Tools for Integrated Basin Flow Management at Lower Mekong Basin Floodplains

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Keywords: Integrated Basin Flow Management, water quality modelling, Mekong, environmental impact assessment tools.

EXTENDED ABSTRACT

Integrated Basin Flow Management (IBFM) approach has been proposed by Mekong River Commission (MRC) to balance the economic and social developments, and maintenance of productive, healthy ecosystems in the Mekong Basin.

The IBFM approach needs analytical tools to be used in solving real management problems. Mathematical models, in this case hydrological, hydrodynamic, and water quality models, are among those tools. While such models are useful in themselves, their full potential is only realised when linked with social, economic and policy issues.

This paper focuses on the estimating impacts of the development scenarios on natural resources and on socio-economy with the help of mathematic modelling. The work presented here is part of the WUP-FIN project, complementary project for Water Utilization Programme under MRC. WUP-FIN focuses on developing and implementing hydrological, environmental and socio-economic modelling tools for the Lower Mekong Basin impact assessment.

The Mekong River is one of the largest rivers in the world having a catchment size of 795,000 km^2 and average flow of 14,500 m^3/s (Mekong River Commission, 2003). The river is shared by six countries (from upstream): China, Myanmar, Lao PDR, Thailand, Cambodia, and Vietnam. The four latter countries form the Mekong River Commission which, following the MRC 1995 agreement (Mekong River Commission, 1995), was established to agree an equitable and sustainable use of water resources in the lower Mekong Basin (LMB).

The Lower Mekong Floodplains is very complex system of rivers, channels, dykes, embankments and large areas of floodplains. In order to be able to simulate this system comprehensively, including the different hydrodynamic conditions and water quality calculations into the same model, a hybrid 1/2/3 D model system is needed. Here 3D EIA Flow Model for floodplains (Koponen et al., 2004) is coupled with 1/2D channel model.

The focus is in two target areas in the LMB floodplains: Tonle Sap Lake and floodplain (Cambodia) and Mekong Delta (Vietnam). The following development scenario indicators have been used in the project:

- Flood characteristics: duration, area, arrival time, depth
- Dissolved oxygen
- Total suspended solids and net sedimentation
- Dry season water quality

One of the main aims of the modelling in the project is to assess the possible impacts of upstream developments, especially the hydropower dams and reservoirs, on lake's ecosystem. The main impacts of the development will most probably be the changes in hydrological regime reducing the water level during floods and reducing the area of the inundated habitats. The upstream reservoirs may trap significant part of the sediments as well. This may impact such ecosystem productivity among other impacts, as bank erosion etc.

The approach for integration between socio-economy, ecology and hydrology can be carried out with two different methodologies that are based on data and modelling, and on experience and knowledge. The context of the integration consists of geographical area and of a specific analysis tool (GIS) coupled with the model results (Nikula, 2005). Ecology acts as a connecting factor between socio-economy and hydrology.

1. INTRODUCTION

Probably the greatest challenge in river basin management is to find the balance between economic and social developments, and maintenance of productive, healthy ecosystems. To that end, several approaches have been developed in the recent decades. In the Mekong Basin the Integrated Basin Flow Management (IBFM) approach has been presented by the MRC to find that balance within the Lower Mekong Basin countries (Figure 1).

The Integrated Basin Flow Management activities being undertaken at the MRC are designed to provide information to the member-States on the predicted benefits and costs of land and water development of the Mekong Basin following the Article 6 in Mekong River Commission 1995 agreement (Mekong River Commission, 1995). This information will aid discussions between the countries on the trade-offs to be made between basin development and natural-resource protection in the quest for sustainable development.

Modelling is used in three roles in the IBFM process:

1. Filling in data gaps in hydrological monitoring
2. Forecasting response of the basin to potential development scenarios
3. Estimating impacts of the scenarios on natural resources and on socio-economy

This paper focuses on the last role – use of modelling in impact assessment. The WUP-FIN project, complementary project for Water Utilization Programme under MRC, focuses on developing and implementing hydrological, environmental and socio-economic modelling tools for the Lower Mekong Basin impact assessment.

