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Article *in* International Journal of Water Resources Development · September 2006

DOI: 10.1080/07900620500482915

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Water Resources Development,
Vol. 22, No. 3, 497–519, September 2006

Ecosystem Management of the Tonle Sap Lake: An Integrated Modelling Approach

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ABSTRACT *The monsoon floods of the Mekong River are a key driver of the Tonle Sap Lake ecosystem. This pulsing system together with a large floodplain, rich biodiversity and high annual sedimentation and nutrient fluxes from the Mekong makes the lake one of the most productive fresh water ecosystems in the world. The livelihoods of people living in and around the Tonle Sap are strongly dependent on the lake's natural resources. An integrated modelling system, supported with primary data collection and analysis, has been developed for the Tonle Sap to assess the impacts of planned developments on the lake's ecosystem and riparian communities. Understanding the ecosystem processes and tools for predicting the development impacts are essential for Integrated Water Resources Management, as well as for sustainable basin-wide planning, and national and regional policy-making.*

Introduction

One of the greatest challenges of our time is to find a balance between economic and social developments, and the maintenance of productive, healthy ecosystems. To that end, several approaches in the water management sector have been developed, of which Integrated Water Resources Management (IWRM) is one of the most important in recent decades (Biswas *et al.*, 2005). IWRM aims to develop democratic and participatory governance practices and promotes the balanced development of water resources for poverty reduction, social equity, economic growth and environmental sustainability (Varis, 2005). The most used definition of IWRM is that used by the Global Water Partnership (GWP, 2000, p.22):

> Integrated Water Resources Management is a process which promotes co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

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0790-0627 Print/1360-0648 Online/06/030497-23 © 2006 Taylor & Francis
DOI: 10.1080/07900620500482915

Ecosystem management is a particularly challenging task in countries where the majority of the population is directly dependent on natural resources. This is the case in the Mekong River Basin in South-East Asia, especially in the poorest countries in its catchment, Cambodia and Lao PDR. The implementation of IWRM is further complicated in the Mekong Basin due to poor understanding of the dynamics of the river and stream ecosystems and their dependence on flow regimes (Campbell, 2005). This leads to severe limitations and uncertainties in environmental impact assessments.

In this paper the focus is on connecting the ecosystem and ecology with the context of IWRM. The importance of comprehending the ecosystem processes in order to be able to manage the system in an integrated way is highlighted.

The focal area for this work is the Tonle Sap Lake in Cambodia. The Tonle Sap Lake with its floodplain is an integral part of the Mekong River system (Figure 1) and among the most productive 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 ideal conditions for feeding, breeding and rearing their young (Poulsen *et al.*, 2002). The lake also operates as a natural floodwater reservoir for the lower Mekong Basin, offering flood protection and assuring the dry season flow to the Mekong Delta.

The achievement of the objectives of IWRM is not a straightforward task. In the Mekong basin and in Tonle Sap Lake, in particular, the implementation of IWRM is particularly challenged by:

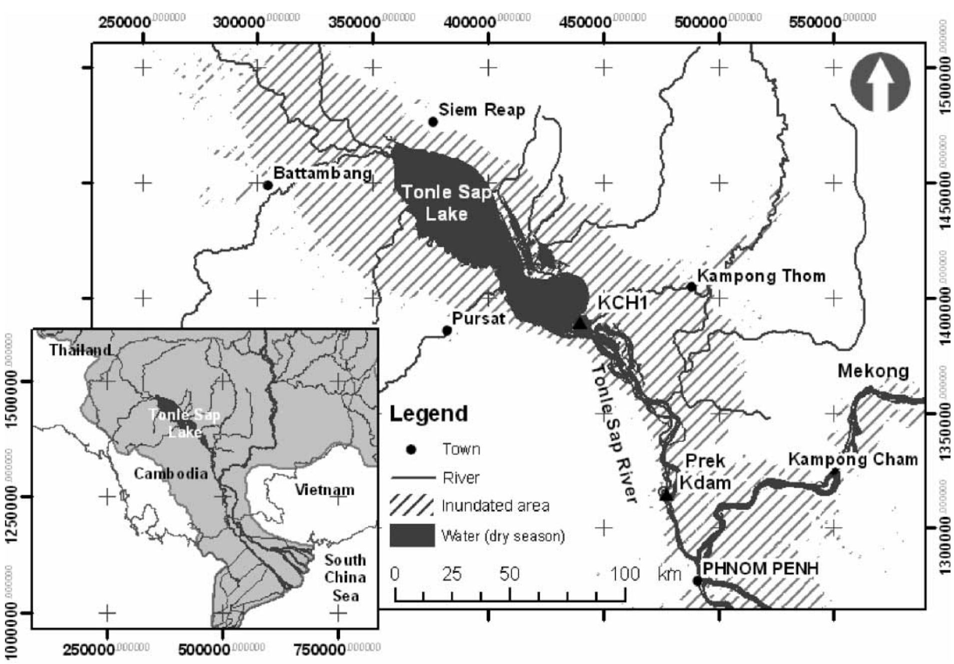


Figure 1. Tonle Sap Lake and its floodplains

- short research traditions in the area and thus, lack of primary data and poor understanding of the ecosystem;
- lack of information on linkages between water resources, ecology and society;
- shortcomings in collaboration and information sharing between and within the riparian countries; and
- absence of upper basin countries China and Myanmar from the Mekong River Commission, hampering basin-wide planning and management.

The implementation of environmental protection and management policies requires continuous development of environmental impact assessment tools, computational models being one of them. Computational models offer many possibilities to enhance the understanding of ecosystems processes as well as enabling the investigation of the response of these ecosystems in various development scenarios. However, integrated water management requires not only understanding of ecosystem processes but also environmental, social, economic and political information. Integration of these very different data can be aided by computational modelling, such as hydrodynamic and water ecosystem models. For the integration, the models are linked with socio-economic information from databases and survey data, often collected by participatory methods. This provides a holistic method and viewpoint for the assessment of the impacts of various water management options on natural resources and, consequently, people's livelihoods.

In cases where the amount and quality of information are limited, the identification of even basic ecosystem processes is difficult. This is certainly the case for the Tonle Sap Lake. Moreover, it is not guaranteed that ecosystem information is taken into account in planning and policy-making, even if a fundamental diagnosis of ecosystem together with sufficient tools for impact assessment were available. Driven by these challenges, the objectives of this paper are to:

- present the current understanding of Tonle Sap Lake's ecosystem;
- present the integrated modelling tools developed for the Tonle Sap Lake, aiming to increase the understanding of ecosystem processes;
- create tools for predictions by integrating model results with socio-economic data; and
- discuss how these tools could be better used for IWRM and policy-making as an active tool for national and basin-wide planning.

Integration between Models and Socio-economics

IWRM calls for an integrated analytical approach. This approach requires the use of analytical tools to solve real management problems. Mathematical models, in this case hydrological and hydrodynamic models, are among those tools. While such models are useful in themselves, their full potential is only realized when linked with social, economic and policy issues (Keskinen & Varis, 2005). The integrated modelling approach developed for Tonle Sap Lake is presented here. In this method the hydrodynamic model is connected with socio-economic data through ecological links, with the help of GIS tools and analysis. Data and modelling products, and qualitative analysis, are used as integration methods.

