, pH, alkalinity and conductivity values in the reservoir and irrigation canals.

| | | $O_2$ mg $l^{-1}$ | CODM mg $l^{-1}$ | pH | ALK+ mgCa | Cond. mS $m^{-1}$ |
|---|---|---|---|---|---|---|
| **Reservoir 2** | min | 1,3 | 1,4 | 5,7 | 8,1 | 2,5 |
| | aver. | 5,6 | 3,1 | 6,4 | 12,0 | 2,9 |
| | max | 8,5 | 8,4 | 7,9 | 17,6 | 3,2 |
| **Secondary canal** | min | 5,7 | 1,4 | 5,8 | 6,2 | 1,9 |
| | aver. | 6,9 | 3,8 | 6,3 | 12,3 | 2,8 |
| | max | 7,6 | 8,5 | 7,4 | 18,6 | 3,3 |
| **Secondary drain** | min | 6,5 | 1,0 | 5,5 | 2,6 | 1,2 |
| | aver. | 7,4 | 3,0 | 6,4 | 7,4 | 2,0 |
| | max | 8,3 | 5,3 | 7,6 | 14,2 | 3,3 |
| **Tertiary drain** | min | 5,3 | 1,0 | 5,3 | 2,0 | 1,5 |
| | aver. | 7,5 | 3,1 | 6,5 | 7,7 | 2,4 |
| | max | 8,4 | 4,8 | 7,7 | 14,2 | 3,2 |

### IV.2.2 Model based Stung Chinit impact assessment

101. The reservoir has a relatively small hydrological impact. This follows from the small volume of the reservoir compared to the through-flow. Filling up of the reservoir is presented in Figure 46. The figure shows the simulated reservoir water level starting from an empty reservoir. The reservoir fills up in less than a week even in June when flow volumes are not at their peak. When the reservoir is full it has an insignificant impact on flows. This is confirmed by field measurements presented in Figure 41.

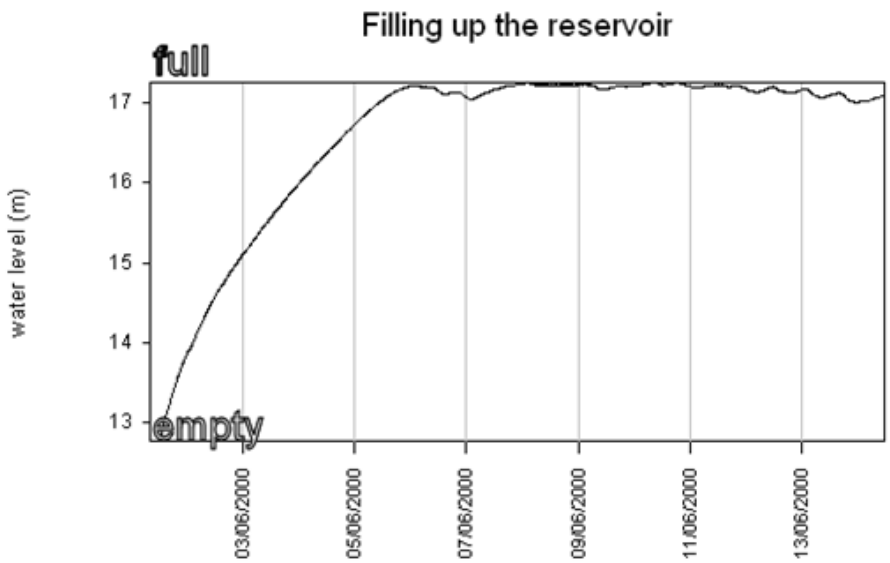



Figure 46. Simulated reservoir fill-up in June 2000 shown by the water level. The simulation starts with an empty reservoir and ends up being full in less than a week.

102. Conditions in the reservoir favor fish growth. Figure 47 presents simulated reservoir oxygen conditions on the surface (line in the middle) and near the bottom (lowest line). The reservoir values are compared to a natural stream (the highest line). Even in the bottom of the reservoir oxygen remains relatively high because of the high through-flow. This finding is supported by field measurements presented in the previous chapter, which gives similar results.

