Mekong (MK1) project
On optimizing reservoir management for livelihoods

CGIAR Challenge Program for Water and Food

Review of water resource and reservoir planning models for use in the Mekong

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Summary

In recent years, great emphasis has been placed on the need to improve the management of the environmental and social impacts of large dams. This is particularly important in the Mekong River Basin where the construction of a large number of new dams are planned and yet a large proportion of the population depend on fisheries and other natural resources, which may be adversely affected by their construction. The environmental and consequent social impacts of large dams are often complex and extremely difficult to predict. Dam planners and operators often have to consider a huge number of factors and often conflicting objectives, which makes decision making difficult. In such situations, computer models that can be used to simulate and optimize dam operations are a useful tool. However, to date, most models have focused on the physical aspects of systems and rarely (if ever) explicitly incorporate environmental and social issues. This report presents a brief review of different models and their application to water resource management, both in the Mekong and elsewhere and outlines a modelling strategy for the MK1 project.

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1. Introduction

Effective water resources development and management is widely recognized as crucial for sustainable economic growth and poverty reduction in many developing countries. Large dams[1], often play a key role in water management, providing water for irrigation and domestic and industrial needs, as well as improving navigation, generating electricity and food control. However, the contribution of large dams to development remains controversial. This controversy stems from the fact that, too often in the past, dam construction has brought fewer benefits than envisaged and has resulted in significant social and environmental costs (WCD, 2000). Historically, large dam projects have often failed to pay sufficient attention to environmental impacts and those (invariably poor) people adversely affected by the construction and operation of the dam and associated changes in hydrological regimes. While reservoirs for irrigation and domestic supply may improve water availability for people living in their vicinity, reservoirs for hydropower generally provide benefits to people who are living at a distance from them. Those who have had to be resettled and those whose livelihoods have been adversely affected by changes in river flows have paid the price of dam construction (Scudder, 2005).

In its report, the World Commission on Dams (WCD) called for a more equitable distribution of the benefits to be gained from large dams and proposed the inclusion of all identified stakeholders in the planning and management of water resources stored in reservoirs (WCD, 2000). To achieve this, dam managers must take into account water uses upstream and downstream of the dam and must give consideration to political, organizational, social and environmental factors, as well as economic and biophysical factors (McCartney and Acreman, 2001). However, in any specific situation, the relationships among these different elements are extremely complex and often not well understood. The need to consider multiple, and often conflicting, objectives for a large number of stakeholders, and across a broad spectrum of scales, means that thousands of decision variables and constraints may need to be considered. This is what makes decision-making extremely difficult.

Over the past few decades, major advances have been made in the development and use of a wide range of computer models to assist in the planning and management of complex water resource systems (Jamieson, 1996). However, although such models are intended to provide water resource managers with assistance in making rational decisions, there remain concerns about their limitations for complex decision-making processes and for inclusion of issues related to the livelihoods of riparian communities. These concerns broadly relate to lack of transparency, lack of communication between model developers, model users, policy and decision makers, and inability to include subjective and value-dominated human elements (Loucks *et al*., 1985; Rogers and Fiering, 1986; Loucks, 1995). As a consequence of the almost exclusive emphasis on the development of ever more sophisticated, complex and bigger models, they often end up not being fully accepted by planners and managers (Savic and Simonovic, 1991). Furthermore, although in the past water resources planning and management was left primarily to technical professionals, this is no longer the case. The need to satisfy societal requirements has expanded beyond the objective of simply water supply and, increasingly, a diversity of concerned parties and organizations (only a fraction of whom may be represented by technical professionals) demand input into the decision-making process (e.g., Kapoor, 2001; Tetra Tech, 2004). Most models are not well suited for this type of participatory process, in particular when the main beneficiary groups of the reservoir are not people who are living in its vicinity.

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[1] Large dams are defined as those greater than 15m in height from base to crest, or storage capacity exceeding 3 million cubic meters for heights between 5 and 15m (ICOLD, 2003)

Against this background, this report provides a brief review of water resource and dam operation models that might be used in the MK1 project, the objective of which is to determine how dam operation can be planned and managed to improve local livelihoods. The report provides a brief review of some of the more prominent computer models used in water resource management. It is based on literature review. It is not intended as comprehensive compendium on computer model application to dam planning and operation but rather provides an overview and discussion of issues pertaining to the decision-making in relation to livelihoods and dams in the Mekong River Basin.

The report is divided into 6 sections. Following this introduction, section 2 briefly describes the Mekong Basin and the issues around dam planning and operation. Section 3 provides a review of modern computer models and their use for dam planning and operation. Section 4 provides a brief review of models actually used in the Mekong basin. Section 5 describes a proposed strategy and modelling framework for the modelling to be conducted in the MK1 project. Section 6 is a short conclusion.

2. Dams, poverty and decision-making in the Mekong Basin

About 60 million people live in the Mekong River Basin, most of whom are rural poor. Agriculture in conjunction with fishing and forestry support the livelihoods of 85% of the population many at subsistence level (MRC 2003). There is increasing pressure from the riparian countries for hydropower development to drive economic growth and many new dams are planned in each of the countries in the near future (Johnston et al., 2009). However, the negative impacts of hydropower infrastructure have been identified as a key factor affecting poverty in the basin (Chaudry and Juntopas, 2005). Changes in the natural flow regime of the rivers, particularly low flows and floods affect fish production by changing migration triggers and fishing opportunities (Baran et al., 2007). Consequently tensions exist in relation to dam development and the impact of such development on fisheries and the poor people who are directly affected (Lawrence, 2009; Foran and Manoram, 2009; Friend et al., 2009).

Furthermore, the development and application of models and even the use of scientific knowledge more generally have been questioned because the poor tend to be excluded from processes that utilize them. Consequently, there is a perceived unequal exercise of power that has the potential to lead to outcomes that do not necessarily benefit the poor (Contreras, 2007). The issue of governance and the involvement of multiple stakeholders in decision-making processes is a key area of concern in the Mekong. There have long been calls for much greater transparency and accountability as well as greater inclusion of non-state actors in decision-making processes (Badenoch, 2002; Lee and Scurrah, 2009). It has been proposed that information on infrastructure development should be freely available and that there should be more dialogue and more cross-sectoral planning. Furthermore, benefits should be better shared and those who lose out should be better compensated (Foran and Lebel, 2006). All these suggestions have implications for computer modeling and how modeling can best contribute to decision-making processes.