Integration Approach

The integrated ecosystem management is principally targeting the ecosystems and associated human communities in the research area. Modelling is one of the potential tools that can be utilized to 'tame' the complexity of the ecosystem and social links, making the integration outcome more understandable and applicable for management purposes. Several approaches for modelling have been proposed by scientists. In general, they follow the principles presented by, for example, Kuper *et al.* (2003):

(1) identify the different mechanisms in interaction in the considered ecosystem;
(2) identify the spatial and temporal relationships, inter and intra, e.g. Blöschl & Sivapalan (1995);
(3) select mechanisms for representing each process;
(4) test the numerical robustness of the aggregation of the representation of the different processes; and
(5) carry out the calibration, validation and robustness tests.

Kuper *et al.* (2003) also bring forward the importance of a comprehensive approach in the modelling work. While a comprehensive approach is emphasized, as the modelling principles imply, equally important are the studies concentrating on the parts and details within the ecosystem management. They provide information on the structure, qualities and relations within the entity.

In the Tonle Sap, many parts and details of the ecosystem and its connections with society lack scientific or other well-founded information. This makes the pure modelling approach difficult, or even impossible. Therefore a specific integration framework was developed based on the emergent needs and ideas. The approach for integration relies on three concepts: substance, methodologies and context (Figure 2). The core of the framework is the actual substance that consists of socio-economy, ecology and hydrology. The integration between these can be carried out with two different

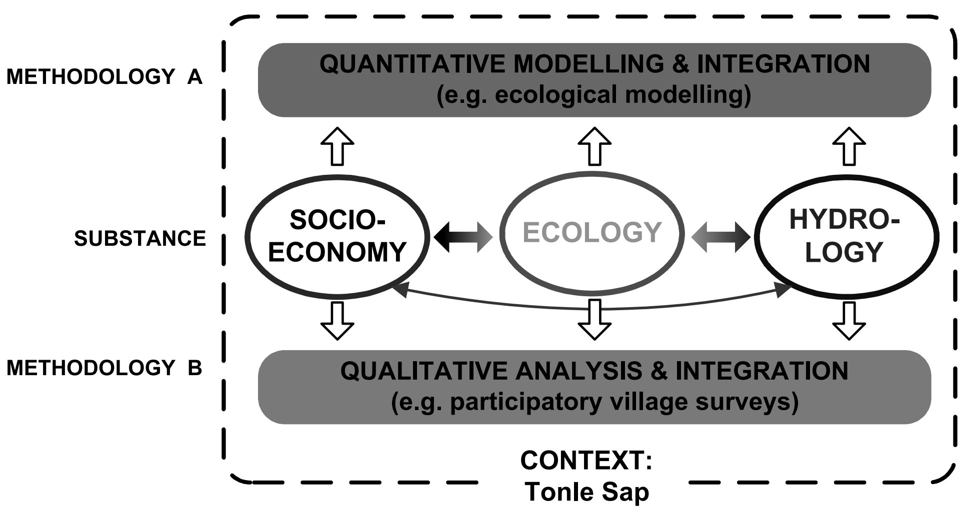


Figure 2. Framework for integration. *Source:* cf. Keskinen *et al.* (2005); Nikula (2005).

methodologies that are based on data and modelling, and on qualitative analysis. Finally, the context of the integration consists of geographical area (Tonle Sap) and of a specific analysis tool (GIS) coupled with the model results.

Ecology acts as a connecting factor between socio-economy and hydrology (Figure 2). The division into hydrological, ecological and socio-economic components or modules reflects the traditions of academic research, but is illustrative only. In reality, the substance forms a continuum from the physical characteristics of water to the abstractions of human cognition with no clear borders between different disciplines.

The two methodologies used in the actual integration are 'Data and model-based integration', and 'qualitative analysis-based integration' (Figure 2). While the former requires comprehensive quantitative data from all three substance areas, the latter utilizes local and scientific knowledge and provides a kind of shortcut through the maze of quantitative data (Keskinen *et al.*, 2005). 'Data and model' methodology is based on the primary data collection and hydrodynamic modelling work done during the WUP-FIN project (WUP-FIN, 2003). 'Qualitative analysis' methodology focuses on descriptive research on the functions of the Tonle Sap system. The most important methods applied in it are literature review, scientific interviews and participatory village surveys (Keskinen, 2006, this issue; Keskinen *et al.*, 2005). The two methods are by no means exclusive, but are ideally used to support and complement each other. Keskinen (2006, this issue) provides closer information on the interaction of these methods in the Tonle Sap studies.

Modelling and Socio-economic Analysis

In the WUP-FIN project's first phase 'Tonle Sap Modelling Project', this integrated modelling approach was applied to Tonle Sap Lake. The project aims to create the means to improve understanding physical, chemical and biological processes in the Tonle Sap and to assist in maintenance of sustainable conditions in the lake and associated wetlands. Extensive physical, chemical, biological and socio-economic primary data collection was carried out (WUP-FIN, 2003).

The mathematical flow models applied to the Tonle Sap Lake are a three-dimensional (3D) EIA Flow Model for the detailed hydrodynamic studies, and 3D EIA Water Quality Model for calculating the transport and concentrations of a selected water quality parameters and hazardous materials (Koponen *et al.*, 1992, 2003, 2004). Model outputs for both real and hypothetical scenarios include, for example:

- tributary inflows;
- 3D flow speed and direction;
- flooding characteristics as flood arrival date, flood duration and flood depth;
- dissolved oxygen concentrations (Figure 7);
- suspended sediment concentrations and net sedimentation (Figure 6);
- larvae and juvenile fish drift; and
- pollution dispersion, e.g. from floating villages.

The model was complemented with extensive socio-economic analysis for the Tonle Sap Area. The analysis consisted of three main components: (1) analysis of the databases and creation of a GIS-based socio-economic database; (2) participatory village surveys and their analysis; and (3) analysis of other sources of information including literature review and expert interviews (Keskinen, 2003; 2006, this issue). The focus of the socio-economic analysis was on water-related livelihoods and trends in water resources use and availability. Additionally, a policy analysis based on Bayesian Causal Networks was conducted (Varis & Keskinen, 2006, this issue).

In order to facilitate integration with the results of hydrodynamic models, the gathered quantitative socio-economic data were arranged and analysed according to topographic location (i.e. elevation) of the villages in GIS. To verify the information derived from the socio-economic databases, all topographic zones were covered also by participatory village surveys (Keskinen, 2003). In total four topographic zones were created. In addition, urban areas were analysed separately and they thus formed the fifth zone. The entire Tonle Sap Lake falls within Zone 1, and most of its floodplain within Zones 1 and 2. Exceptionally high floods such as in the year 2000 can also cover most of Zone 3 and parts of Zone 4 (Keskinen, 2006, this issue).

The Ecosystem of the Tonle Sap Lake

The Tonle Sap Lake in Cambodia is the largest permanent body of fresh water in Southeast Asia. Cambodian floodplains, including the Tonle Sap floodplain, contain the most extensive wetland habitats in the Mekong system (Figure 1).

