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Water Resource Models in the Mekong Basin: A Review

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Abstract Development of the water resources of the Mekong Basin is the subject of intense debate both within the Mekong region and internationally. Water resources modelling is playing an increasingly important role in the debate, with significant effort in building integrated modelling platforms to describe the hydrological, ecological, social and economic impacts of water resource development. In the hydrological domain, a comprehensive set of models has been effective in building understanding of the system, and in identifying and describing the issues and trade-offs involved in basin-scale water planning. In the ecological and social domains, quantitative modelling has not progressed very far; geo-spatial analysis and qualitative frameworks remain the most commonly used tools. Economic models have been used to assess the costs and benefits of water resources development and to describe the trade-offs between different sectors and users. These analyses are likely to play an important role in the policy and planning debate, but are hampered by uncertainties in valuation of ecosystem services. Future efforts should focus on optimising the use of existing model platforms for the Mekong, including structured comparison of multiple hydrological models to quantify errors and identify an optimum set of modelling tools for different applications. A comprehensive research effort is needed to incorporate groundwater into hydrological models for regional planning. Options for social impact assessment should be reassessed before major investments are made in complex modelling platforms, and participatory social survey methods evaluated as part of an integrated assessment framework.

Keywords Hydrological modelling · Water resources modelling · Impact assessment · Mekong River Basin

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1 Introduction

As one of the few large rivers globally whose flow has not yet been drastically modified by human development, appropriate directions for the development of water resources of the Mekong River Basin is the subject of intense study and debate both within the Mekong Region and internationally (see, for example, Molle et al. 2009). Since the 1960s, hydrological modelling using mathematical simulation has played an increasingly important role in the debate. However, for all but a few experts, such models function as "black boxes" with little transparency in the way that results are obtained and limited understanding of their significance and limitations.

In this paper we examine the role of simulation models in water resources planning in the region. The paper gives a synthesis of macro-level water allocation issues in the Mekong and reviews how these will impact on hydrology at different spatio-temporal scales. It outlines the history of water resources modelling in the Mekong, and the range of models and associated tools developed for use at the basin scale. It reviews the insights that models have offered to understanding of the Mekong system, the issue of consistency between different modelling approaches, and the significance and limitations of models in planning and policy. We also review the contribution of models to water resource planning, analyse gaps and make recommendations for future investments in modelling.