In the MK1 project the objective is to develop methods to determine how to optimize the productivity and equitable use of water stored in reservoirs. This will be achieved by analyzing trade-offs and promoting synergies between different use options (farming, fishing and hydropower) simultaneously ensuring environmental sustainability and minimizing negative impacts. This is to be achieved in part through the development of a DSS that can be used in conjunction with stakeholder dialogues to identify options, assess tradeoffs and optimize design and operation of large reservoirs, with the use of various participatory techniques. It is envisaged that the DSS will comprise a number of interlinked models. The key requirements for the DSS are that it:

- Facilitates the examination of the wider social and ecological context of any particular dam, through better evaluation of trade-offs
- Sharpens the focus on stakeholder involvement in decision-making so that all stakeholders can contribute to the process
- Enables distribute information sources to be incorporated, including local knowledge
- Assists in conflict mitigation, enabling compromises to be identified by facilitating negotiation based approaches to decision-making

The new feature of the MK1 project is much more detailed consideration of livelihoods of people who are living around the reservoirs. With this in mind, the objective of the modelling approach is that it leads to increased cooperation and consensus building as well as dam planning and operation that improves the livelihoods of local people.

3. Modelling approaches and applications

Numerous computer models have been developed for improved understanding and management of river systems and for the management and operation of dams (e.g., Simonovic and Savic, 1989; Jolma, 1994; DeGagne *et al*., 1996; Koutsoyiannis *et al*., 2002). There are three basic types of river system models: hydrological, hydraulic and water resource models (Table 1). These models provide a broad range of analysis capabilities, which can be used either in isolation or in combination, to contribute to the planning and management of dams in large river basins such as the Mekong. Such models aim at providing quantitative information on the:

- spatial and temporal variation in a basin's hydrological response to rainfall
- hydrological/hydraulic consequences of land-use change or climate change in a basin
- implications of water resource development (including dams and irrigation) at different locations in a basin

Table 1: *Types of computer model that can contribute to planning and management of water resources in basins*

Types of model	Description
Hydrological models	Hydrological models simulate those morphological and processes-related controls that influence temporal and spatial patterns in the conversion of rainfall to flow. The models are of different types and have been developed for a variety of purposes. However, many of them share structural similarities because the underlying assumptions are the same. Hydrological models do not provide information on water levels or velocities, but typically simulate water fluxes at the catchment and sub-catchment outlets.
Hydraulic models	Hydraulic models simulate hydraulic conditions (i.e. not just of volumes of water, but also water velocities and levels, both in the river channel and on floodplains). The fact that there is considerable spatial and temporal variation in water levels and velocities down a river system makes the mathematics for predicting them very complicated. Hence, hydraulic models can only usually be used to cover relatively small areas. Hydraulic models utilise information on boundary conditions, channel geometry and roughness to solve partial differential equations that describe the movement of water within a river reach. Because of the non-linearity of the governing equations, and the complexity of boundary conditions, numerical solutions are necessary.
Water resource models	Models developed specifically for water resources related data management and analyses, including simulation of spatial and temporal variation in water storage, demand and supply throughout a basin. This may include predictions of future water uses and plans for managing future demands.

All three types of model have been used extensively in the Mekong basin (see section 4). Both hydraulic and water resource models will often include hydraulic structures including dams with corresponding operating rules. Reservoir models (a sub-set of water resource models) are specifically designed to simulate either single or multiple dam operation.

Currently, the vast majority of dam system planning and operation is undertaken using simulation and optimization models (e.g., de Monsabert *et al*., 1983; Lund and Guzman, 1999). To date, these have focused primarily on the physical aspects of the system (Reitsma, 1996). They are frequently based on simple engineering principles for dam operation, such as keeping reservoirs full for water supply or empty for flood control. As such, they provide a great deal of flexibility in the specification of system operations under various flow, storage and demand conditions. Many rules are based on largely empirical or experimental success, determined either from actual operational performance, performance in simulation studies or optimization results. These experimentally-supported rules are common for large dams where multiple objectives must be attained.

3.1 Simulation techniques

Simulation modeling replicates the physical behavior of a system on a computer. In effect, it is an abstraction of reality. The key characteristics of the system (i.e., the main system processes and variability) are reproduced by a mathematical or algebraic description. Simulation is different from mathematical programming techniques which find an "optimum decision" for system operation meeting all system constraints while maximizing or minimizing some objective (Yeh, 1985). In contrast, simulation models provide the response of the system to specified inputs under given conditions or constraints. Hence, simulation models enable a decision-maker to test alternative scenarios (e.g., different operating rules) and examine the consequences before actually implementing them.

Simulation models for the operation of reservoirs have been applied for many years (e.g., Emery and Meek, 1960; Hall and Dracup, 1970; Biswas, 1976; Stansbury et al., 1991; Huang and Yang, 1999; Ito et al., 2001; Thorne et al., 2003). Many models are customized for a particular system. However, more recently, the trend has been to develop general simulation models that can be applied to any basin or reservoir system. For example, HEC-ResSim has been designed and developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers specifically to perform Reservoir System Simulation. It is designed to perform reservoir operation modeling at one or more reservoirs for a variety of operational goals and constraints, including release requirements and constraints, hydropower requirements and downstream needs and constraints (HEC 2007).