The Tonle Sap system is important for the Cambodian people as a source of food and income. However, the lack of ecological understanding is acute in the Mekong basin (Campbell, 2005), and the impacts of various development scenarios on the ecosystem and, ultimately, on the people's livelihoods, are poorly comprehended.

The basic hydrological and limnological processes, such as sediment transport and dissolved oxygen levels, are now adequately documented (e.g. Bonheur, 2001; Carbonnel & Guiscafre, 1963; Koponen *et al.*, 2004; Kummu *et al.*, 2005; Lamberts, 2001; Penny *et al.*, 2005; Sarkkula *et al.*, 2003, 2004; Tsukawaki, 1997; van Zalinge *et al.*, 2003; WUP-FIN, 2003), but the status and dynamics of biological productivity within the lake have not been well studied. This is a major shortcoming in the understanding of the lake's ecological system. 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 seems very suitable to be utilized in Tonle Sap studies.

Hydrological Regime

The Tonle Sap River, which flows from the southeastern end of the Tonle Sap Lake, joins the Mekong River at Chaktomuk, immediately north of Phnom Penh, after which the river immediately splits into the smaller Bassac River and the larger Mekong River (Figure 1). In the wet season, flooding in the Mekong River causes the Tonle Sap River to change its direction and flow northwest (upstream) into the Tonle Sap Lake. Therefore, the lake functions as a natural floodwater reservoir for the Mekong system during the wet season. Equally, the slow release of floodwaters from the lake is a very important source of water for the Mekong delta during the dry season.

Between the dry and wet seasons the area of the lake varies from 2500 km^2 up to approximately 15 000 km^2, while the depth of the lake increases from less than 1 m to 6–9.5 m, depending on the year. During the wet season, the volume of the lake increases from about 1.3 km^3 during the dry season up to 60–70 km^3, depending on the flood

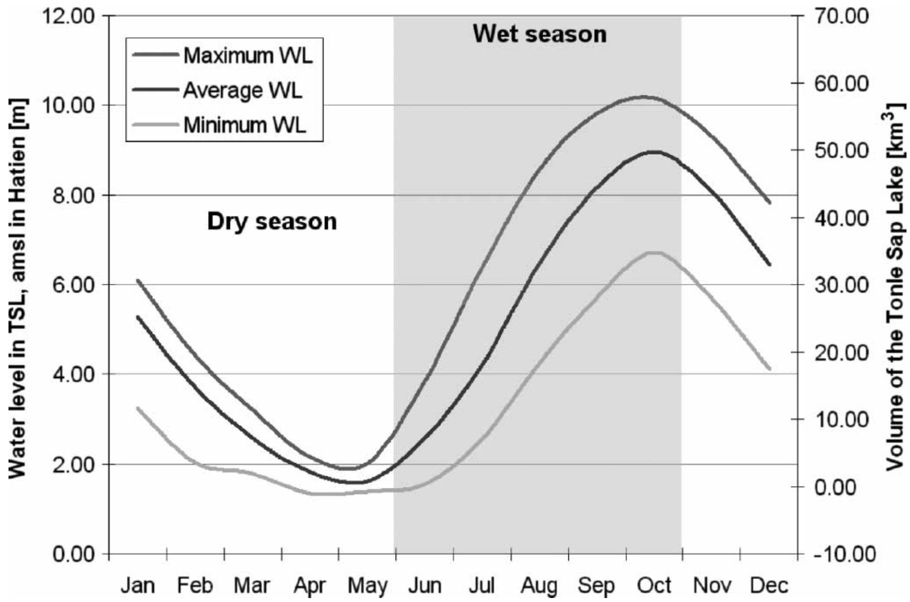


Figure 3. Minimum, average, and maximum monthly average water levels and volumes in Kampong Lung, Tonle Sap Lake, during 1996–2003. Levels are above the mean sea level in Hatien, Vietnam. Bottom of the lake lies about 0.7 m above the mean sea level

intensity. The bottom of the lake lies approximately 0.5–0.7 m above the mean sea level in Hatien datum. Hence, during the year the surface of the lake varies on average between 1.2 m and 9.0 m above the mean sea level, respectively (Figure 3). As presented in Figure 3, the natural variation of flood levels in the lake is substantial.

According to the hydrological data in MRC database (years 1997–2002) and the water balance calculation carried out during the WUP-FIN project (WUP-FIN, 2003), the average yearly inflow to the lake was 79.7 km^3. The main source of inflow is the Mekong River, which yields 51% of the inflow via the Tonle Sap River. Other sources of inflow are tributaries, overland flow from the Mekong and precipitation, which consist of 31%, 5% and 13% of the total inflow, respectively. Outflow from the lake is via the Tonle Sap River 70.4 km^3/year and evaporation 9.3 km^3/year.

The flood duration and flooded area of the floodplain are important for the productivity according to the pulsing system approach. With the model it is possible to calculate flood duration and area in each zone and also land-use class, as shown in Figure 4.

Pulsing System

On floodplains, the fluctuation of water levels 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 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

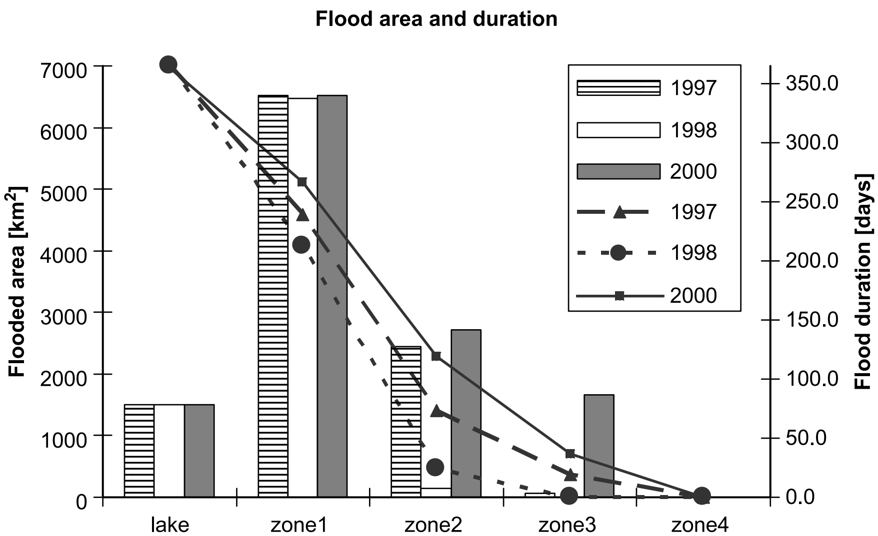


Figure 4. Modelled flooded area and flood duration in different zones of the Tonle Sap Lake and floodplain (zoning presented in Keskinen, 2006, this issue). *Source*: Keskinen *et al.* (2005)

basins with similar characteristics, such as the Lower Mekong Basin that, as the lower Amazon, experiences large water level variation and one flood pulse per year. The importance of the flood pulse concept has been recognized by many authors working on the Mekong River/Tonle Sap system (see, for example, Bonheur & Lane, 2002; Fox, 2004; Lamberts, 2001, 2006, this issue; Poulsen *et al.*, 2002; Sverdrup-Jensen, 2002).