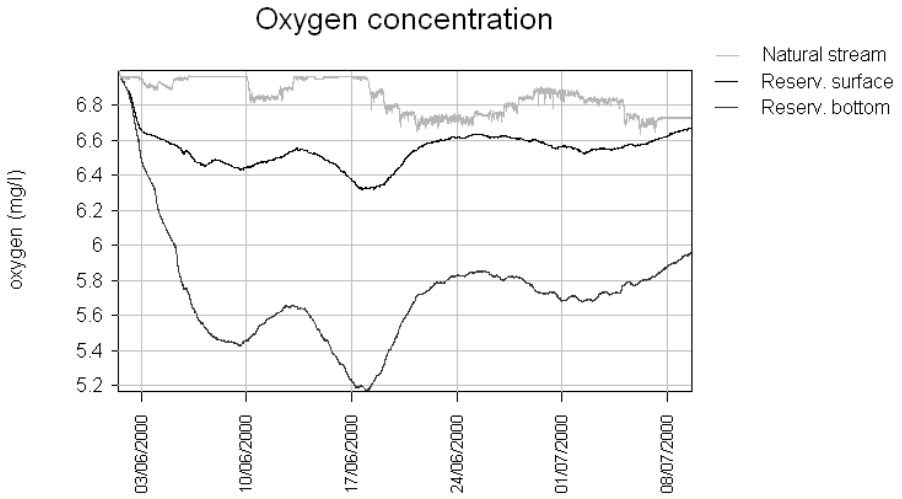



Figure 47. Simulated reservoir oxygen. Uppermost line natural river, middle one reservoir surface and lowest one near the bottom.

103. The simulated reservoir impact on sediment concentration is shown in Figure 48. Based on upstream measurements, the suspended sediment concentration in a free flowing stream is around 25 mg/l. The simulated outflow concentration is slightly below 20 mg/l. In the simulation resuspension from the bottom has not been taken into account. Measurements do not show any clear trapping impact. If there is trapping the downstream productivity could be influenced slightly. On the other hand the reservoir productivity would be enhanced by the trapped sediments.

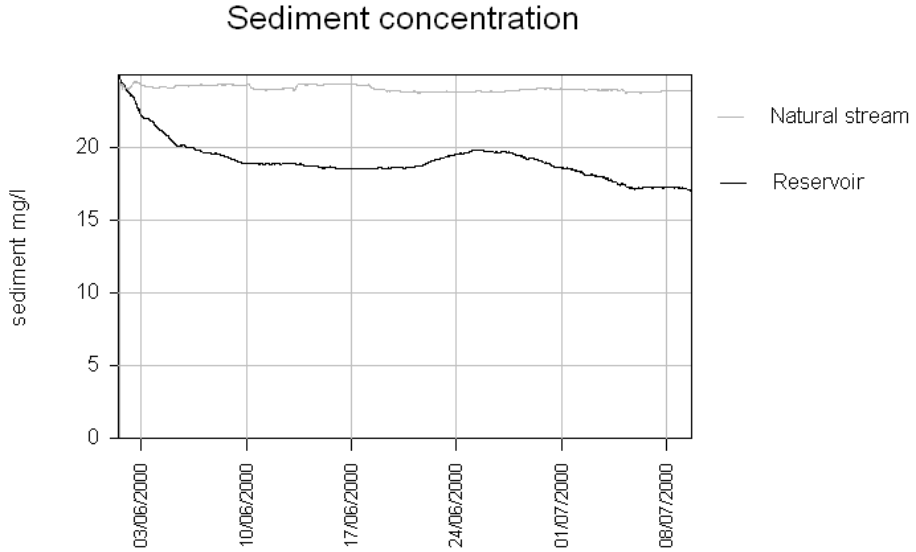



Figure 48. Simulated reservoir outflow suspended sediment concentration. The green line shows concentration in a natural river and black one in the reservoir outflow. Observe dam trapping effect of the reservoir.

104. The sediments provide a source of nutrients for productivity. Figure 49 shows the simulated sedimentation pattern in the reservoir after 1.5 months. Sedimentation varies between 50 and 100 g/m$^2$, which corresponds to about 0.05 mm sediment thickness.

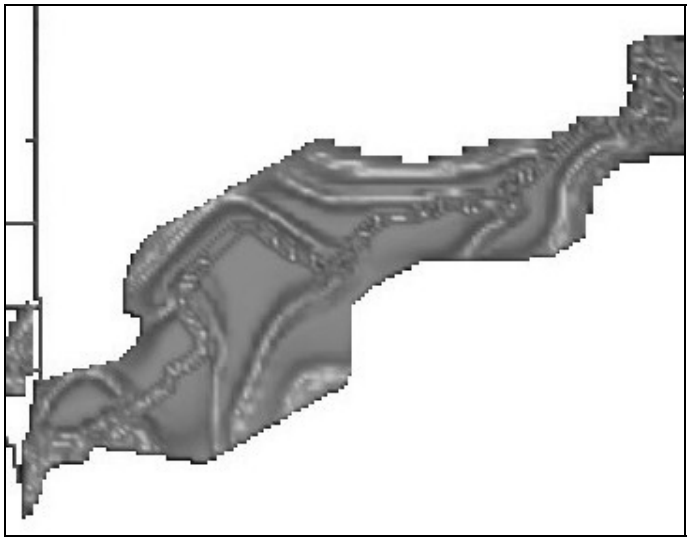


Figure 49. Simulated 1.5 month sedimentation. Sedimentation is about 50 to 100 g/m$^2$ corresponding to about 0.05 mm in sediment thickness.