3.2 Optimization techniques

Simulation models can accurately represent system operations and are useful in examining long-term reliability of operating systems. However, they are not well suited to determining the 'best' or optimum strategies when flexibility exists in coordinated system operations. Instead, prescriptive optimization models are often used to systematically derive optimal solutions, or families of solutions, under specified objectives and constraints. The application of optimization techniques in reservoir studies has a long history (e.g., Yakowitz, 1982; Yeh, 1985; Wurbs et al., 1985; Wurbs, 1993; Labadie, 1997) and a diverse array of optimization methods for dam operation has been formulated. In all the mathematical optimization techniques, the problem of reservoir operation is formulated as a problem the objective of which is to maximize or minimize a set of benefits over time, subject to a set of constraints. Such constraints include explicit upper and lower bounds on storage (e.g. for recreation, providing flood control space, for assuring minimum levels for dead storage and/or power plant operation) and/or limits on releases (e.g. to maintain desired downstream flows for water quality control, fish and wildlife maintenance as well as protection from downstream flooding). The most commonly used techniques are Linear Programming (Mannos 1955), Dynamic Programming (Lee and Waziruddin 1970) and Non-Linear Programming (Young 1967). In recent years, these techniques have been combined with new approaches such as “optimal control theory” (Wasimi and Kitanidis 1983), “fuzzy logic” (Fontane et al. 1997) and “artificial neural networks”(Funahashi 1989).

3.3 Examples of water resources model applications

In nearly all the major basins of the world, the need for improved water management is recognized as a priority and models have been proposed as tools to assist with water allocation and in the planning and operation of large dams (Table 2).

Although in the past the focus of dam operation and planning was primarily on optimizing releases for one particular sector and, in most cases maximizing financial returns, increasingly, consideration is being given to the wider socioeconomic implications. For example, in Ethiopia, HEC-5, a precursor to the HEC-ResSim simulation model has been used to improve operating rules for the Koka Dam located on the Awash River. The model enabled the operating rules to be updated and improved, allowing for reservoir sedimentation and the increase in downstream irrigation since the dam was built (Seleshi 2006). For the same dam the inclusion of a possible malaria control strategy has been simulated and the implications for hydropower production and irrigation deduced (Reis et al., 2011). Similarly, in Zambia, operating rules for the Itezhi-Tezhi Reservoir on the Kafue River, a major tributary of the Zambezi, initially developed to maximize hydropower, have been modified to incorporate broader aims and objectives and in Lesotho, the DRIFT methodology, which takes into account social factors in determining environmental flow requirements (Brown and King 2000) was applied and used to assist the development of operating regimes for the dams constructed as part of the Lesotho Highlands Water Project (Watson 2006). Hence, broader objectives are increasingly being incorporated in dam planning and management (McCartney and King, 2011).

Table 2: *Examples of computer models used for water resource planning*

Models	Description
Lake Victoria Decision Support Tool (LVDST)	Database, utility tools (i.e., to process and prepare data) and control models have been combined to support long-range planning and short-range operation of the Lake Victoria reservoirs and hydropower units. Allows short-term hydropower production to be optimized within constraints imposed by long-range planning decisions (Georgakakos 2006).
NileSim	Simulation model of the water resources of the entire Nile Basin. Developed primarily as a learning tool to explain complex river behaviour and management to non-technical people. Enables scenarios to examine the effects of policy options and changes caused by manipulating dams and regulating river use (Levy and Baecher 2006).
River Basin Simulation Model (RIBASIM)	This water balance simulation model enables evaluation of measures related to infrastructure, operational and demand management. It generates water distribution patterns and provides a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs. It has been used to simulate water flows in the whole of the Nile Basin as part of the Lake Nasser Flood and Drought Control project that aimed to evaluate risk and mitigation measures for different flood and drought control scenarios (Delft Hydraulics 2006).
Ruaha Basin Decision Aid (RUBDA)	A water resource simulation model developed to assess the impact of development scenarios in the Great Ruaha River Catchment in Tanzania. Designed with the involvement of key stakeholders in the basin and intended to help assess, among other things, the hydrological and socioeconomic impacts of different allocation decisions (Cour et al. 2005).
Water Resources Planning Model (WRPM)	Developed in South Africa, this simulation model is used for assessing water allocation within catchments. The model simulates surface water and groundwater as well as inter-basin transfers. The impact of dams on catchment water yield is accounted for. The model is designed to be used by a range of users with different requirements and can be configured to provide output of different information (Schultz et al. 2000; Mwaka 2006).
Agro-hydrological modelling system (ACRU)	Developed in South Africa, this is a multi-purpose simulation model that has been used to simulate land use/management influences on water resources, sediment yield and selected water quality constituents, dam water budgets and operating rules, irrigation water demand and supply, and crop yields. It includes modules for dam operating rules which have been applied in South Africa (Butler 2001; Schulze and Smithers 2004; Smithers 2006).
GLOWA Volta DSS for the Volta Basin	A scientific information system developed as part of the GLOWA Volta Project to integrate knowledge and provide decision support for the planning, management and use of water resources in the Volta Basin. The nucleus of the DSS is a water optimization model, which represents the decision rules and constraints of water users, the physical water resources system as well as production functions and technology sets (GLOWA Volta 2006).
DSS for Komati Water Resources Planning	The Komati Basin Water Authority (KOBWA) manages water resource development in the Komati River Basin which is shared by South Africa, Mozambique and Swaziland. KOBWA uses a suite of three DSSs to plan and manage dams in the catchment. These are DSSs for water allocation (yield), water curtailment *(*rationing*)* and river hydraulic application (Dlamini 2006).
Decision Support Systems for the Senegal River Delta	The hydrodynamic model, MIKE 11, has been used in conjunction with a digital elevation model, to assess hydraulic functioning of different release regimes on the Senegal River Delta and the consequent implications for the ecology and hence livelihoods of local people (Duvail and Hamerlynck 2003).
The Nile Decision Support Tool (Nile DST)	Developed as part of the FAO Nile Basin Water Resources Project to objectively assess the benefits and trade-offs associated with various water development and sharing strategies. Comprises six main components: databases, river simulation and management, agricultural planning, hydrologic modeling, remote sensing and user-model interface (Georgakakos 2003, 2006).
Kafue DSS	A hydrodynamic model (KAFRIBA-Kafue River Basin) has been developed to improve the operation of dams located upstream and downstream of the Kafue Flats (wetland system) on the Kafue River, Zambia. Used in conjunction with improved forecasting of flows into the upstream reservoir, the DSS enables the dam operator (Zambia Electricity Supply Corporation) to make decisions on releases in a systematic way that balances hydropower requirements with other water uses and protection of the ecology (and hence livelihood