Junk (1997) states that a river and its floodplain must be considered as an indivisible unit because of their common water and sediment budget. The same holds true for the exchange of organisms, biomass and energy. Those areas that oscillate between a terrestrial and an aquatic status are designated as the Aquatic/Terrestrial Transition Zone (ATTZ) by Junk *et al.* (1989). Plants and animals within the ATTZ use the available nutrients during their active growth phase and transfer some of them into the less active phase, thus fuelling an internal nutrient and energy cycle within the floodplain. For instance, plants that grow during the terrestrial phase take up nutrients from the sediments, store them in their tissue, and release them into water when decomposing during the aquatic phase.

According to Junk (1997) aquatic organisms can directly use biomass produced during the terrestrial phase. For example, some fish feed on fruit of the floodplain forest, detritus and terrestrial invertebrates. Bacteria, aquatic algae and macrophytes take up the nutrients released from the decomposing terrestrial organic material. Organisms living during the terrestrial phase make use of the stranded aquatic material and of the nutrients released by them during decomposition. This nutrient cycle in the form of an exchange of energy and nutrients between the two phases by different groups of organisms is the principal reason for the high productivity of most floodplain systems.

The river channel itself supplies the floodplain with water and dissolved and suspended solids from the catchment area. The suspended load of materials in the floodwater ensures a periodic enhancement of the nutrient stock. However, organic material derived from the catchment area is of relatively low importance for floodplain food webs because the floodplain provides such large amounts of high quality organic material.

Lamberts (2006, this issue) discusses the need of developing Tonle Sap ecosystem productivity indicators, instead of using fish catch statistics as is often done. He proposes to combine the surface area of the natural vegetation in the floodplain and its productivity, taking into account the heterogeneity of the floodplain vegetation. The production of biomass per area over time provides an indication of the actual productivity of a major component of the ecosystem's primary production apparatus (Lamberts, 2006, this issue).

Sediment Dynamics

Suspended sediment (SS) flux from Mekong River during the flood season dominates the sediment transportation dynamics of the Tonle Sap System. The Mekong River is responsible for the majority (ca. 75%) of the sediment delivered to the Tonle Sap Lake, based on measurements taken at Prek Kdam on the Tonle Sap River during 1996–2002 (MRC database) and suspended sediment measurement from tributaries during 2001–03 (WUP-FIN, 2003). The average suspended sediment flux into the Tonle Sap Lake from the Mekong and the lake's tributaries is 7 million tons (MT) and 2 MT, respectively (Kummu *et al.*, 2005). The outflow flux from the lake is only 1.6 MT. Thus, more than 80% of the sediment the system received from the Mekong River and the tributaries is stored in the lake and its floodplain. Figure 5 shows the monthly average suspended sediment fluxes and concentrations (1993–2003) of Prek Kdam (located in Figure 1). The positive and negative values in Figure 5 correspond to fluxes into the Tonle Sap Lake and out from the lake, respectively.

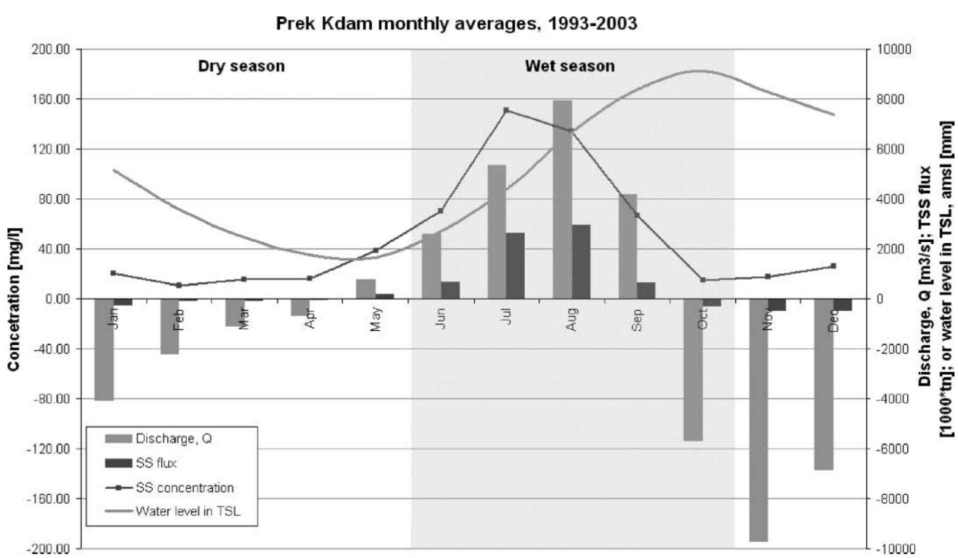


Figure 5. Monthly average flows, sediment fluxes and sediment concentrations in Prek Kdam (1993–2003). Positive = inflow to the Tonle Sap Lake and negative values = outflow. *Source:* Kummu *et al.* (2005). Note: SS = suspended sediment. TSL = Tonle Sap Lake.

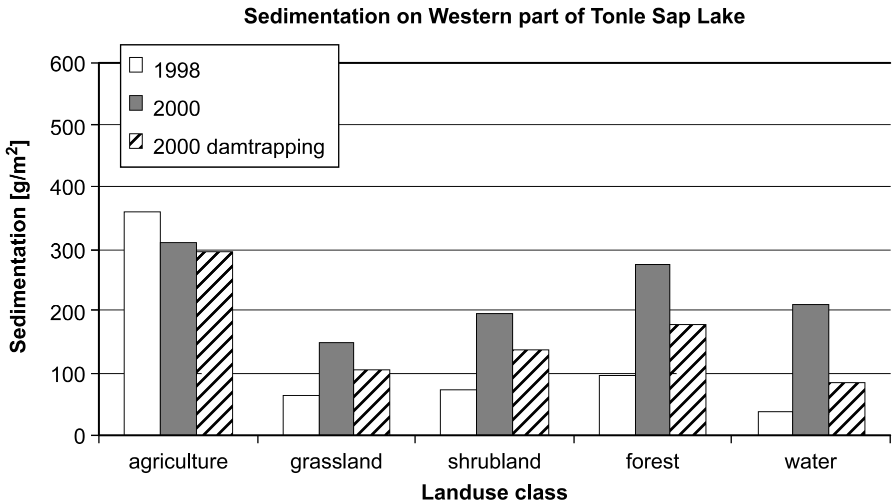
It is often claimed by local people and international organizations alike that the lake is rapidly filling up with sediment as a result of increasing sediment yields from the catchment area. However, rapid rates of infilling often cited in the literature have not been demonstrated, and recent sedimentation studies show that net sedimentation within the Tonle Sap Lake proper has been in the range of 0.1–0.16 mm/year since ca. 5500 years ago (Penny, 2002; Penny *et al.*, 2005; Tsukawaki, 1997). This means an accumulation of only 0.5–0.7 m of sediment in the lake since the middle Holocene era. These data, and the model-based results (WUP-FIN, 2003), indicate that the rate of sediment accumulation within the lake is low and has not accelerated with respect to the long-term sediment dynamics of the system. However, even though the overall net sedimentation within the Tonle Sap Lake is not an immediate problem, there are many local problems associated with high sedimentation and erosion rates in the area (e.g. Heinonen, 2006, this issue). Most of the villages around the lake are located by the tributaries and the situation there is completely different from the average within the lake proper, and calls for further investigations.