105. Although the reservoir favors fish growth, it has substantial impacts on fish migration and the breeding of local species. Also, the reservoir may have some negative impact on downstream productivity. Because of this, the total impact of reservoirs should be assessed by qualified fisheries experts.

106. The generalization of the results to other reservoirs should be done cautiously. The characteristics of the reservoir including storage capacity, area, water depth, through-flow, residency time, soil properties, vegetation, inflowing water quality etc. govern the impacts and are difficult to be generalized. Each planned reservoir should be studied properly.

## IV.3 FLOODPLAIN IRRIGATION RESERVOIRS

107. Intensive irrigation structure development is ongoing on the Tonle Sap floodplain. Figure 50 shows the recent developments in Kampong Thom province. The total area of the structures in the figure is about 30 $km^2$.

108. The cumulative storage capacity of the floodplain irrigation structures is quite limited because the trapped water depth is only 1.5 m. Even assuming further development of 400 1 $km^2$ reservoirs would amount to only 0.6 $km^3$ storage volume. This can be compared to the total flood volume between 40 and 107 $km^3$. However, in the upper reaches of the floodplain the reservoirs trap a significant part of the flood.

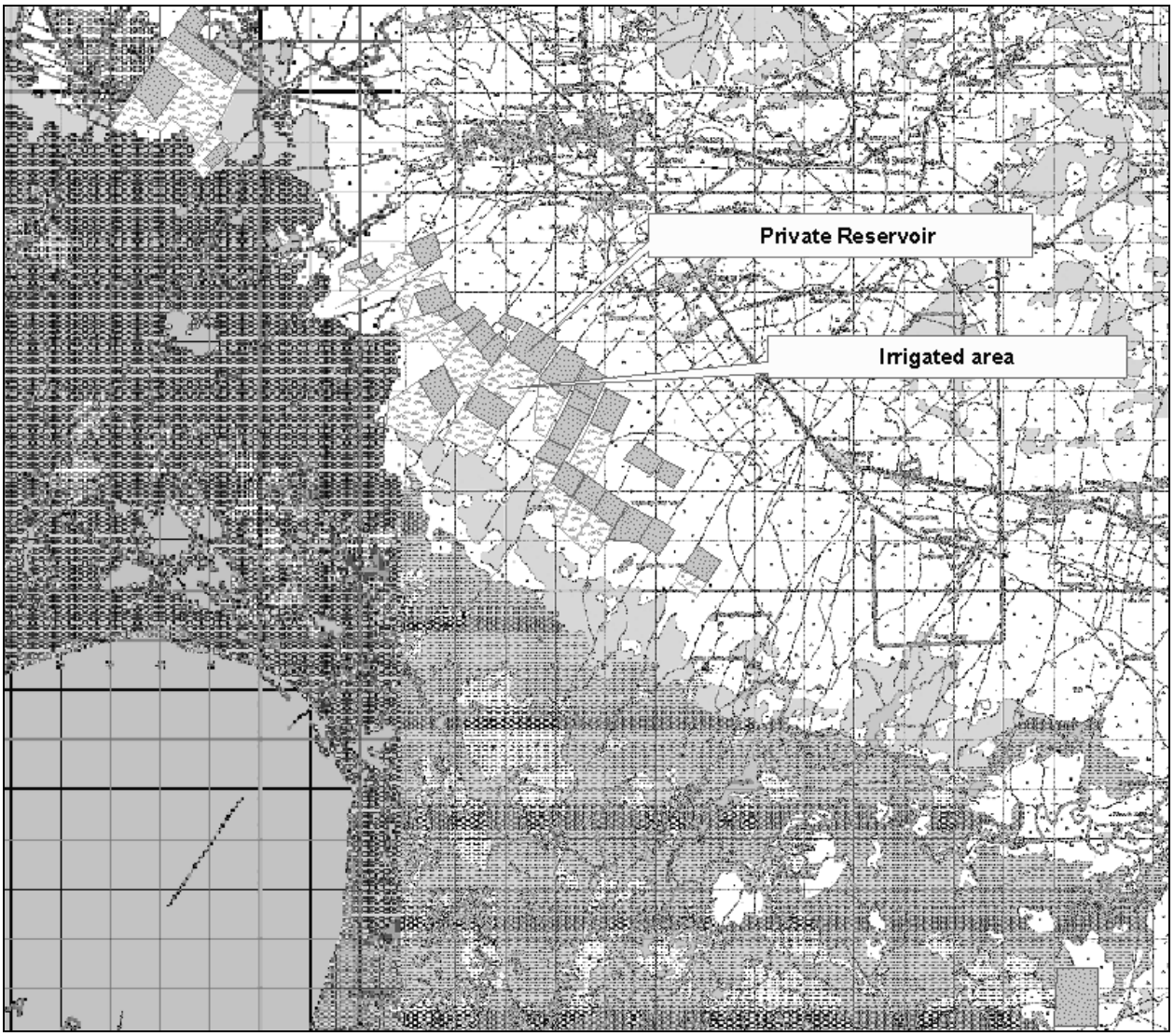



Figure 50. Private irrigation structures in Kampong Thom province. Blue indicates irrigation dams and green the accompanying irrigated rice paddies.