	benefits) of the Kafue Flats (DHV Consultants 2004).
Global Water Availability Assessment (GWAVA) model	This model provides a global/regional or catchment scale approach to modeling hydrology and assessing water resource availability. It provides assessments of water availability on a spatial basis (GIS), in terms of indices of water supply versus water demand. It enables impacts of climate and population change to be investigated and can also be used to look at land-use change impacts and development of hydropower schemes. It has been used to simulate regional water resources across eastern and southern Africa as well as, more specifically, in Swaziland and the Okavango Delta (Tate et al. 2002).
Water Evaluation and Planning (WEAP) model	A simulation model developed to evaluate planning and management issues associated with water resource development. WEAP can be applied to both municipal and agricultural systems and can address a wide range of issues including: sectoral demand analyses, water conservation, water rights and allocation priorities, stream flow simulation, reservoir operation, ecosystem requirements and project cost-benefit analyses (Stockholm Environment Institute 2005). The model has been applied to assess scenarios of water resource development in the Olifants Catchment in South Africa (Arranz and McCartney 2007), and for the Pangani Catchment in Tanzania (King pers. comm. 2006).
DamIFR	Developed and applied in South Africa to derive dam operating rules that satisfy environmental flow requirements. The model is intended to compliment traditional reservoir yield models. It can be used to simulate several linked reservoirs and computes what proportion of daily environmental flow requirements to release during periods of low reservoir storage when there is competition from other users (Hughes and Ziervogel 1998).
Desktop Reserve Model	Developed in South Africa, this is a hydrological model for estimating environmental flow requirements in situations where a rapid appraisal is required and data availability is limited (Hughes and Hannart 2003). The model is built on the concepts of the Building Block Methodology (King et al. 2000) and provides estimates of both low and high flow requirements. It has been used extensively in South Africa to provide initial estimates of the Ecological Reserve .

4. Models used in the Mekong Basin

In recent years, there has been considerable effort to model the hydrology and water resources of the Mekong Basin. It is estimated that the Mekong River Commission (MRC) has spent US$ 20 million on the development of models since 2000 (Johnston, 2011). A comprehensive set of models has provided insights into system functioning and thereby contributed to an increased understanding of the system. In addition, these models, used in conjunction with economic analyses, have assisted in identifying and describing the issues and trade-offs involved in basin-scale water planning (Johnston and Kummu, 2010). Table 3 briefly describes models developed and/or applied in the Mekong Basin. The list of the models is based on a previous review compiled by Johnston and Kummu (2010), supplemented with some additional examples. Most of the models applied to date in the Mekong have focused on the large-scale societal benefits/costs arising from the construction of dams. Generally they have neglected the livelihood implications for those people living in the vicinity of the reservoirs.

Table 3: *Models used in the Mekong basin* (adapted from Johnston and Kummu, 2010).

HYDROLOGICAL MODELS	
Delta Model	Developed by SOGREAH between 1962 and 1965, this is the first hydrological model applied to the Mekong Basin. It was used to provide detailed simulated flows in the Mekong Delta.
Streamflow Synthesis and Reservoir Regulation model (SSARR)	This model was developed by the US Army Corps of Engineers in 1967 to simulate flows in the mainstream of the Mekong River from Chiang Saen to Pakse. Both SSARR and Delta model were used for weekly flood forecasting and to study the feasibility of proposed mainstream dams which were then postponed because of the war and the communist take over
Hydro System Seasonal Regulation model (HYSSR)	This model is a sequential stream flow routing model developed to evaluate reservoir operations at specific locations in the Mekong Basin (Phanrajasavong, 1986).
Massachusetts Institute of Technology River Basin Model (MITSIM)	This model was developed by the World Meteorological Organization in 1984 to evaluate reservoir operations at specific locations in the Mekong Basin.
Soil and Water Assessment Tool (SWAT)	SWAT is a distributed physically-based hydrological model which simulates runoff, including snowmelt from daily climate variable, topography, soils and land cover (Neitsch et al., 2001). It has been used by the Mekong River Commission in the scope of the decision support framework established in 2001.
Variable Infiltration Capacity (VIC)	VIC was developed by Liang et al. (1994), was calibrated for the whole Mekong Basin in order to study hydrology, sediment transport and the carbon cycle (Costa-Cabral et al., 2008). It is a macro-scale semi-distributed hydrologic model specifically designed to represent interactions between land cover, climate and runoff generation. It solves full water and energy balances. The land surface is modeled as a grid of large (>1km), flat, uniform cells. Inputs are time series of daily or sub-daily meteorological drivers. Land-atmosphere fluxes, and the water and energy balances at the land surface are simulated at a daily or sub-daily time step. Routing of stream flow is performed separately from the land surface simulation, using a separate model.
VMod	Vmod is a distributed physically based/conceptual hydrological model based on a gridded representation of the modelled catchment (Lauri et al., 2006). Hydrological processes are simulated using simplified physical formulations. Runoff and leaching of nutrients are calculated separately for each grid cell. The model can be used, for example, to inspect the effect of land-use changes on catchment hydrology and water quality.
Semi-distributed Land Use-based Runoff Processes (SLURP)	SLURP has been applied to the Lower Mekong Basin to assess the impacts of climate change and basin development on fisheries productivity (Kite, 2000, 2001). SLURP is a hydrological model that simulates the hydrological cycle from precipitation to runoff, including the effects of reservoirs, regulators, water extractions and irrigation schemes. It first divides a basin into sub-basins based on topography. The sub-basins are further divided into areas of different land covers. Each land cover class has a distinct set of parameters in the model.
YHyM	YHyM is a grid-based distributed hydrological model developed at the University of Yamanashi (Japan) to simulate large river basins (Takeuchi et al., 1999). The model has been developed since 1999 and includes several modules: meso-scale precipitation, potential evapotranspiration, snow accumulation/melt, runoff generation, sediment transport, water quality and water use/control (dam operations). Each module can be executed independently. Runoff is generated based on the extended TOPMODEL concept for large river basins and flow routing is carried out using the Muskingum-Cunge method. This model was applied to the Mekong Basin to assess the precipitation elasticity of the river flow (Hapuarachchi et al. 2008).
GR2M	GR2M is a 2-parameter monthly lumped rainfall-runoff model (Mouelhi et al. 2006). It has been used to determine the broad-scale hydrological impact of bomb-induced deforestation and post-exodus forest regrowth during the last half century in the Lower Mekong Basin (Lacombe et al., 2010). The 2 parameters of this model need to be optimized against rainfall, runoff and potential evapotranspiration data. GR2M was empirically developed using a sample of 410 basins representing a wide range of climate conditions from semi-arid through temperate to tropical humid. It includes a production store and a routing store. The two parameters of the model determine the capacity of the production