The suspended sediment data, secchi depth measurements and sediment traps on the floodplain, together with the WUP-FIN mathematical model calculations, show that efficient sedimentation takes place in the flood season in the vicinity of the Tonle Sap River and the tributaries, in the delta area and in the flooded forests around the permanent part of the lake (Sarkkula *et al.*, 2003; WUP-FIN, 2003). This explains the low sedimentation rate in the lake proper. The efficient sedimentation at the lake's margin can be observed in the water quality data, which indicate an effective reduction of SS concentrations and turbidity values within the vegetated zone. This is due to the damped wind forcing and wave activity and, consequently, low flow velocities and less turbulence compared to the open lake conditions (Sarkkula *et al.*, 2003).

The model has been developed to allow the analysis of hypothetical development scenarios. One of the several scenarios that have been investigated with the model was the 'dam trapping' scenario, where the flood of 2000 was used but the sediment load from the Mekong halved. This could represent the effect of the regional development scenario utilizing Mekong water, such as extensive damming of tributaries and the mainstream. This may lead to excessive upstream trapping of sediments (e.g. Kummu *et al.*, 2006). It can be seen that the 'dam trapping' scenario would mean a dramatic reduction in the net sedimentation and supply of sediment-bound nutrients to Tonle Sap system and evidently, reduction of its biological productivity (Figure 6).

Oxygen Levels

Dissolved oxygen is naturally one of the most important parameters for the life of the lake and its floodplain. In this sense the Tonle Sap Lake and the floodplain differ greatly. The lake is typically well oxygenated from surface to bottom. On the contrary, most parts of the floodplain are highly hypoxic or anoxic for the most of the flood period (Lamberts, 2001; WUP-FIN, 2003; see Figure 9). The reasons for anoxia in these areas are the relatively weak mixing of the water column and the decay of large amounts of inundated organic material produced during the terrestrial phase in the floodplain. In the surface layer a limited amount of dissolved oxygen is available through atmospheric mixing and photosynthesis. There is a sharp concentration gradient between the lake and the nearby flooded forest (see model results in Figure 7). The



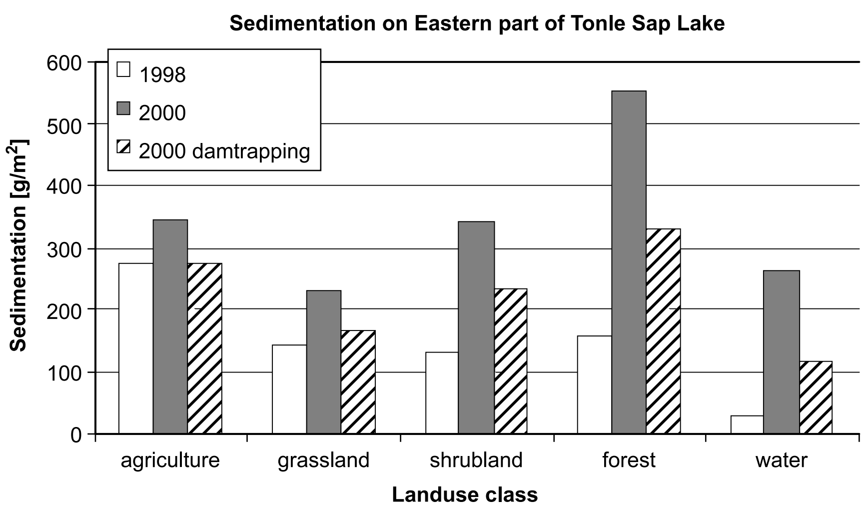


Figure 6. Calculated sedimentation results for different land use classes (agriculture, grassland, shrubland, forest and water). Left sedimentation for the western part. Right sedimentation for the eastern part

right profile in Figure 9 shows the oxygen conditions in the lake proper. Typically, the lake water is well oxygenated from top to bottom even during the high flood due to extensive mixing of the water column.

This gradient of oxygen levels between the lake proper and floodplain divides the fish into two groups with regard to their movement: white fish that live in the lake and its vicinity, with good enough oxygen conditions, and black fish that can tolerate less favourable oxygen conditions of the floodplain (Hoggarth *et al.*, 1999; Lamberts, 2001). The 3D EIA Water Quality Model calculates the oxygen dynamics in various parts of the

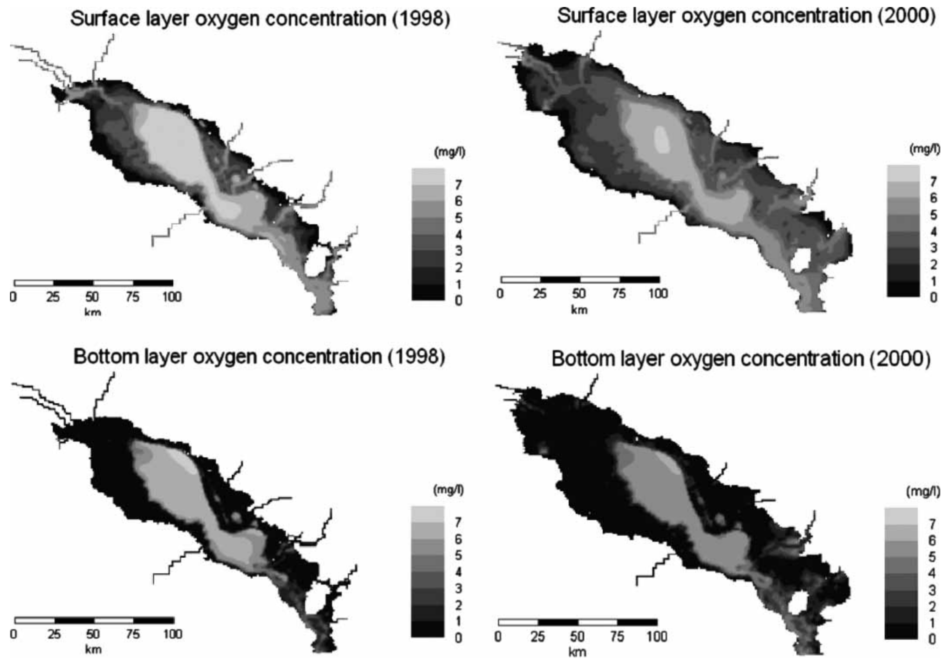


Figure 7. Calculated average surface (top) and bottom oxygen concentrations in the Tonle Sap Lake and floodplains. Left 1998. Right 2000

lake and floodplain system. Furthermore, it combines this information with other parameters such as sedimentation and nutrient input to the different ecosystem compartment and creates a basic matrix for the living and growing conditions for the fish in the system. Additional information that needs to be integrated is the quantity and quality of food available in each habitat. This complicated issue is dealt with in the discussion below.