2 Mekong Basin

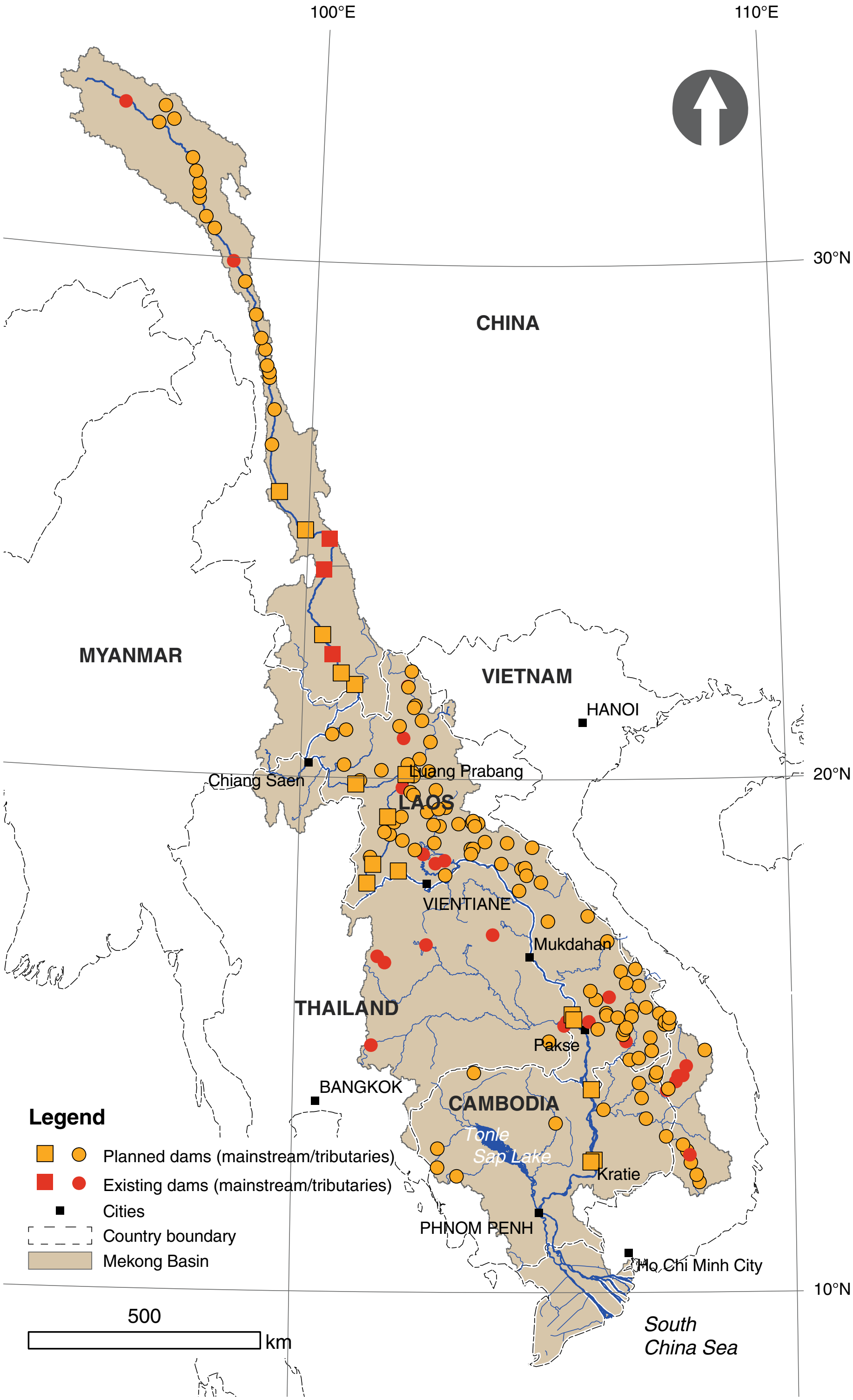
The Mekong Basin encompasses parts of six countries (Fig. 1) with a total population of around 70 million people. The Mekong River is the largest river in South East Asia, and has immense cultural and economic significance for the people of the region, as well as supporting diverse and unique ecosystems such as Tonle Sap Lake in Cambodia. The water resources of the basin contribute substantially to the economies of the countries as well as to local livelihoods and food security. A comprehensive overview of the Mekong Basin and its resources are available in MRC (2010a).

2.1 Water Resources in the Mekong

The climate in the Mekong Basin varies from temperate to tropical and is distinguished by highly seasonal rainfall controlled by the southwest monsoon, with wet season between May and October. Long-term mean annual runoff in the basin is estimated at 475 km^3. The tributaries in central and southern Laos are the most important contributors to the Mekong flow, providing over a third of total flow volume (MRC 2005). Part of the dry season flow and the rise to the wet season stage come from snowmelt from the Tibetan Plateau. Although only 16% of the total discharge originates from the upper Mekong, it is important part of the basin as 35% of the spring flow and over 55% of the sediment flux originates from there (Kummu and Varis 2007).

The hydrology of the Mekong is dominated by the annual flood pulse, and from an ecosystem productivity point of view it is important to maintain the natural hydrological pattern (Kummu and Sarkkula 2008). The Cambodian floodplains and the Mekong Delta are among the most productive ecosystems in the Mekong. They receive more than 90% of

Fig. 1 Map of the Mekong Basin showing planned & existing dams. Based on Mekong River Commission data (MRC 2008a) and HydroChina (2010) ▶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CHINA
MYANMAR
VIETNAM
HANOI
LAOS
Luang Prabang
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VIENTIANE
Mukdahan
THAILAND
Pakse
BANGKOK
CAMBODIA
Tonle Sap Lake
Kratie
PHNOM PENH
Ho Chi Minh City
South China Sea
Legend
Planned dams (mainstream/tributaries)
Existing dams (mainstream/tributaries)
Cities
Country boundary
Mekong Basin
500
km

flow and 95% of total suspended sediment flux from upstream. This part of the basin is thus directly dependent on upstream conditions and is vulnerable to changes in flow or sediment flux due to the upstream development (Kummu and Sarkkula 2008).