	store and the flow of underground water exchange.
Mordor	Mordor is a conceptual rainfall-runoff model which was used to simulate river inflow into the dam reservoirs of the Nam Ngum River Basin (Paquet, 2004). Mordor was originally created in the 1990s for basins ranging from 100 to 10,000 km^2. It works at hourly and daily time step. It consists of 4 reservoirs representing stored water into the sub-surface soil and deep soil layers (groundwater). 17 parameters need to be calibrated against observed hydro-meteorological time series. Mordor can be used to: i/ reconstitute missing period of flow data series from rainfall and temperature, ii/ forecast inflow and floods and iii/ test hydrological scenarios. The model outputs are river flow and evapotranspiration.
WATER BALANCE MODELS Integrated Water Quantity and Quality" (IQQM)	IQQM is a basin simulation model which routes catchment flows through the river system, taking into account control structures such as dams and irrigation abstractions (Podger and Beecham, 2003). IQQM is based on a node-link concept. The important features of a river system such as reservoirs, irrigators, towns, etc. can be represented by one of thirteen node types.
Water accounting model of the Commonwealth Scientific and Industrial Research Organization (CSIRO)	This model (Kirby et al., 2010a,b) has been used to assess the water productivity (Mainuddin et al., 2008) and the impact of climate change (Eastham et al., 2008) in the Lower Mekong Basin.
MIKE BASIN	MIKE Basin, developed by DHI, has been used to assess the diverse hydrological impacts of the Hydropower dam Nam Theun 2 (ADB, 2004). It is a multi-purpose, GIS-based river basin simulation package designed for analyzing water sharing problems and environmental issues at international, national and project scales.
WEAP (Water Evaluation And Planning)	WEAP has been used in the Mekong Basin with several objectives and in the scope of different projects. The Mekong Basin Focal Project (2005-2008) aimed at identifying causal links between water-related issues and poverty and assessing in which way enhanced water productivity could reduce poverty and improve the health of populations. Key components of the project were: i/ to assess both biophysical and socio-economic dimensions of current water use within the basin, with a focus on water productivity, ii/ to analyse the opportunities and risks of change in water management that influence water poverty; iii/ to identify appropriate research paths for promoting change, based on trend analysis, assessment of interventions and analysis of impact; iv/ to develop an integrated knowledge base to support change throughout and beyond the life of the project; v/ to identify potential water-related interventions that could alleviate poverty in key hotspot areas in the basin. Another project that used WEAP focused on the Bang Pakong River Basin with the aim i/ to establish methodologies for water allocation; ii/ to strengthen the work of integrated water resources management in the river basin and iii/ to strengthen the capacity of the river basin committee to fulfil its mandate in reducing conflicts within the river basin.
PARSIFAL	PARSIFAL, together with the Mordor model, was used in the scope of the Nam Ngum River Basin Development Sector Project (Government of Lao PDR, 2009). PARSIFAL is a decision support tool software for the management of hydropower systems. The main objective of this model is to minimize the operating cost while respecting several constraints such as satisfying the electricity demand, the drinking water supply, the irrigation demand and environmental flows constraints. Parsifal optimizes the use of each available power station of the plant to satisfy the demand at the lowest cost, while accounting for the uncertainty related to inflow, power demand variations linked to temperature, availability of the generators.
HEC-ResSim	The HEC-ResSim model has been proposed for use in a Regional Technical Assistance (RETA) project supported by Asian Development Bank (ADB). The aims of this project are to improve coordination and beneficial impacts of future development initiatives, and to strengthen the arrangements for cross-border collaboration between Lao PDR, Cambodia and Vietnam in managing the Sesan, Sre Pok, and Sekong river basins (3Ss) (http://reta.3sbasin.org/). The intention is for the HEC-ResSim model to be used for analysis of hydropower systems and to simulate a range of possible options.
HYDRODYNAMIC MODELS ISIS hydrodynamic model	ISIS (Halcrow/HR Wallingford, 1999) is used for modelling both steady and unsteady flow in networks of open channels and flood plains. ISIS comprises an integrated modular

	structure. The hydrodynamic module (ISIS Flow) provides solution of the fully dynamic equations for both steady and unsteady flow, with options that include simple backwaters, flow routing and full unsteady simulation. In addition to channels and floodplains, ISIS Flow contains units to represent a wide variety of hydraulic structures including several types of sluices and weirs, compound structures and head losses through bridges. Closed conduits and culverts are represented by cross-sections and several standard shapes are available. Other units include Reservoirs (to represent flood storage areas) and Junctions. ISIS has been used to simulate water level, discharge and salinity in the flat plain of the Mekong Delta, and the Tonle Sap lake.
EIA 3D	This fully three-dimensional (3D) model was developed by the Environmental Impact Assessment Centre of Finland Ltd (EIA Ltd.). It is based on a rectangular grid representation (Koponen et al., 2008) and uses meteorological, hydrological, topographic, land use and infrastructure characteristics as input. Outputs include 3D hydrodynamics and water quality. The modelling platform includes several components for processing the data, controlling the model run and providing GIS representations. The model aims at describing the 3D characteristics of flooding, flow, water quality, erosion and sedimentation in lakes, reservoirs, river channels and floodplains. The EIA 3D model was calibrated for the Nam Songkhram sub-basin in Northeast Thailand. It has also been used to model the Tonle Sap flood pulse, the Mekong delta and the transport of sediment and nutrient.
MIKE 11	This model was originally designed to analyse flood and design flood alleviation structures, to forecast real time flood and to analysis dam break. It has been used to model the Tonle Sap Lake and the Cambodian Delta (Fuji et al, 2003), the flow regime and water quality of the Tonle Sap (Kummu et al. 2006) and the Delta and Nam Songkhram Basin (MRC WUP-FIN 2007).
Vietnam River Systems and Plains (VRSAP) model	Developed by the Vietnam Sub-Institute for Water Resources Planning and Management in the 1980s (Hien, 1999; Hoanh et al. 2009), VRSAP has been used to simulate water flows, tidal effects and salinity intrusion in the Mekong delta.
Mekong Delta Master Model	Developed by Delft Hydraulics in 1991 (van Mierlo and Ogink, 1991), this model was used to simulated water flows, tidal effects and salinity intrusion in the Mekong delta.