From the modelling results Figure 8 shows that oxygen conditions are generally better during the years with higher floods. In particular, inundated forests and shrublands, which are regarded as the most important habitats for fish, are better oxygenated when the flood is greater. The differences are highlighted even more between rapidly rising floods and stagnant periods at the beginning of flooding, when anoxic conditions tend to prevail longer.

Flooded Forest

The flooded forest forms a narrow, 500–2000 m wide band of high trees along the dry season lake shoreline. The flooded forest is characteristic for the riparian vegetation and offers an important flood season habitat for the fish (Lamberts, 2001). Figure 9 illustrates the differences between the lake proper and floodplain conditions due to the flooded forest and floodplain vegetation:

- In the lake proper, conditions are rougher because of lack of sheltering vegetation. Therefore water is well oxygenated because of the effective wind and wave

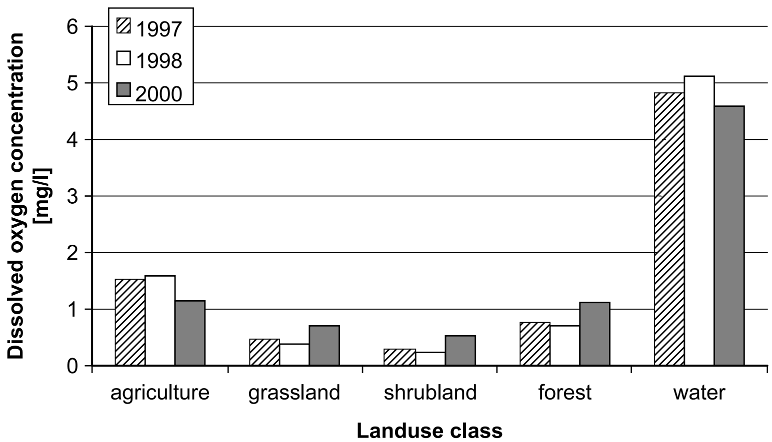


Figure 8. Average dissolved oxygen concentration by landuse (west)

induced mixing. The suspended sediment concentrations are high and secchi depth varies from about 2 decimetres in the dry season to a maximum of 2 m in flood season.

- In the floodplain the inundated areas are to a large extent anoxic. The sedimentation is effective because of calmer hydrodynamic conditions and sediment trapping vegetation. Secchi depths of 4 m have been measured in these areas.

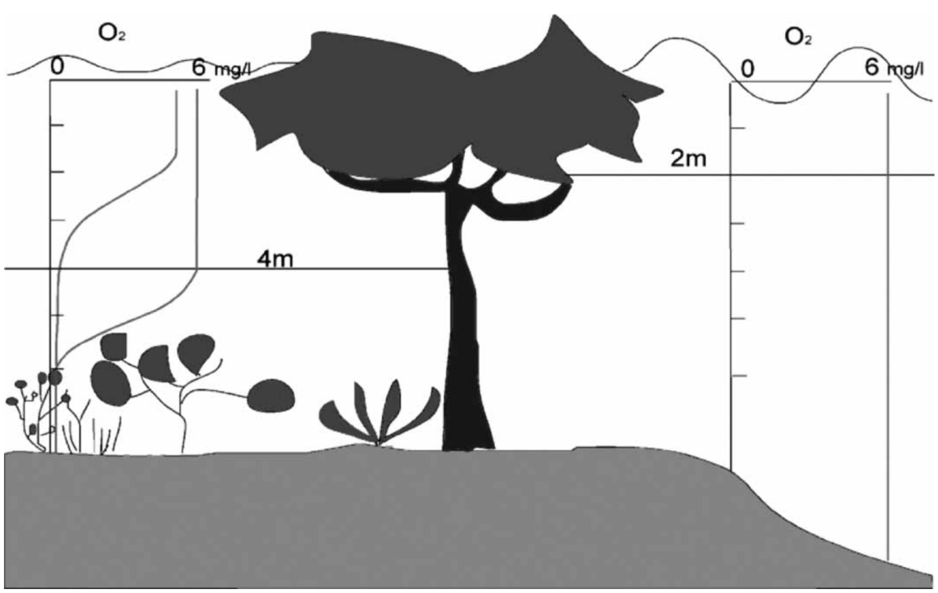


Figure 9. Differences in oxygen levels and water transparency between the Tonle Sap Lake proper (right) and floodplain (left). *Source*: WUP-FIN (2003)

The Importance of the Tonle Sap Lake

The Tonle Sap Lake is important for the Mekong system. It works as a natural reservoir offering storage for the flood pulse and essentially contributes to the dry season flow to the Mekong Delta. The lake's aquatic biodiversity is significant at the international level and it has been listed by UNESCO as an international biosphere reserve. The lake is also known to be rich in bird species.

Here, the importance of the Tonle Sap Lake has been divided into three levels: local and national, regional, and international (Table 1).

The importance of the Tonle Sap Lake at the local and national levels is crucial. It is estimated that almost half of Cambodia's population benefits directly or indirectly from the lake's resources. The Tonle Sap Lake and Tonle Sap River also offer the most important source of food and income for up to 1 million people (Bonheur, 2001). Cambodia's history revolves around the Tonle Sap Lake and the Mekong River. Angkor, capital of the former Khmer empire and one of greatest ancient civilizations in the Asia, is located in the proximity of the lake.

The lake acts as a natural reservoir for the Lower Mekong River Basin (LMRB), regulating the floods downstream from Phnom Penh during the wet season (June–October) and makes an important addition to the dry season flow to the Mekong Delta in Vietnam. From December to February the lake provides an average 50% of the total inflow to the delta (Fuji *et al.*, 2003; Morishita *et al.*, 2004). The annual flood-pulse is responsible for the creation of vast seasonal floodplain habitats. These areas are highly productive for fish and other aquatic animals and most Mekong species take advantage of this opportunity for feeding, breeding and rearing their young (Sverdrup-Jensen, 2002).

Threats

The Tonle Sap's ecosystem is vulnerable to the impacts of development at the local and regional levels. In Table 2 the threats due to the human activities (see, for example, Adamson, 2001; Bonheur, 2001; Campbell, 2005; Dore & Yu, 2004; Keskinen, 2003;

Table 1. Local and national, regional and international importance of Tonle Sap Lake

Local and national	Regional	International
Fisheries	Fish migrations: feeding, breeding, rearing	Biodiversity
Agriculture	Natural reservoir → dry season flow to delta, flood protection	Water bird sanctuary
Aquaculture	Cultural heritage	Cultural heritage
Navigation	Biodiversity	Unique hydrological regime in that scale
Cultural heritage	Water bird sanctuary during the dry season	
Flood protection		
Rich biodiversity		
Water bird sanctuary		
Other natural resources (wood, crocodile, etc)		

Table 2. Local and national, regional, and international threats for the Tonle Sap ecosystem

Local and national	Regional	International
Overuse of natural resources as over fishing, logging of flooded forest, etc.	Damming the Mekong and its tributaries → decreasing downstream sediment and nutrient fluxes, changes in flood regime, blocking fish migration routes	Climate change
Water quality problems as pollution from floating villages, industry and pesticides		Oil drilling (some evidences from oil has been found from underneath the Tonle Sap Lake's floodplain)
Impact of mines in tributaries (Cyanide, Mercury, high sediment loads)	Pollution from industry and agriculture	
Illegal use of natural resources as illegal fishing, illegal logging, etc.	Irrigation activities → changes in flood regime, water quality problems	Illegal wild life trafficking
Increased navigation → possible oil spills and water quality problems	Blasting the rapids → destroying the natural breeding areas of fishes and changing the flow regime	
Built structures → changes in flooding and flow regimes, decreasing sediment and nutrient transport, blocking the fish migration routes	Built structures, both upstream and downstream → changes in flooding and flow regimes, decreasing sediment and nutrient transport, blocking the fish migration routes	

Kummu *et al.*, 2006; MRC, 2003; Sarkkula *et al.*, 2004; Sverdrup-Jensen, 2002; WUP-FIN, 2003) have been categorized as three levels: local and national, regional and international.