2.2 Water Resource Development Plans

The Mekong region is experiencing rapid population growth and economic development, with associated increase in demand for and development of water resources. All countries in the region have ambitious plans for development and significant water-related infrastructure has already been built, or is under construction, in major tributaries and upper reaches of the mainstream (King et al. 2007; MRC 2008a). Developments include:

- Construction of dams and reservoirs for hydropower or irrigation
- Withdrawals for irrigation, domestic and industrial use
- Deforestation and other land use changes (including urbanization)
- Inter- and intra-basin diversions
- Construction of roads, embankments, levees and bank protection works

A recent inventory of existing and potential hydropower projects in the 6 Greater Mekong Subregion (GMS) countries listed 261 hydropower projects (King et al. 2007). At least 28 were under construction and a further 179 large projects were identified as “probable” development sites. Figure 1 shows the main proposed dams based on MRC data (MRC-BDP2 2009). The active storage capacity of the Mekong reservoirs may increase from around present 5 km^3 to over 100 km^3 if all the planned dams are constructed (see Fig. 2). This would lead to significant modification and reallocation of flows from wet to dry season (e.g. ADB 2004), substantial trapping of sediments (e.g. Kummu et al. 2010), and changes in water quality (e.g. Wei et al. 2009).

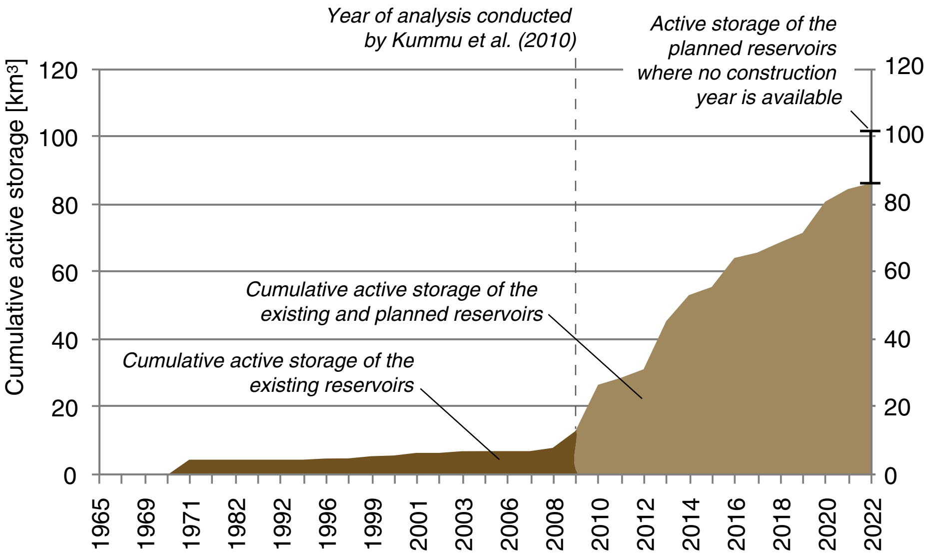

Fig. 2 Cumulative storage of existing and planned reservoirs in the Mekong Basin (modified from Kummu et al. 2010)

Current irrigation intensity in the region is low compared to other parts of Asia (Barker and Molle 2004), and all national governments see expansion of irrigation as an important priority, both to increase production and to reduce risk from climate change (Hoanh et al. 2009a). Only 2.9% of total land area was equipped for irrigation in the Mekong basin in 2002 (FAO Statistical Databases 2005). There are, however, significant differences in the extent of irrigation in different areas of the basin: in Laos only 1 to 2% of the cropland area is irrigated, while in the Vietnam Delta the same figure is approximately 60% (MRC 2002). Recent years have brought new players in the field of agricultural development in the Mekong, with substantial investment from China and the Arab world (Economist 2009). For example, Thuon (*pers. comm*. March 2010) reports that in 2009, 26 large irrigation projects were officially approved for execution in Cambodia between 2008 and 2015 with a total budget of over US$1 billion, mainly from external investors.

In much of the region, groundwater is used to supplement surface water supplies, or in areas remote from surface water resources. Groundwater consumption is more prevalent during the dry season and in low rainfall years. Groundwater use in agriculture is generally not extensive, but is likely to increase (Hoanh et al. 2009a).

There are various plans to divert water from the Mekong Basin to Thai internal basins (Molle and Floch 2008). None of the plans have materialised so far, although there have been water diversions between the Mekong tributaries (ADB 2004) within Lao PDR. The impacts of such actions can be significant at the local scale, although basin-wide impacts are not necessary significant.