WUP-FIN impact analysis is concentrating on four target areas:

- Vientiane – Nong Khai, Lao PDR and Thailand
- Nam Songkhram, Thailand
- Tonle Sap Lake and floodplain, Cambodia
- Mekong Delta, Vietnam

Scenario impacts are modelled on bed and bank erosion, sedimentation, soil fertility, flooding, fish habitats (dissolved oxygen, nutrients), fish larvae drift, water quality and saline intrusion. The main modelling tool used in these case studies is a three dimensional EIA hydrodynamic and water quality model (Koponen et al., 2004) supplemented with distributed and lumped hydrological modelling (WUP-FIN, 2003).

Last part of the paper discusses the connection between bio-geo-chemical and socio-economic impact assessment, quantitative links between these dependencies, and the difficulties in establishing those dependencies.

Figure 1. Lower Mekong Basin.

2. MEKONG BASIN

With approximately 475 km^3 of water that the Mekong carries each year from a basin of 795,000 km^2, the Mekong is the world's 8th largest river (e.g. Campbell, 2005; Mekong River Commission, 2003). It is also one of the world's most pristine large rivers. The Mekong Basin is shared by six countries, and is usually divided into two parts which are:

- Upper Mekong Basin (including the parts of the basin in China and Myanmar)
- Lower Mekong Basin (including the parts of the basin in Lao PDR, Thailand, Cambodia and Vietnam).

Altogether, more than 70 million people live in the basin, about 54.8 million in the lower Basin (Mekong River Commission, 2003). A large part of the lower basin population depends directly on natural ecosystems for their livelihood. Fisheries and croplands are important sources of food and income. Contradictory, for China the Mekong is especially important as a source of hydropower and for transportation (Makkonen, 2005).

The interests differ greatly in water use in the LMB area. LMB countries have established the Mekong River Commission to agree on equitable and sustainable use of water resources based on the 1995 Mekong agreement.

3. LOWER MEKONG BASIN HYBRID MODEL

The complex system of Lower Mekong Floodplains includes rivers, channels, dykes, embankments and large areas of floodplains. In order to be able to simulate this system comprehensively a hybrid 1/2/3 D model system is mandatory. Thus, the 3D EIA Flow Model for lakes and floodplains (Koponen et al., 2004) is coupled with 1/2D channel model.

3.1. Concept of the 1/2/3 D river channel model

Traditionally the river channel models have been 1-dimensional (1D) especially for large river stretches. For restricted stretches such as critical junctions, erosion zones, coastal areas, floodplains and where the river channel is wide also 2D and lately 3D models have been devised. Here the 1D, 2D and 3D approaches are combined into a flexible system where any reach of the river can be modelled in any dimensionality and combined with a model of other dimensionality. The change of the dimensionality is made to be automatic. For instance, there may be local erosion or water quality study necessitating switching from 1D to 3D and this should be accomplished without major work in generating the grid, data input and re-construction the model.

The advantages and necessity of using a hybrid 1D/2D/3D river channel model become pronounced in the Vietnamese Delta. The Delta has an extensive river channel network and inundated area. The elements of the Delta modelling are:

- extensive river and channel network
- numerous dikes and control structures
- flooding
- saline water intrusion and regulation of saline and fresh water for aqua- and agriculture
- strong tidal effects
- erosion
- sedimentation and connected floodplain productivity
- water quality, acidification due to acid sulphate soils

Part of the processes such as water transport in the channels can be modelled 1D. Flooding and flooding related processes necessitate at least the 2D approach. Saline water intrusion, erosion, sediment transport and at least part of the water quality processes necessitate the 3D approach. On top of the complexity comes the interplay of large scale influences such as upstream discharges and tidal forcing and local small scale phenomena such as flow in critical junctions. Sediment processes in general and erosion modelling in particular necessitate 3D.