The majority of the people living in the Tonle Sap Area are deeply dependent on the natural resources in their livelihoods (Keskinen *et al.*, 2005). Unfortunately, the natural resources in the area are deteriorating rapidly, primarily due to legal over-exploitation and illegal exploitation of the lakes resources. The over-use and illegal use of natural resources are probably the biggest local threats to the ecosystem.

Upstream developments in the Mekong, such as hydropower dam and reservoir construction, have already led to significant trapping of sediments and nutrients in reservoirs (e.g. Kummu *et al.*, 2006). These continuing developments will have an increasing impact on flood regime, timing and duration of flood in the Lower Mekong Basin and Tonle Sap. The changes will be not only hydrological ones but may have a significant negative impact on the productivity of the Tonle Sap Lake and floodplain ecosystem due to:

- delayed flooding and a period of reduced fish growth;
- deduced flow velocities and incomplete transport of fish larvae and juveniles to the floodplain in the early stages of the flood;
- worsening dissolved oxygen conditions in the floodplain at the beginning of flooding due to a shortage of floodwaters;
- reduced floodwater levels; and
- reduced supply of sediments and nutrients to the lake and floodplain system.

One possible tool to assess the impacts of the development on the Tonle Sap ecosystem could be an integrated ecosystem productivity indicator proposed by Lamberts (2006, this issue). It should be based on the existing data and knowledge that could be easily updated, i.e. hydrodynamic characteristics of the flood pulse, sedimentation, flooded vegetation cover and its composition and fish migration obstacles (Lamberts, 2006, this issue).

All in all, there is an urgent need to improve understanding of the Tonle Sap ecosystem productivity and its vulnerability. The Tonle Sap is facing many threats while being a very important part of the Mekong system and vital for Cambodia. One of the biggest challenges for Cambodia and other Mekong Basin countries in the near future is how to manage socio-economic development without compromising the important ecosystems and natural resources upon which millions of people rely, especially in Cambodia.

Discussion

In this paper the work and some of the findings of the WUP-FIN Project have been presented. During this work the understanding of the Tonle Sap system has improved considerably, regarding its basic processes, flooding, sedimentation, dissolved oxygen and nutrient dynamics, pollution dispersion etc. Cornerstones in this work have been extensive primary data collection, model development and close cooperation with many national counterpart teams.

The most difficult task in the integration is to define the ecosystem links between hydrological (and hydrodynamical) processes and the socio-economic impacts. The starting point in the Tonle Sap system has been even more complicated because of the almost total lack of primary data and information on the ecosystem behaviour. During the last few decades the political conditions almost completely stopped all research on the Tonle Sap, as well as building research capabilities in the riparian countries. Now, in the normalized and improved conditions it is important to speed up and promote basic studies and hasten environmental impact assessment for a better understanding of the consequences of ongoing and planned developments in the basin. Cooperative efforts are needed, as well as utilization of comparative studies and experiences from other parts of the world.

To effectively support the IWRM process, and integrate and adapt the models for part of the planning and management processes, further steps must be taken. These include ecosystem issues, the biological productivity in particular, and the dissemination of key information to the planning and decision-making processes. These questions are discussed below.

The Tonle Sap Lake Ecosystem

One of the main open questions in the Mekong Basin development is how and to what extent the upstream developments will affect the downstream ecosystems. It is hypothesized that sediments carried by the Mekong waters to the Tonle Sap Lake bring in the bulk of the nutrients that fuel the lake's food webs (Sarkkula *et al.*, 2003, 2004). The higher the flood the more sediments and nutrients are imported (Kummu *et al.*, 2005; van Zalinge *et al.*, 2003; WUP-FIN, 2003). Sediment-bound phosphorus is assumed to become available for phytoplankton via higher plants growing in the transition zone between the aquatic and terrestrial ecosystems. The nutrients metabolized in higher plants during the terrestrial phase are released to the water by the decomposition of plant material during the rising-water period (Furch & Junk, 1997). However, the significance of the sediment in the productivity of the floodplain needs closer consideration. The nutrients carried by the sediments are undoubtedly important. The system needs refreshments by the incoming floodwaters, especially to maintain its long-term sustainability. The contribution of floodwaters' suspended load to total productivity is yet to be studied, as well as how it is channelled through terrestrial and aquatic food webs. After all, the nutrient cycle between different organisms in the floodplain is very intensive, and "is the principal reason for the high productivity of most floodplain systems" (Junk, 1997, p.10).

Studies in the Amazon show that the main source for food in the wetland is derived from the terrestrial growth in the dry season floodplain. This organic material becomes available for fish and other aquatic animals during the aquatic phase by nutrient release from decomposing leaves and plants or by direct feeding on the plants, fruits and other food sources. So far there is no information from the Tonle Sap system on the quantity and quality of food available in different parts of the ecosystem. Starting with simple experiments by measuring the surface area and biomass of the vegetation around the floodplain would give initial information about this important link in the Tonle Sap food web. Satellite and airborne imagery may be useful in extrapolating the estimate over the habitats. This data can be directly used as input to the existing GIS type of model system. Further model development must then address the link of the Mekong main stream suspended load input and effect in the floodplain system.

Integrated Modelling Tools: Part of IWRM?

One of the greatest challenges remains how to ensure that integrated modelling is utilized efficiently and meaningfully in management and planning. How, then, to bridge the gap between modellers and managers?

The transfer of model products to the end users and stakeholders has grown in importance together with the need for the promotion of sustainable use of the developed tools. In recent years, there has been a general and firm intention to involve environmental managers and planners, limnologists, biologists and other 'non-modellers' as model users. In many cases this diminishes their distance to the 'modellers' and improves the usefulness of the models for management, as well as research and development purposes (Sarkkula *et al.*, 2006).

However, this brings new challenges, as individuals working in different disciplines will often have contrasting approaches to problem-solving and decision-making. This is partly due to the constantly evolutionary state of the field, and partly to its great interdisciplinarity; the field is at crossroads of several traditions of pure and applied sciences. Engineers, economists, scientists, etc., have all their own paradigmatic backgrounds. Communication problems and intolerance approaches are very common (Somlyódy & Varis, 1993).