There are increasing concerns about the potential impacts of water resource development on the riverine and floodplain ecosystems that sustain the Mekong's highly productive fisheries (Dugan et al. 2010, ICEM 2010). The freshwater capture fishery is critical to food security and livelihoods in the Mekong: fish provide up to 80% of total protein (Hortle 2007), and a very high proportion of rural people participate in fishing on a full or part-time basis (Van Zalinge et al. 2004). Freshwater fisheries make an important contribution to the regional economy—estimates of the total value of the Mekong fishery are as high as $2 billion per year (Dugan et al. 2010). Sustainability of freshwater fisheries is inextricably linked with water resource management, and protection of the ecological systems that sustain the fishery is an important regional priority.

A changing global climate may place additional pressure on Mekong water resources (Eastham et al. 2008; Penny 2008; TKK and SEA START RC 2009; Västilä et al. 2010). However, based on the recent estimates, the timescale for significant change in climate is much longer than that for development; dams, diversions and withdrawals are likely to have much greater impact on water resources in the next 20 to 30 years than the direct effects of climate change (Johnston et al. 2010; TKK and SEA START RC 2009; Keskinen et al. 2010).

The trans-boundary nature of the river, running through six countries (China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam), adds an extra dimension of complexity to the debate about equitable sharing of the river's resources.

3 Water Allocation, Impact Assessment and Models

The debate around water resources development in the Mekong can be framed, in its simplest terms, as a debate about allocation of water and water-related benefits between sectors and users, explicitly including subsistence livelihoods and the environment. The degree to which such allocations can be considered as "fair" or otherwise can only be determined by a comprehensive analysis and comparison of the impacts of development. The impacts of water resources development will be felt in five main domains, which must be approached more or less sequentially:

- Hydrological: flow volume and distribution, river water level, river connectivity, flood dynamics, water quality, sediment and nutrients
- Ecological: habitat quality, wetland functioning, fish migration, aquatic organisms
- Livelihood: water availability for agricultural and aquacultural production, availability of fish and other aquatic products, vulnerability to floods and droughts
- Economic: economic costs and benefits of different water use options
- Social: migration, gender relations, family structure, public health.

Coherent assessment frameworks must be developed in each of these domains in order to characterise impacts comprehensively. Because of the importance of Mekong inland fishery, and the large proportion of subsistence and semi-subsistence users who depend on it, realistic assessment of the impact of changes in flow on aquatic ecology is of particular significance.

In the context of water management in large basins, both the drivers and impacts of hydrological change act over a wide range of spatial and temporal scales resulting in a very complex set of interactions, with cumulative impacts across both sectors and scales (Kummu 2008). Impact assessments in the Mekong Basin can be grouped into four main groups:

- Basin-scale assessment of changes due to projected broadly-based WR development or climate change (usually scenario-based) (e.g. World Bank 2004; Costa-Cabral et al. 2007; Eastham et al. 2008; ICEM 2010; MRC 2011).
- Basin-scale assessment of the impact of a specific large-scale development [e.g. Nam Theun 2 CIA (ADB 2004), Nam Ngum 3 CIA (ADB 2008)]
- Local assessment of impacts of basin-scale changes including climate change (e.g. Friend et al. 2006; Kummu and Sarkkula 2008)
- Local assessment of impacts of specific developments (environmental impact assessments) (Hoanh et al. 2009b).

Defining appropriate spatial and temporal scales is an important part of impact assessment. Kummu (2008) concludes that, instead of down-scaling or up-scaling, a multi-scale approach can address local impacts of basin-scale changes and the contribution that local changes make to basin-scale impacts. Multi-scale approaches also help to build better connection between researchers, decisions makers and stakeholders. Modelling is one of very few tools able to assess impacts at multiple spatio-temporal scales and across a range of disciplines, and it therefore plays an important role in the impact assessment process (Sarkkula et al. 2007).