109. A private irrigation structure in Stung Staung District was selected for impact study. Details of the area are presented in the “Methods and Tools” chapter. Results presented below are based on field measurements of the reservoir.

110. Water level reached maximum level on the flood plain next to the reservoir on 24.10 and started to decrease. The gates of the reservoir were closed on 6.11 when the water level was 1.7 meter high and the risk of collapse of the embankment was small. Water level outside and inside the reservoir is presented in Figure 51. The trapping effect of the reservoir is shown by the grey line representing the water level in the reservoir. Initially, the water level goes down as reservoir water evaporates and possibly seeps through the embankment and ground. The water level starts to go down significantly in the middle of December when the flood waters have receded outside the reservoir and the reservoir water starts to be used for irrigation.

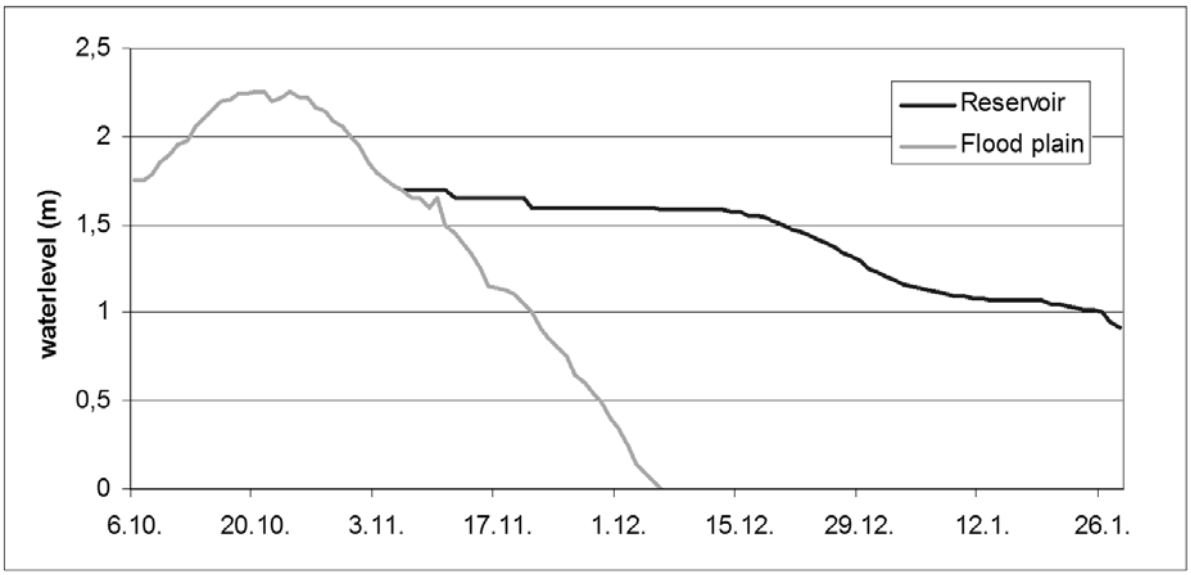



Figure 51. Water level on the floodplain and in the reservoir. Figure illustrates the water trapping function of the reservoir during the receding flood

111. Oxygen concentrations inside and outside of the reservoir were good except near bottom in some locations both inside and outside of the reservoir (Figure 52). Decaying organic material consumes oxygen resources on the bottom and oxygen concentration decreases if flow and wind driven waves are not able to mix the entire water mass. The area of the reservoir on the floodplain is very open, so even a light wind can mix effectively the shallow water. The maximum reservoir water depth is only two meters and the open fetch is several kilometers.