The following steps could be helpful to bridge the gap between modellers and managers and to bring out the essential information from modelling applications:

- formulate modelling strategies and applications jointly with environmental managers to create interaction and confidence between scientists and decision makers;
- produce model simulation scenarios to respond to real and relevant management questions, e.g. implementation of national agendas and international agreements and conventions;
- present results in a demonstrative and concise way;
- train users and managers to use models and their results;
- pay specific attention to disseminating the results to decision-makers and the public;
- pay more explicit attention to stakeholder interests (fears, hopes, desires and beliefs) in defining the model outputs;
- develop simpler, more integrated and more easily understandable indicators for model outputs, to crystallize the essential of effects without smoothing down differences by averaging; and
- couple model results more closely with their socio-economic consequences.

The Mekong River Commission and IWRM

In Mekong Basin the Mekong River Commission (MRC) is one of the main stakeholders applying basin-wide IWRM and developing tools in support of planning and management. The MRC member countries are Cambodia, Lao PDR, Thailand and Vietnam. The upstream Mekong countries of China and Myanmar are not members of the Commission. In 1995 an agreement was made between the member countries to shift the focus in the basin from large-scale projects to cooperating in sustainable development and equitable use of natural resources (MRC, 1995). The basin development planning strongly supports community participation in natural resource management in the basin. The overall approach of the plan is:

- to achieve basin-wide benefits while taking account of national interests;
- to balance development opportunities with resource conservation;

- to encourage broad public participation; and
- to achieve knowledge-sharing and capacity building.

The plan is expected to involve the themes of environment, human resource development, socio-economics, poverty reduction and gender equity and public participation (MRC, 2003). Other programmes including environment, fisheries, navigation, capacity building and agricultural, irrigation and forestry programmes, are also being undertaken to implement the 1995 agreement. For more information of MRC's role in IWRM on Mekong see e.g. Campbell (2005).

Conclusions

Balancing economic growth, poverty reduction and the conservation of ecosystem health and productivity is among the biggest challenges of our time. Integrated Water Resources Management (IWRM) is an ambiguous concept to do this through developing democratic governance practices and sound water resources development for poverty reduction, social equity, economic growth and environmental sustainability. In this process a major question often emerges: do we know enough about the consequences of the chosen water resources policies for the ecosystems and the people?

The knowledge about the Tonle Sap ecosystem has remained largely a white spot on the map. Excellent work done by Carbonnel & Guiscafre (1963) on the Tonle Sap sedimentology in the 1960s was followed by political turbulence and civil war in Cambodia for more than two decades. Research work was only restarted in the late 1990s, still in unsettled social conditions. Tsukawaki (1997) and Lamberts (2001) were among the first to initiate studies based on field observations. These works formed a firm cornerstone for continuing studies, Tsukawaki (1997) clarifying essential features on the history and existence of the lake and its past and present sedimentation, Lamberts (2001) looking at the physico-chemical properties and fish feeding habits in the lake and the wetlands.

The mission of the WUP-FIN project has been to develop analytical tools (models) for increasing the understanding of the Tonle Sap system behaviour, its flooding and water quality regime, and to help the Mekong River Commission to promote sustainable management of the Tonle Sap water and natural resources. An essential part of the work has been to collect primary data on meteorology, hydrology, hydrodynamics and water quality, and to study how the changes in water regime may impact people and their livelihoods in and around the lake. To this end, participatory village surveys and interviews were carried out in different parts of the area.

With the help of the models and data, cooperation with MRC and with national counterparts and other collaborators, the understanding during the project duration improved and the information on ecosystem processes increased, namely:

- water balance of the lake and the dominant role of Mekong water and suspended sediments in the system;
- the role of the Tonle Sap tributaries waters and sediment input to the system; sediment input is mainly restricted to the surrounding floodplain in the proximity of the tributaries' outlets;
- flooding characteristics in various parts of the floodplain (flood arrival time, flood duration and flood depth);

- dissolved oxygen dynamics in the lake and the floodplain (so confirming and extending the findings of Lamberts);
- suspended sediment transport and net sedimentation distribution over the area; results are in full agreement with Tsukawaki's and Penny's conclusion that the lake is not filling up with sediments;
- sedimentation: WUP-FIN data and model results point out that sedimentation favours areas in the flooded forest bordering the Tonle Sap River and the lake proper; these areas also gain from sufficient dissolved oxygen concentrations, a sheltered environment from strong waves and currents and seem thus to be ideal habitats for fish to live and grow;
- fisheries productivity: a set of favourable conditions for fish growth was composed and the distribution and dynamics of these characteristics over the lake and the flood plain produced, with the help of integrating the model results with fisheries expertise (e.g. Baran *et al.*, 2004; Lamberts, 2001; van Zalinge *et al.*, 2003); and
- people's livelihood: socio-economic analysis has effectively demonstrated the drastic dependency of the people in and around the lake on its natural resources; furthermore, the declining trend in the availability of the resources per capita has become very clear, mainly due to population growth and over-exploitation of the resources.

The modelling tools (hydrological, hydrodynamic and water quality, user framework) developed for the MRC Secretariat form part of the model and information base of the MRC. The Commission Secretariat is the custodian of the modelling tools that are aimed for sustainable use by the modelling experts at the MRCS. Thus, much effort is being put into training and building sufficient capacity of the MRCS modelling team. Moreover, to increase the potential for the maintenance and future use of the developed models, capacity building has been extended to the Cambodian ministries and line agencies and universities. The model package is presently extended to cover the entire Cambodian floodplains and the Mekong delta in Vietnam, with corresponding enlargement of the training activities.

The functioning of the flood pulsing system in the Tonle Sap needs to be better understood before the changes and threats to it can be assessed and effectively demonstrated. This work can benefit a great deal from the studies made and experience gained in the Central Amazon floodplain by Junk (1997) and his colleagues since the 1960s. This can hasten and direct the investigations on the role of the terrestrial and aquatic shifting mechanisms, as well as the critical components that are driving and controlling the biological productivity of the Tonle Sap system. In addition to the flooding process itself and the material transports (sediments, nutrients, larvae), the role of different organisms in channelling the food web items must be clarified. Concerted and coordinated research efforts must be amplified and accelerated, involving riparian institutions and researchers as well as international teams.

Acknowledgements

The work presented in this paper is part of Lower Mekong Modelling Project under the Mekong River Commission (MRCS/WUP-FIN) funded by the Development Cooperation Department of the Ministry of Foreign Affairs of Finland. Olli Varis, Marko Keskinen and Ulla Heinonen are greatly acknowledged for organizing this special issue and giving constructive comments during the writing process. Dan Penny is very much acknowledged for proofreading and commenting on the paper. The authors would also like to acknowledge all of the WUP-FIN team, particularly Markku Virtanen, Mikko Kiirikki, Seppo Hellsten, and all of the Cambodian co-workers, especially Mao Hak and Yin Than, and trainees. Professors Pertti Vakkilainen and Tuomo Karvonen, and the staff from the Water Resources Laboratory of Helsinki University of Technology are equally acknowledged. This work has received funding from the Academy of Finland Project 211010.

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