3.2. 2/3 D floodplain, lake, reservoir and coastal model

The 1D/2D/3D river channel model and the regular 2D/3D model are based partly on the same core engines and solution methods. The main difference between these two is the internal representation of the model domains – the description of the river channel uses specialized grid whereas the regular 2D/3D model uses a regular rectangular grid. The 2D/3D model is suitable for modelling floodplains, lakes, reservoirs and coastal areas. In these cases the grid usually should have same resolution in both directions.

The core engine of the modelling work is based on the 3-dimensional (3D) EIA Hydrodynamic Model and 3D EIA Water Quality Model (e.g. Koponen et al., 2004). The flow model can be classified as a 3-dimensional baroclinic z-level model and is based on the standard Navier-Stokes equations in a rectangular grid (Koponen et al., 2004). Reasonable simulation times are reached by using appropriate algorithms (e.g. time splitting and implicit solvers) and model resolutions. The model also has a geographic information system (GIS) user interface. The 3D EIA Water Quality Model has been coupled with the flow model for simulating the transport and processes of selected set of water quality indicators and hazardous materials.

Modelling system uses rectangular grid cells. The cell width can vary in x- and y-directions. It is possible to model whole domains with varying grid resolutions and couple them together even in a nested way.

3.3. Coupling of the river and floodplain models

Figure 2 illustrates the coupling of the different models in the hybrid channel/floodplain model. The 1D river channel model is connected longitudinally to the 2D/3D channel model. Both of these in turn are connected laterally to the 3D (2D) floodplain and lake model. Hydrological model provides discharge data as boundary values for the channel and floodplain models.

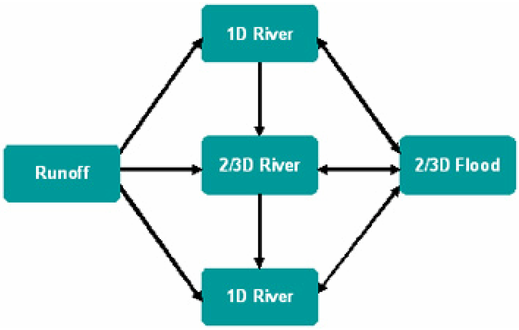

Figure 2. Schematic coupling of the hybrid channel/floodplain model components.

As can be seen from Figure 2 there are two basic types of boundaries between the channel and floodplain model: longitudinal channel – channel (or channel - lake) and transversal channel – floodplain ones.

3.4. Computational issues and results

The usability of the modelling tools is lost if they are computationally too heavy, and consecutively model computation times are long. The parameters which govern the model execution times are:

- number of grid cells
- process time steps
- processes included in the model
- selected hydrodynamic equations
- grid cell dimensions
- maximum and minimum water depths
- friction calculation mode
- numerical solution method
- required accuracy
- coupling mode
- use of stored simulation values (e.g. flows and fetch)
- multiprocessing and parallelization
- compiler and operating system.

The 1 km resolution Lower Mekong Basin (LMB) model that includes Cambodia and Vietnamese Delta contains about 270’000 grid cells in the horizontal plane and altogether 2.7 million 3D grid points. Calculation of the fully flooded situation takes about 40 minutes per month with a ADM 64 bit 2 GHz processor. Assuming that the average wetted area over a flood cycle is 50% the total calculation time over one year flood cycle is 5 hours with the 1 km grid. An Athlon XP 32 bit 1.73 GHz processor takes almost twice that time. This is still acceptable from a practical point of view.

Experiments with a 5 million grid cell LMB-model (0.5 km resolution) create an executable that is too big for a 32 bit operating system. (The 32 bit operating systems can allocate only 2 GB of memory space for any particular process.) In order to avoid this problem the model was ported to 64 bit Linux. Parallelization and cluster processing offer an obvious way to go forward in resolution improvements.