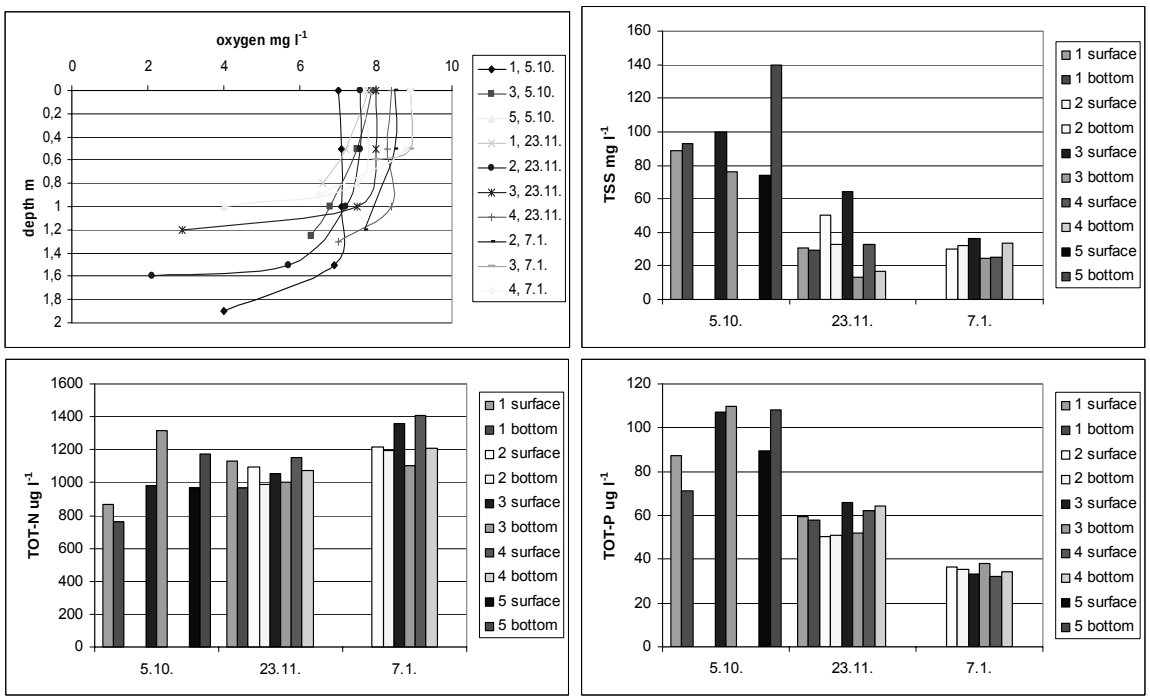



Figure 52. Oxygen, total suspended sediment, total nitrogen and total phosphorus concentrations in the reservoir (points 2,3 and 4) and outside of the reservoir (points 1 and 5).

112. According to the point measurements, the total impact of the structures on floodplain water quality is minor. Total suspended sediment (TSS), total nitrogen and total phosphorus concentration values vary at the same level inside and outside of the reservoir (figure 52.). Similar to the total nutrient concentrations, there is not any significant change in the nutrient fractions.

113. The oxygen values are higher in the reservoir in January than in October. This follows from the fact that temperatures are lower in January and consequently the oxygen saturation values higher. The total suspended sediment and total phosphorus values show a decrease in November and January. This shows the trapping effect of the floodplains in general. When comparing the November and January TSS values the reservoir does not seem to trap sediments, but the conclusion is based on only two measurements. On the other hand total phosphorus concentrations seem to diminish, which would point to net utilization of the phosphorus in the water column by vegetation. Again the conclusion is inconclusive.

114. Values of pH, alkalinity and conductivity of the reservoir water do not differ from the values of flood water outside of the reservoir (Table 11.). Significant change can be seen only in the values of chemical oxygen demand. Values are higher in the reservoir compared to the values outside of the reservoir. Higher values in the reservoir can be caused by organic matter that is trapped and sedimented in the reservoir. The biomass production period is also longer in the reservoir than on the floodplain, which is increasing the amount of sedimented organic matter on the bottom of the reservoir.

Table 11. Chemical oxygen demand, pH, alkalinity and conductivity values in the private irrigation reservoir (points 2, 3 and 4) and outside of the reservoir (points 1 and 5).

| | | CODM mg $l^{-1}$ | pH | ALK+ mgCa | Cond. mS $m^{-1}$ |
|---|---|---|---|---|---|
| **1** | min | 3,4 | 6,3 | 8,8 | 2,0 |
| | aver. | 4,2 | 6,4 | 9,7 | 2,3 |
| | max | 4,9 | 6,5 | 10,9 | 2,6 |
| **2** | min | 6,6 | 6,4 | 9,7 | 2,3 |
| | aver. | 7,7 | 7,1 | 10,0 | 2,4 |
| | max | 9,3 | 7,8 | 10,4 | 2,6 |
| **3** | min | 3,2 | 6,2 | 5,4 | 1,8 |
| | aver. | 6,5 | 6,7 | 8,4 | 2,3 |
| | max | 10,2 | 7,4 | 10,7 | 2,6 |
| **4** | min | 7,0 | 6,5 | 9,2 | 2,3 |
| | aver. | 8,6 | 7,0 | 9,6 | 2,4 |
| | max | 9,8 | 7,7 | 10,0 | 2,5 |
| **5** | min | 3,0 | 6,3 | 7,7 | 2,2 |
| | aver. | 3,0 | 6,3 | 8,5 | 2,2 |
| | max | 3,0 | 6,3 | 9,4 | 2,2 |

115. The floodplain irrigation structures have only a relatively limited impact on the flood and water quality. Even the cumulative impact is relatively low. However, the destruction of habitat and blocking of fish movement may be important for fisheries.

## IV.4 INFLUENCE OF LARGE SCALE FISHING GEARS

116. The set-up for the field and laboratory work for finding out fishing gear impacts is presented in the “Tools and Methods” chapter.