4 Historical Review of Mekong Modelling

The initial development of hydrological models for the Mekong Basin was driven by two related objectives: flood forecasting to mitigate the human and economic cost of large floods; and ambitious plans for development. The Mekong Commission, instituted in 1957 by the United Nations Economic Commission for Asia and the Far East (ECAFE), was charged with formulating a "Mekong Project" that would lift mainland Southeast Asia out of poverty through development of hydropower, irrigation and flood control projects. Early studies for the Mekong Plan (cited in Jacobs 1995) identified potential for both mainstream and tributary dams, and recommended establishment of a flood forecasting and early warning system. Two models were commissioned to support these plans: the Streamflow Synthesis and Reservoir Regulation (SSARR) model by the US Army Corps of Engineers (US Army Corps of Engineers 1972) installed in 1967 to simulate flows in the main river from Chiang Saen to Pakse; and the DELTA model developed by Société Grenobloise d'Études et d'Applications Hydrauliques (SOGREAH) between 1962 and 1965 to provide detailed flow simulation for the Mekong Delta. Both models were used for weekly flood forecasting (from 1970) as well as to study the feasibility of proposed mainstream dams and flood control measures, including Pa Mong and Sambor dams, and a dam across the Tonle Sap Lake (Kite 2000).

These early models were directed mainly at assessment of technical feasibility of projects, but there was also an appreciation of their potential to describe impacts. White (1963—cited in Jacobs 1995) suggested that the work of the Mekong Committee during this period represented one of the first large-scale efforts in Asian river basin planning to study economic, social and institutional aspects of development prior to actual construction.

Grand plans for mainstream dams were shelved during the 1970s due to political instability in the region. The focus for development shifted to projects on the tributaries, mostly in Thailand, and then to development of the Delta for irrigated rice production as Vietnam began to recover from the effects of the war. Hydrological modelling efforts reflected this shift, with the development of models such as Hydro System Seasonal Regulation (HYSSR) (Phanrajasavong 1986) and Massachusetts Institute of Technology River Basin Model (MITSIM) (WMO 1984) to evaluate reservoir operations in specific locations. This type of modelling has continued mainly in the private sector, with the application of large commercial modelling suites, such as the use of DHI's MIKE BASIN suite to assess the downstream impacts of Nam Theun 2 (ADB 2004). A number of different models were developed for the Delta to simulate water flow, tidal effects and salinity intrusion. These include the Vietnam River Systems and Plains (VRSAP) model, developed by the Vietnam Sub-Institute for Water Resources Planning and Management in the 1980s and continuously updated and improved since then (Hien 1999; Hoanh et al. 2009b); the Mekong Delta Master Model developed by Delft Hydraulics in 1991 (van Mierlo and Ogink 1991); and models to study salinity intrusion and tidal dynamics, for example, MEKSAL (Nguyen 1987).

In 2000, the Mekong River Commission (MRC) instituted a major new phase of hydrological modelling under the Water Utilisation Programme (WUP), to create a "*Basin Modelling Package…capable of predicting impacts of planned river-related development*" which would "*help to formulate, test and monitor the "Rules"*[1] *themselves, support decision-making for river basin planning and management, and provide a thorough assessment of any proposed developments*" (MRC 2001). The core of this package is the Decision Support Framework (DSF), conceived as a 'toolbox' with a knowledge base, simulation models and impact assessment tools to provide a broadly based assessment of environmental and socioeconomic impacts of water resources development (MRC 2005). More detailed models were developed for limited areas to complement the DSF: MIKE 11 modelling of Tonle Sap Lake and the Cambodian delta (Fuji et al. 2003) by the MRC WUP/

[1] Rules for maintenance of flow in the Mekong mainstream and to ensure reasonable and equitable use of the Mekong River Basin's water and related resources, mandated under the Mekong Agreement, 1997.

Japan International Cooperation Agency (WUP-JICA); and modelling of the flow regime and water quality of the Tonle Sap (MRC WUP-FIN 2003, 2007; Kummu et al. 2006) and later the Delta and Nam Songkhram Basin (MRC WUP-FIN 2007) by the MRC WUP/Finnish Environment Institute Consortium (WUP-FIN).

Since the mid-1990s there has been a proliferation of hydrological models for the Mekong in academic and research circles. In some cases these models have been developed as application of an of existing tool to the specific context of the Mekong; for example, Kite (2000) applied the Semi-distributed Land Use-based Runoff Processes (SLURP) model to the Lower Mekong Basin to assess the impacts of basin development on fisheries productivity and climate change (Kite 2001); Costa-Cabral et al. (2007) applied the Variable Infiltration Capacity (VIC) model for the entire Mekong Basin to study hydrology, sediment transport and the carbon cycle; and Kirby et al. (2010a, b) applied the water accounting models of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to assess water productivity (Mainuddin et al. 2008) and the impacts of climate change (Eastham et al. 2008). In other cases, models have been purpose-built to address particular questions in the Mekong: for example, Ringler (2001) examined the economic optimisation of water allocation in the Lower Mekong; Khem et al. (2006) developed inundation models for the Delta; and Yoshimura et al. (2009) developed a distributed hydrological model (YHyM) to simulate the nutrient loads in the Mekong.