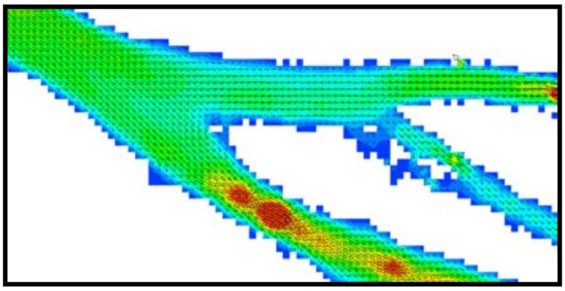

Figure 3. Modelled Tieu River surface flows in the Vietnamese Delta.

4. SEDIMENT MODELLING

4.1. Sediment flux of Mekong

Estimates of annual sediment flux of the Mekong range from 150×10^9 kg to 170×10^9 kg (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Roberts, 2001). However, no reliable definitive study has been done so far according to this issue (Kummu et al., 2006b).

The studies of the measured and possible future changes in sediment transport due to the sediment trapping in reservoirs have been started only very recently (e.g. Gupta and Liew, 2006; Kummu et al., 2006b; Lu and Siew, in preparation). After the closure of the Manwan dam in China, first dam in Mekong mainstream, in 1993 the total suspended solid concentrations in Chiang Saen have dropped from 484 mgl^{-1} to 216 mgl^{-1} (Kummu et al., 2006b). Along with the hydrologic changes the changes in sediment transport may have great impacts on the downstream ecosystems (see Kummu et al., 2006b).

4.2. Sediment model

A sediment transport module has been developed within the 3D EIA model package to assess the possible impacts of changes in the sediment transport rates in the Mekong (Kummu et al., 2005).

The governing equation for the i^{th} fraction including advection, dispersion, bed erosion by re-suspension, and deposition retains the conventional form of the general transport equation. The model is able to deal with multi-fraction sediment classes, both cohesive and non-cohesive. The sediment module formulation is described in more details in Kummu et al. (2005).

Suspended sediment data collection has been made in various locations coupled with ADCP measurements to be used for model calibration and validation. Model results of net sedimentation from Tonle Sap Lake EIA 3D model application are presented in Figure 4.

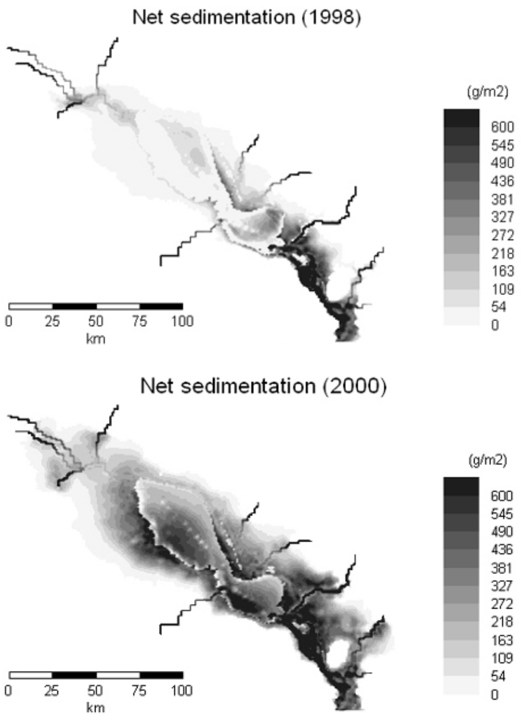

Figure 4. Modelled net sedimentation of the Tonle Sap Lake in years 1998 (dry year) and 2000 (record flood).

5. TARGET AREAS

The WUP-FIN project focuses on four target areas as listed in the introduction. However, here we concentrate only on two of those:

- Tonle Sap Lake and floodplain (Cambodia) — Research is undertaken to understand processes in the lake and its floodplain, as well as their impact on the region and the vulnerability of their ecosystem and biological productivity to developments in the upstream basin.
- Mekong Delta (Vietnam) — the models are applied to the delta to enhance understanding of the complex hydrological, ecosystem and socio-economic processes and understand how conflicting water needs can be met. The Mekong Delta model will be combined with the Cambodian floodplain and Tonle Sap models.