117. During the study the flow fields of the Prek Toal area were measured at four locations in entire water profile from the bottom to the surface on 5.8.2006 and 23.8.2006 Velocities of the flow were mostly below 10 cm $s^{-1}$ and directions varied between 62 and 250 degrees (Table 12).

Table 12. Range of flow velocity and direction in the Tonle Sap Lake at Prek Toal area, 5.8 and 23.8.

| | | cm $s^{-1}$ | degrees |
|---|---|---|---|
| 5.8. | min | 2,6 | 62,1 |
| | aver. | 5,1 | 214,1 |
| | max | 9,9 | 265,8 |
| 23.8. | min | 1,8 | 98,8 |
| | aver. | 9,6 | 190,7 |
| | max | 18,5 | 250,0 |

118. Cross section measurements on the lake do not indicate significant hydrological changes caused by the bamboo fences. Measurements were carried out at the end of January 2007 when bamboo fences were installed on the lake and the depth of the lake was about three meters. The direction of the fence was 300 degrees and it was located in the north-west corner of the lake off Prek Toal (48 P 0359713, 1459834). Average flow velocities of 200 m long cross sections were low on both sides of the fence, from three to four cm $s^{-1}$ (Figure 53). Direction of the flow varied between 320 and 355 degrees on both sides of the fence. According to these results bamboo fence does not decrease the velocity and change the direction of the flow with such slow flow velocities. The lowest possible velocity recorded by the survey boat (>1 m $s^{-1}$) was considerably high compared to the flow velocities of the lake (<0,1 m $s^{-1}$). Therefore, accuracy of the measured data was not very high and these results should be taken with caution.

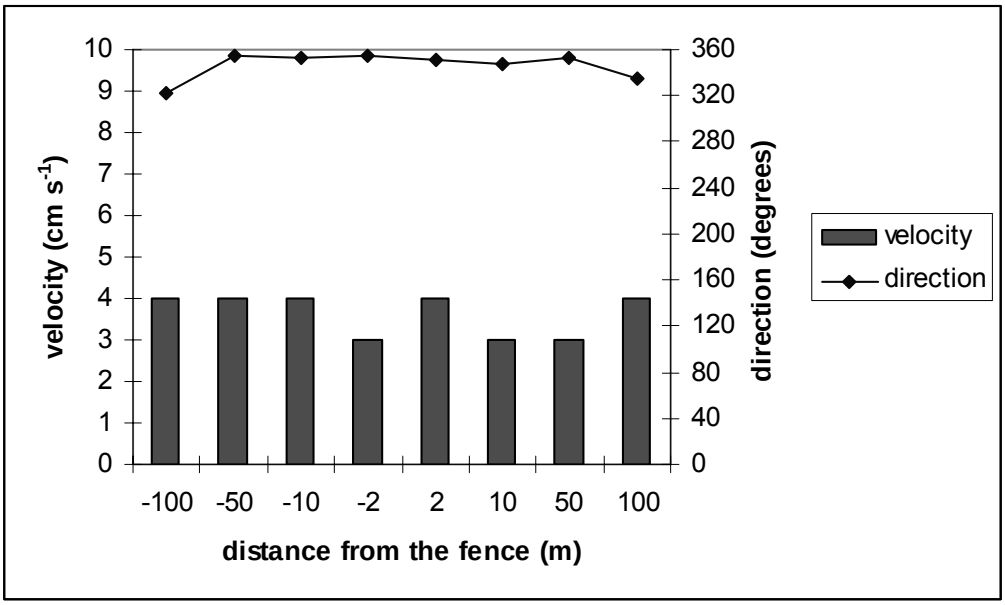



Figure 53. Average velocity and direction of the flow on both sides of the bamboo fence on the lake in Prek Toal area.

119. Laboratory experiments in the fixed bed flume show that the slight opposing influence of the bamboo fences on flow velocities can be observed when the velocity in the flume rises higher than 10 cm $s^{-1}$ (Figure 54). Water level clearly rises upstream of the fence with higher velocities. The opposing influence of the nylon net is minor, the slight influence appearing when flow velocity is higher than 20 cm $s^{-1}$, but even with the maximum velocity of the flume the influence is still slight.