5 Mekong Modelling Tools

A large number of hydrological models and related impact assessment tools have been developed for the Mekong at different scales and for different purposes. Table 1 provides an inventory of those used in the Mekong in the last 10 years. Kite (2000) reviewed models developed for the Mekong prior to the year 2000 and lists a further seven models which are no longer in use.

The greatest focus to date has been in the hydrological domain: a number of quantitative models have been developed and applied for assessment of hydrology, hydrodynamics and sediment dynamics. Four main suites of hydrological models are currently used in the Mekong, mostly within or associated with MRC programs:

- MRC's DSF (SWAT, IQQM and iSIS) (MRC 2005)
- VIC (Costa-Cabral et al. 2007; Thanapakpawin et al. 2007)
- MIKE suite developed by DHI (MIKE BASIN, MIKE 21 and MIKE 11) (ADB 2004)
- WUP-FIN suite (EIA, VMod) (MRC WUP-FIN 2003, 2007).

None of the major models provide assessment of groundwater resources or address the issue of groundwater—surface water connectivity.

While there is a plethora of hydrological models available for the Mekong, there are very few quantitative tools to link hydrology to the environmental, social and economic domains. Quantitative models have been developed to describe some physical ecosystem processes such as sediment transport (see for example Kummu et al. 2008a; Kummu et al. 2010). Two fisheries models have been developed for the Mekong: a Bayesian (probability based) model to simulate fish production in Tonle Sap under different scenarios (Baran et al. 2004); and a detailed fish population model to examine the impact of mainstream dams

Table 1 Hydrological and water resources models and tools used in the Mekong since the year 2000

	Model	Application	Area	Source	Mekong application
Hydrological models	SWAT	Rainfall-runoff model in MRC DSF	LMB 700 sub-basins	MRC MRC Technical Reports, described in Adamson (2006)	MRC DSF—input data for IQQM Sediment yield and transport
	SLURP	Semi-distributed hydrological model	LMB	IWMI Kite (2001)	Hydrology of Mekong—fisheries impacts Climate change
	VIC	Distributed hydrological model	Whole basin	Washington University Costa-Cabral et al. (2007); Thanapakpawin et al. (2007)	Hydrology, sediment transport; carbon cycle Climate change
	VMod	Distributed hydrological model	Whole basin	WUP-FIN MRC WUP-FIN (2006, 2007)	Basin wide model developed by EIA Ltd under IKMP programme of MRC. Several smaller scale applications exists, e.g. for Nam Songkhram sub-basin
	YHyM	Distributed hydrological and water quality model	Whole basin	Yoshimura et al. (2009)	Hydrological model to simulate nutrient loads in the Mekong.
Water balance models	Lancang model	Rainfall – runoff model	UMB	Chinese Academy of Surveying and Mapping Liu et al. (2007)	Lancang flows
	IQQM	Water balance, flow routing	LMB to Kratie	MRC MRC Technical Reports, described in Adamson (2006)	MRC DSF—Scenario assessment Assessment of flow regimes as input to negotiation of rules and procedures for water utilisation
	CSIRO Water use account	Water accounting	LMB	CPWF/CSIRO Kirby et al. (2010a, b); Mainuddin et al. (2008)	Assess impact of climate change on water resource Water productivity assessment

Table 1 (continued)