Since 2001, in an attempt to consolidate the modelling endeavour in the basin, a number of models have been used in combination in a Decision Support Framework (DSF). This has been used to assess the impacts of different levels and types of development. Three types of model have been combined in the DSF:

- A series of hydrological (rainfall-runoff) models based on SWAT have been set up to simulate catchment runoff based on estimates of daily rainfall and runoff and the topography, soils and land-cover of each of a number of sub-basins.
- Basin Simulation (water resource) models based on the IQQM software originally developed for the Murray Darling Basin in Australia. The simulation models route flows through the river system making allowance for control structures such as dams and irrigation abstractions.
- A hydrodynamic model, based on ISIS software, is used to simulate to river system downstream of Kratie, including the Tonle Sap and the East Vaico in Vietnam where wet season flooding extends beyond the Lower Mekong basin boundary. The hydrodynamic model simulates the complex interactions caused by tidal influences, flow reversal in the Tonle Sap River and over-bank flow in the flood season with the varying inflows from upstream.

The models are used in combination with impact analyses tools used to translate hydrological changes of different interventions in the basin into environmental and social impacts. To date the DSF has not focussed on single projects, but on development scenarios (i.e. dams, irrigation, land use change, urban demands) at the scale of the lower Mekong Basin, based on probable trajectories of change. The intention was to quantify hydrological change, and consequent ecological, social and economic impacts and thereby to identify the costs and benefits as well as the “winners” and “losers” at the basin scale.

Projected impacts of different scenarios have been presented as cumulative costs and benefits across sectors (e.g. trade-offs between fisheries and hydropower) and differential benefits/loses across countries. The overall aim was to define a hydrological "development space" within which the riparian countries can develop without adversely impacting their neighbours (Johnston, 2011).

5. DSS for the MK1 project

Though providing a very comprehensive database and understanding of the hydrology and water resources of the Lower Mekong, the DSF has not been a complete success. It has not been adopted by the riparian countries for operational use and it is not being used to assist decision-making in the way originally envisaged. There are several reasons for this (Johnston, 2011):

- Though linked to hydrology, it is impacts on other issues, particular ecological impacts and the consequent effects on livelihoods (e.g. fisheries), which are of primary interest. These impacts are not well simulated within the DSF.
- Development is being driven in a piece-meal way by individual projects and foreign investment, not by a coordinated plan as was foreseen when the DSF was established.
- Investors /governments perceive model outputs as too complex and not sufficiently targeted.
- NGOs /communities perceive that the analysis is skewed to system components that can be quantified so that economic outcomes tend to be emphasized and the impacts on ecology and livelihoods are insufficiently considered.

Against this background the aim of the MK1 project is to demonstrate the applicability of a more focussed approach for decision-making in relation to individual dams by providing a framework for discussion of the likely livelihood impacts and trade-offs of different reservoir operating options. The intention is to develop a decision support system (DSS) comprising a number of models that can be used to assess the likely social and economic implications of different dam operating options. The research is to be conducted at three sites in the Mekong basin (Figure 1):

- In Cambodia: the planned Sesan 2 dam,
- In Laos: the Nam Gnouang dam
- In Vietnam: the Yali dam