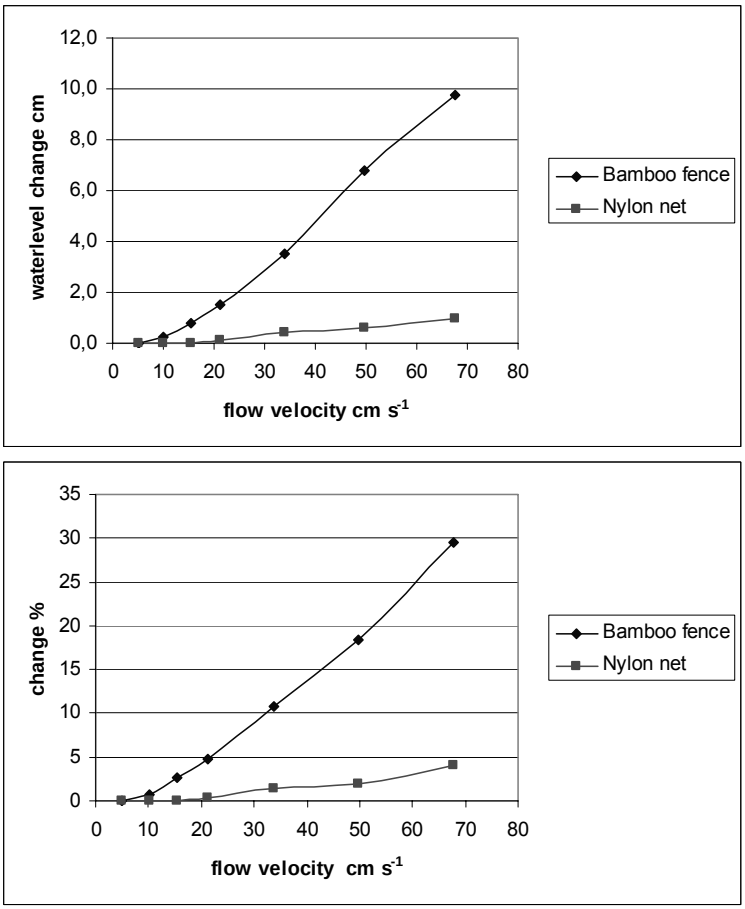



Figure 54. Influence of fishing gears on water level (upper picture) and flow velocity in the fixed bed flume.

120. As a summary typical low floodplain flow velocity causes only small impact on water levels and flooding. The water level changes caused by the fishing gears are in general small, and the low flow velocities encountered in the floodplain cause only slight resistance to the flow. The flood will not be delayed by the gears. The water quality impacts are similarly small because water can flow relatively easily through the structures. The impact of fishing gears on hydrology and water quality is small. However, other impacts to fish such as obstruction of fish movement can be serious.

# V CONCLUSIONS AND RECOMMENDATIONS

121. The report describes built structure impacts on Tonle Sap hydrology and water quality. The impacts have been studied by analysis of existing data, new field measurements and mathematical modelling. Currently the Tonle Sap fisheries productivity and its dependence on hydrology and water quality is not understood very well, and consequently quantitative fisheries impact analysis is not possible. However, the study demonstrates the relative importance of different types of structures to the fisheries and presents conclusions related to the main risks and benefits of the developments.

122. The built structures development scenarios that have been studied represent intensive Mekong tributaries, Mekong mainstream and Tonle Sap tributaries/floodplains developments. Also, small-scale Tonle Sap structure impacts including different types of irrigation reservoirs, roads and fishing gears have been studied in detail. The actual development of the Mekong region cannot be exactly predicted, and the scenarios are only indicative.

123. The Tonle Sap system's hydrological characteristics show great natural variability. The lake area is about six times larger during the peak flood season compared to the dry season. The water depth increases about seven and volume about sixty times compared to the dry season. There is also large variability between different years. The flow volumes into the lake can be over two times higher in a wet hydrological year compared to a dry year. The maximum flooded area varies by about 50% between dry and wet years.

124. During wet years, even massive developments have relatively small impacts on the Tonle Sap compared to the natural variability. The study estimates that intensive upstream hydropower and irrigation development will decrease the Tonle Sap inflow by only 4 – 10% during wet years.

125. Upstream developments have the largest impact during dry years. Then storage volumes are relatively larger than during the wet years compared to flow volumes. The Tonle Sap inflow can decrease 10 – 25% during a dry year. A 10% inflow decrease corresponds to about a 0.5 maximal flood height decrease and a 10% decrease in the flooded area. A decrease in the area flooded means less breeding habitat for fish, and a decrease in flood height means less volume for fish food production.

126. The upstream dam developments delay flood arrival from one week to one month. The flood duration is correspondingly shortened. The delay can be critical for breeding fish which may have adapted to the quite regular onset of the flood season. It is also clear that shortened inundation shortens the time fish can feed on the floodplain.

127. The dry season impacts are aggravated by the fact that the fisheries are already stressed during dry years. Whether the additional stress caused by built structures can significantly affect the fisheries cannot be reliably assessed based on the available fisheries data. However, it is clear that realisation of all hydropower and irrigation potential in the Mekong Basin represents a serious threat to fisheries especially during dry years.

128. The water stored in the reservoirs is released during the dry season. Although water release can have a beneficial impact on river water quality and river channel fish habitats, it can also negatively impact floodplain habitats. The river water levels are increased during the dry season and consequently the Tonle Sap water level will stay higher during the dry

season. Because the floodplain vegetation has been adapted to alternation of dry and wet (terrestrial and aquatic) periods, it cannot survive permanent inundation. The flooded forest near the lake edge will be destroyed. The flooded forest is an important fish habitat and it also acts as a protective barrier against strong lake currents and waves. The estimates for the dry season water level rise vary. The estimated increase of the permanently inundated area is 300 – 900 $km^2$, or 15 – 45% of the dry season lake area.