	Model	Application	Area	Source	Mekong application
	MikeBasin	Water balance, flow routing	LMB to Kratie	NORPLAN and EcoLao for ADB (ADB 2004)	CIA for Nam Theun 2
Hydrodynamic models	iSIS	Hydrodynamic model	Tonle Sap and Delta	MRC—Halcrow MRC Technical Reports, described in Adamson (2006)	MRC DSF—Scenario assessment Sediment transport
	VRSAP	Hydrodynamic model	Delta	Viet Nam Sub-Institute for Water Resources Planning Khue (1986); Hoanh et al. (2009b)	Water allocation in the Mekong Delta; sluice gate operations
	EIA 3D model	Hydrologic, hydrodynamic & WQ models	Sub-basins of LMB	MRC WUP-FIN (consortium of SYKE; EIA Ltd. and TKK)	Modelling of Tonle Sap flood pulse
				MRC WUP-FIN (2003, 2007)	Modelling of Songkhram basin
					Modelling of Delta
					Sediment transport and erosion; nutrient transport
	MIKE21	Hydrodynamic model	Cambodian floodplain	MRC WUP-JICA MRC technical reports and Fuji et al. (2003)	Modelling of Cambodian floodplain
	MIKE11	Hydrodynamic model	Tonle Sap and Delta	NORPLAN and EcoLao for ADB (ADB 2004)	CIA for Nam Theun 2
		Hydrodynamic model	Mekong Delta	Khem et al. (2006)	Inundation models for the Delta
Economic, policy, and Bayesian models	Economic –hydrology model	Economic – hydrology model	LMB	IFPRI Ringler (2001); Ringler and Cai (2006)	Economic optimisation of water allocation; valuing fisheries
	RAM	Economic – hydrology model	LMB	MRC – Rowcroft (2005)	Resource allocation model

Table 1 (continued)

	Model	Application	Area	Source	Mekong application
	MRC-WorldFish	Fish population dynamics model	LMB	WorldFish/MRC Halls and Kshatriya (2009)	Model of cumulative effects of mainstream hydropower dams on migratory fish populations in LMB
	Bay-Fish	Bayesian decision model	Tonle Sap, Bac Lieu	WorldFish Baran et al. (2004)	Fisheries productivity and management model
	WUP-FIN Policy model	Bayesian decision model	Tonle Sap	TKK Varis and Keskinen (2006)	Exploration of links between water policy and social and environmental outcomes
	ComMod	Agent-based models and role playing games	Nam Haen, Bac Lieu	Bousquet and Trebuil (2005); Dung et al. (2009)	Support collective decision making on water resources (aquaculture and agriculture)
Impact assessment frameworks	GCEWR–ER	Ecological flow assessment	Lancang	Bo et al. (2009)	Index based method for estimating ecological flow requirements based on hydrological characteristics
	IBFM	Impact assessment framework	LMB	MRC MRC/IBFM (2006)	Impacts of flow change on environment and livelihoods in LMB.
	BDP2-CIA	Impact assessment framework	LMB	MRC-BDP2 (2009), MRC (2011)	Impacts and trade-offs from water resources development in the Mekong—scenario analysis

as barriers to fish migration (Halls and Kshatriya 2009). For the Upper Mekong (Lancang) Bo et al. (2009) estimated ecological water requirement using indices of ecological characteristics for annual and seasonal hydrological variables.

Tools for assessing ecological and livelihood impacts of changed flow regimes in the Mekong are mainly assessment frameworks or methods, rather than numerical models. Much of the quantitative analysis of ecological and social impact of hydrological change relies on using geographic information systems (GIS) to estimate the extent and location of vulnerable habitats and populations (for example, World Bank 2004; Kummu et al. 2006; Kummu and Sarkkula 2008; MRC-BDP2 2009). Analytical frameworks for qualitative assessment of ecological and livelihood impacts have been formulated by the MRC under different programs. The Integrated Basin Flow Management program (MRC-IBFM 2006) provided a conceptual framework for assessing the impact of changes in river flows on ecology and riparian livelihoods, based on field studies, stakeholder consultations and expert input. MRC is now developing a vulnerability-based approach for social impact assessment (Social Impact Monitoring and Vulnerability Assessment (SIMVA) (MRC WUP-FIN 2007; M-POWER 2010). SIMVA has two components: a GIS tool to describe vulnerability based on population at risk and their dependence on aquatic resources; and a monitoring system to collect and analyze information on livelihoods and link these quantitatively to changes in aquatic resources.

Economic assessments of water resources development in the Mekong have taken two different approaches: analysis of economic costs, benefits and trade-offs (Rowcroft 2005; MRC 2011); and economic optimisation of water allocation by maximising net benefits to water use (Ringler 2001). In both cases, results are heavily dependent on the values set for different water uses. Valuation of ecosystem services and in-stream uses including fisheries is particularly problematic (see for example Norman-Lopez and Innes 2008) which means that such values are often either under-reported or omitted from the analysis.