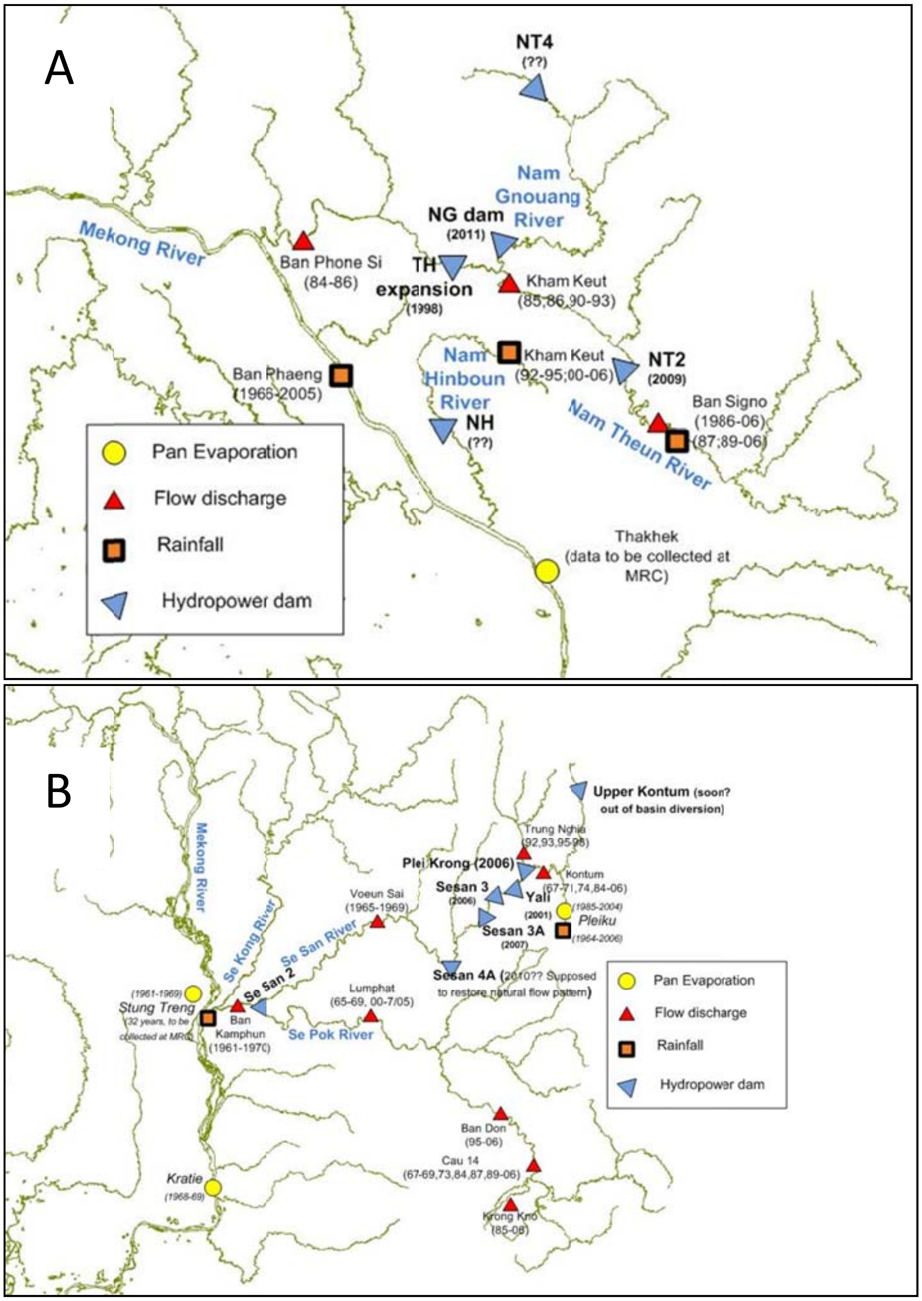
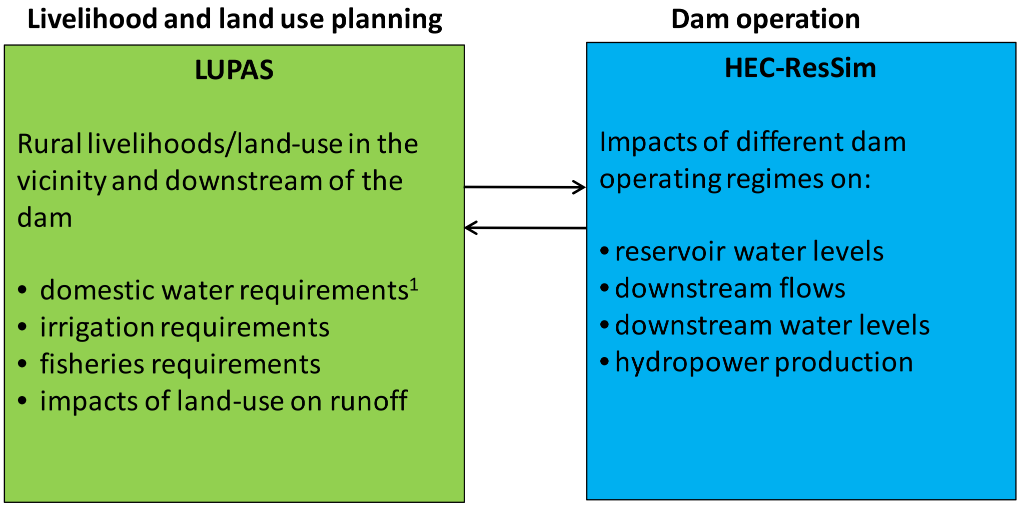


Figure 1: *Location of dams and hydro-meteorological stations around case study sites. A: Nam Gnouang dam in Laos. B: Yali and Sesan 2 dams in Vietnam and Cambodia, respectively. Values in brackets inform about the start year of dams operation and the availability of hydro-meteorological records*

For the optimization of land use around, upstream and immediately downstream of the reservoirs, the Land Use Planning and Analysis System (LUPAS) will be used as appropriate for each case study (van Paassen et al., 2007). Since changes in land use affect water demand (e.g. through irrigation requirements) and the reservoir operation affects water availability, the intention is to simulate water and land options in tandem. One challenge will be to link the dam operation and LUPAS models within a common framework with the appropriate feedback mechanisms between them (Figure 2). By simulating and quantifying water needs (i.e. in terms of both volumes and/or reservoir and river levels) for different livelihood uses (e.g. fisheries and small-scale agriculture) the LUPAS model will be used to identify livelihood constraints (which in the past have been frequently neglected) in the optimization of dam operation.



[1] refers to both volumetric needs and if appropriate water levels

Figure 2: *Linking LUPAS and the dam operating model*

Figure 3 presents a simple conceptual picture of the modelling framework to be adopted. Although this will need to be adapted for the specific conditions in each location it illustrates the key components to be simulated within the modelling framework. Irrigation and other livelihood requirements will be specified using LUPAS. For the reservoir simulation, we propose to adopt a simple modelling approach which can be relatively easily modified to incorporate different issues and explained to different stakeholders. To this end we propose to use the HEC-ResSim model.

As noted above, the HEC-ResSim is a reservoir system simulation model. It comprises a computational program to simulate reservoir operation as well as data storage and management capabilities and graphics and reporting facilities. Extensively used in the USA and globally, it is both comprehensive and adaptable and provides a useful tool for reservoir simulation. The main component of the model is the equation of the reservoir water balance which is calculated on a daily time step. On day n, the total water storage Q_n is computed from the water storage volume of the previous day Q_{n-1}, accounting for water input (I_n: inflow and P_n: precipitation) and water output (E_n: Evaporation, T_n: Turbine outflow, S_n: Spillway outflow, I_{run}: Irrigation, Se: Seepage and Dr: Drainage). Time series of required input data will, depending on what is available, need to be derived either from observation, hydrological analyses or other models for each of the three study sites.