129. The local Tonle Sap dam development has similar impacts to the upstream Mekong developments. Realisation of the full hydropower and irrigation potential in the Tonle Sap catchment would result in impacts of the same order of magnitude as intensive Mekong upstream tributaries' development. When both local and upstream developments are realised they cause significant impacts together.

130. As described above the dam build-up decreases flows especially in the beginning of the flood season. Decreased flows cause reduced water exchange in the floodplain and can worsen the oxygen conditions. The oxygen conditions are naturally critical in the floodplain because of the large amounts of decaying organic material and because of the sheltering effect of vegetation decreasing aeration and water mixing. The young juveniles feeding in the floodplain are especially sensitive to oxygen conditions and could suffer critically from the oxygen decrease.

131. Although sediment impacts on productivity are not well understood in the Mekong region, there are indications that sediments play a central role in providing nutrients to both aquatic and flooded terrestrial ecosystems. In the worst case scenario the planned Chinese dam cascade will trap nearly all sediments originating from the upper Mekong reaches. This could cause about a 50% sediment concentration decrease in the Lower Mekong Basin. Because most of the sediment in the Tonle Sap originates from the Mekong, this would cause a correspondingly significant sediment input decrease to the Tonle Sap. The exact assessment of the dam impact would require a Mekong scale in-depth sediment study that has currently not been done. Also, the sediment relation to the fisheries productivity needs to be understood better, but potentially the sediment trapping can have serious impact on fisheries productivity.

132. Modelling results show that changing flow regimes alter larvae and juvenile drift especially from the Tonle Sap River. The significance of this drift change cannot at the moment be assessed but needs more in-depth study.

133. Compared to the large-scale upstream and Tonle Sap developments, local small-scale floodplain and near floodplain dams have a rather small impact on hydrology and water quality. The floodplain irrigation reservoirs that are increasingly being built have, even in large numbers, a small storage capacity. Also, their impact on water quality is small. The same applies to the relatively small-scale upstream irrigation schemes such as Stung Chinit. The reservoir provides good conditions for fish breeding. However, structures can significantly disturb fish habitats and block fish migration and movement. Also, the cumulative impact of a large number of small-scale structures may be significant, although it is not well understood.

134. Especially when assessing the impact of any planned reservoir, generalizations drawn from one case should be avoided. The characteristics of the reservoir including storage capacity, area, water depth, through-flow, residency time, soil properties, vegetation, inflowing water quality, etc. govern the impacts and are difficult to be generalized.

135. The floodplain roads in general do not have a significant impact on floodplain hydrology or water quality. However, if built on important flow routes they may decrease oxygen and sediment rich water flows as well as larvae and juvenile drift to important fish breeding grounds. The floodplain's hydrological and hydrodynamic characteristics should be understood before road construction begins, and mitigation structures such as bridges should be built in appropriate places.

136. Fishing gears including bamboo fences and nylon nets have a small impact on hydrology and water quality. However, they can seriously block fish movement and have a significant impact on fisheries.

137. As discussed above, the major uncertainty in the fisheries impact analysis stems from the poor understanding of fisheries dependence on hydrological, hydrodynamic, water quality and habitat conditions. It is necessary first to understand primary productivity and its dependence on these factors. Both terrestrial and aquatic productivity are important for providing food for fisheries and the (quantitative) pathways from primary productivity to fisheries need to be clarified. When the productivity and fisheries are understood, the potential risks to them can be identified and the quantitative impacts of different development scenarios can be estimated.

138. As well as biological uncertainties, physical and chemical ones need to be decreased. The major uncertainties are related to the fate of the sediments, nutrient dynamics, Tonle Sap flow changes, and the magnitude of dry season water level changes. Existing data needs to be utilized more intensively, new field measurements conducted and modelling tools developed and further verified.

139. Especially because the fisheries are understood poorly, upstream and local developments should be planned carefully and cautiously. The operation of reservoirs should take into account downstream conditions and impacts. For instance, the reservoirs could be filled more cautiously in the beginning of the flood season to minimize impacts on early flooding.

140. Although the natural variability of the Tonle Sap system is high and the fish have adapted to it, upstream developments may change conditions in the lake especially during critical periods in a way that the fish can not cope with. The above discussion highlights dry years in this respect.

141. The impacts of the built structures have been discussed mostly individually. The cumulative impact of the individual changes is rather difficult to assess. For instance, changes in flood timing and changes in the floodplain's early flood oxygen conditions both have negative impacts on fisheries, but together they may have a overall impact more important than the sum of individual impacts. However the cumulative impact of many small structures has not been understood very well. This applies especially to the Mekong upstream, but also locally.

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