The Tonle Sap Lake is one of the most important parts of the Mekong system. The lake is among the most productive freshwater ecosystems in the world. Its high productivity depends on the flood pulse (Junk, 1997) from the Mekong which transfers terrestrial primary products into the aquatic phase during flooding (e.g. Lamberts, 2001). Limited data and understanding exists from Tonle Sap ecology. Thus, research made in Central Amazon floodplain (Junk, 1997) could be utilised; quantitative data necessary for water – socio-economic integration process.

The socio-economic issues in the Tonle Sap Area are extraordinarily diverse. This is due to various reasons that include the unique nature of the lake, its floods and ecosystem, growing population pressure and massive incidence of poverty as well as people's deep dependence on the lake and other natural resources. Cultural and ethnic divisions, remarkable seasonal variation of livelihood sources, unequal access to natural resources, and insufficient rights of land tenure have also their impact on the area (Keskinen, 2006). See Keskinen (2003; 2006) for more detailed information.

The Mekong Delta with its 20 million people is a society where water is present everywhere. Its landscape is shaped by one of the most extensive networks of canals in the world that serve for transportation, communication and agricultural needs. The settlement wriggles along the rivers and canals rather than following any clearly articulated boundaries of different centres of towns or villages. The junctions of rivers and the primary irrigation and drainage systems are the most heavily populated areas.

6. INTEGRATED BASIN FLOW MANAGEMENT

Integrated basin flow management calls for an integrated analytical approach. This approach needs analytical tools to be used in solving 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 realised when linked with social, economic and policy issues (Keskinen et al., 2005). Here the indicators of the development scenarios and their socio-economic linkages are presented.

6.1. Development scenario indicators

The following development scenario indicators have been used in the project:

- Flood characteristics: duration, area, arrival time, depth
- Dissolved oxygen
- Total suspended solids and net sedimentation
- Dry season water quality

6.2. Integrated impact assessment

Integrated ecosystem management is principally targeting the ecosystems and associated human communities in the target area. Modelling is one of the potential tools that can be utilised in the efforts of "taming" the complexity of the integration between ecosystem and society in order to gain sufficient understanding of the substance for management purposes (Kummu et al., 2006a).

The approach for integration relies on three concepts: substance, methodologies, and context (Nikula, 2005). 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 methodologies that are based on data and modelling, and on experience and knowledge. Finally, the context of the integration consists of geographical area and of a specific analysis tool (GIS) coupled with the model results (Nikula, 2005). Hydrology is connected to socio-economy through ecology.

7. DISCUSSION AND CONCLUSIONS

The following conclusions can be drawn

- MRC is carrying out an Integrated Basin Flow Management process to analyze impacts of flow regime change on basin hydrology and environment, resulting from basin developments
- Advanced models are being developed to sufficiently simulate the complicated hydrodynamics and water quality processes in Tonle Sap and in the delta, including a hybrid model for the entire LMB to describe the connected river channel-floodplain processes with water quality component
- LMB model runs are encouraging and computational times tolerable despite the very large number of 3D grid cells (2.7 millions)
- Sediment transport and sedimentation are key processes and indicators of changes due to basin developments, reflected e.g. in bank erosion and floodplain productivity and deserve special attention in modelling and data collection
- Actual use and validation of WUP-FIN LMB models is still in an early phase. Lot remains to be done in cooperation with the counterparts, the MRC staff and the riparian institutions, for the models, impact assessment and technology transfer

ACKNOWLEDGMENTS

Olli Varis and Janos Jozsa are greatly acknowledged for reviewing the article and giving constructive comments. The authors would like to acknowledge also all of the WUP-FIN team, especially Marko Keskinen, Jussi Nikula, Markku Virtanen, Hannu Lauri, Arto Inkala, and, of course, all the counterparts in Cambodia, Vietnam, Laos and Thailand. Equally Professors Pertti Vakkilainen and Tuomo Karvonen, and the staff from the Water Resources Laboratory of Helsinki University of Technology are acknowledged.

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