Livelihood requirements (e.g. minimum downstream flows required for fisheries and/or minimum water levels required for reservoir fisheries and irrigation requirements) will be deduced from LUPAS and the livelihood analyses. For example, irrigation demands will be evaluated based on actual and potential agriculture and irrigation practices. Irrigated areas, cropping pattern, crop water requirements and irrigation calendars will be the main source of information to assess this demand. Similarly fisheries requirements (both within the reservoir and downstream) will be determined based on local knowledge of fish breeding and fishing practices. HEC-ResSim will be used to determine operating rules that maximize hydropower production within the constraints arising from livelihood needs.

For each location the combination of LUPAS and HEC-ResSim model will be used to evaluate site specific trade-offs associated with different operating rules envisaged for different scenarios. For example:

- what will the livelihood implications be (in relation to both agriculture and fisheries) of maximizing hydropower production?
- what reduction in hydropower production is required if specified irrigation/fisheries requirements are to be achieved?

Other factors that affect livelihoods and may emerge from the livelihood surveys will also be included as constraints in the scenario modelling.

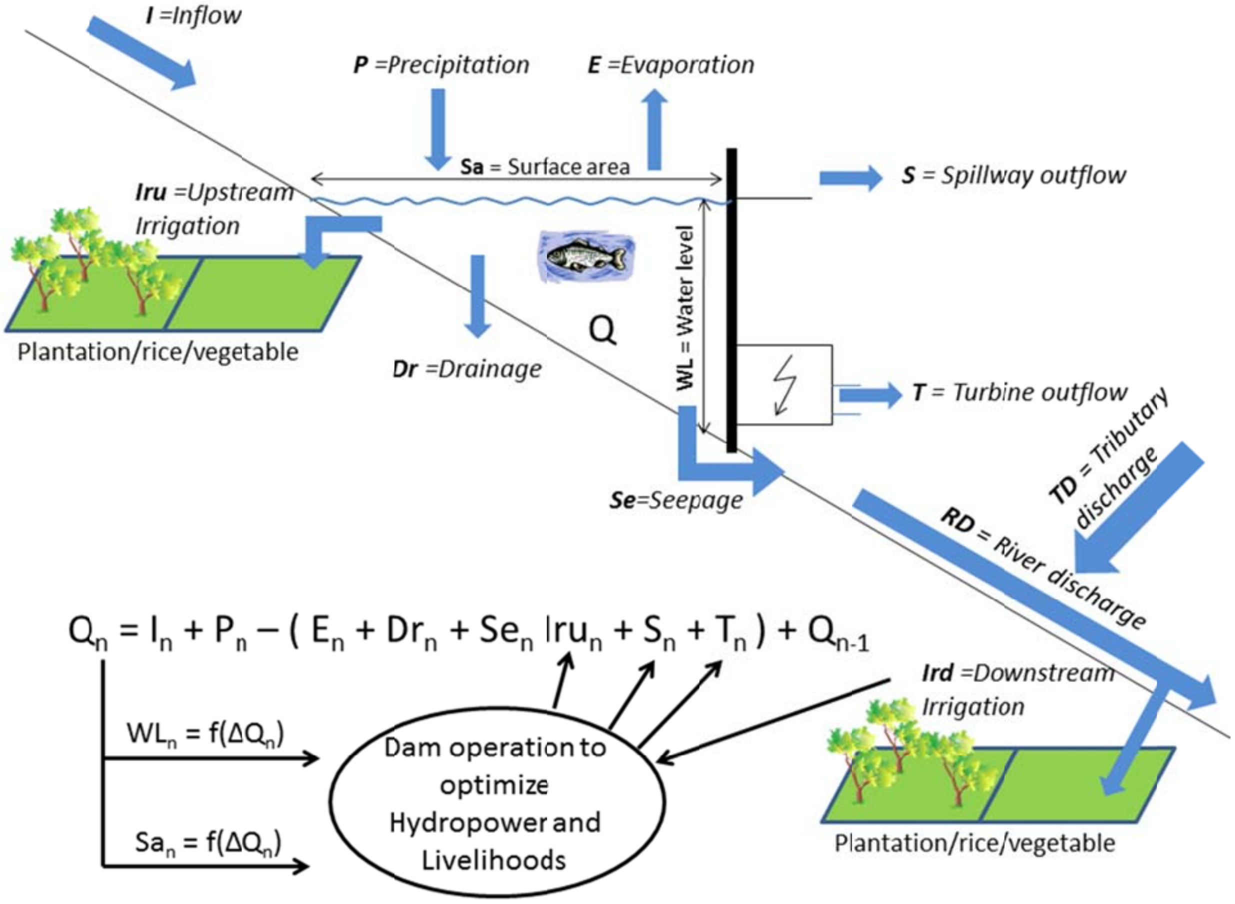


Figure 3: *Structure of proposed reservoir water balance model accounting for water requirements from neighbouring communities*

6. Conclusion

Managing water resources is a complex task that requires complex tools describing the interactions between hydrology, hydraulics, environment, economics and livelihoods. Models capable of analyzing many pressing water resource issues are available, and have significant potential for increasing the accuracy and effectiveness of information available to managers and decision makers. However, such tools have rarely been used to directly evaluate livelihood concerns. Furthermore, as has been seen in the Mekong, despite considerable expenditure in terms of human and financial capital, models often fail to live up to expectations and they are rarely used to assist decision-making in the way envisaged.

In the current study we propose to combine a land-use model and a reservoir simulation model with the aim of evaluating the site specific livelihood implications of different reservoir operating regimes at three reservoirs in the Lower Mekong Basin. To our knowledge this is the first time that land-use and reservoir systems models will have been combined in this manner. By integrating this modeling with livelihoods research being conducted at the sites we will ensure that the modeling conducted addresses the key issues of concern to local communities located both in the vicinity of the reservoirs and immediately downstream of each dam. The intention is to produce results that are relevant to communities, the dam operators and decision-makers. Consideration will be given to how the DSS can be used by the dam operators and possibly other stakeholders and how information and results derived from it can be presented in a way that is comprehensible to all. Even if the dam operators or communities living in the vicinity of the reservoirs are unable to use the DSS directly, we believe that by linking livelihoods and land-water use to the reservoir operation, it will contribute significantly to a better understanding of how reservoir operations affect livelihoods and may be improved for the benefit of local people.

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