6 Model Applications and Outcomes for Policy

The main applications of water resources modelling at the basin scale in the Mekong to date have been in planning and policy development. The only operational modelling program at the basin scale is MRC's flood forecasting program. The program has been in operation for 40 years and provides 5-day flood forecasting and flow forecasts along the Mekong mainstream which is updated daily during the wet season; and 7-day river monitoring during the dry season updated weekly. Flood reports are published on the MRC website and bulletins are emailed daily to a wide range of stakeholders and concerned parties (Apirumanekul 2006; Tospornsampan et al. 2009). At more local scale, VRSAP has been used successfully in the Delta in Vietnam to asses sluice operation modalities to balance the different water quality needs of rice and brackish water shrimp culture (Hoanh et al. 2009b).

Hydrological and water resources models have played an important role in shaping the Mekong development debate in three areas: as "eye-openers" identifying relevant issues, and the opposing, but linked, roles of creating consensus and generating dissent (Van Daalen et al. 2002). Models have been used to investigate a range of planning and policy questions, for example:

- Cumulative impacts of hydropower development on the Tonle Sap flood pulse, and on the ecosystems of Tonle Sap (Kummu and Sarkkula 2008)

- Impacts of changes in land cover on regional hydrology (Kummu et al. 2008b; Costa-Cabral et al. 2007)
- Impact of built structures on fisheries in Tonle Sap (Baran et al. 2007)
- Impact of range of potential water resource development scenarios under the MRC Basin Development Plan (on-going) (MRC 2011; ICEM 2010; World Bank 2004; MRC-BDP 2005)
- Impacts of projected climate change on Mekong hydrology (TKK and SEA-Start 2009; Eastham et al. 2008; Västilä et al. 2010).

Insights provided by the models have influenced and reoriented the development debate. For example, in the early 2000s, the focus of concerns about disruption of flows to Tonle Sap by upstream storage broadened from mainstream dams in China to include dams on the tributaries in Lao PDR as models clarified the relative flow contributions and potential impacts from each region (see for example MRC 2005, World Bank 2004). Preliminary quantification of projected increases in dry season flows associated with construction of storage for hydropower (Hang and Lennaerts 2008; World Bank 2004) shifted the focus of policy debates from dry season shortages for irrigation, to concerns that increased dry season flows may impact on fish spawning and migration (Baran 2006).

More recently, the fish barrier model of Halls and Kshatriya (2009) examining the impacts of mainstream dams on migratory fisheries has generated new arguments in the debate. The current discourse is predicated on the assumption that, although mainstream dams will disrupt migration paths, the impacts could be mitigated by appropriate technologies. Halls and Kshatriya (2009) demonstrated that the very high survival rates for fish passes and turbines needed to maintain viable populations in the Mekong have never been achieved elsewhere, and that mainstream dams in the Lower Mekong Basin (LMB) are likely to have catastrophic and immitigable impacts on migratory fish populations. These results cast a new light on the debate surrounding mainstream dams and will undoubtedly feed controversy.

Models are used within MRC explicitly to create consensus between the four governments of the LMB. Two examples illustrate the strengths and weaknesses of this approach: MRC's Basin Development Plan program; and the negotiations within the MRC Water Utilisation Programme around rules for maintenance of flow.

The Basin Development Plan is based around analysis of development scenarios using the DSF to provide a common understanding of the issues, problems and opportunities inherent in developing the shared water resources of the Mekong. To this end, considerable effort has gone into building a common platform and input data, quality assurance processes and agreed criteria for acceptance of results, and capacity building and training of national staff in the use of the model (World Bank 2004; MRC-BDP2 2009). A synthesis of initial findings from the second phase of the BDP (BDP2) (MRC 2011) presented projected impacts of different options for Mekong development over the next 20 years, in terms of economic net present value (NPV) of the cumulative costs and benefits across sectors. The results identify critical differences between scenarios: in particular, the trade-offs between hydropower development and fisheries production under different combinations of mainstream and tributary development; the potential benefits to irrigation through augmentation of dry season flows by hydropower dams; and the variance in distribution of benefits between countries. While the analysis is acknowledged to be preliminary and incomplete, it provides a potent summary for policymakers of some of the major decisions that governments of the region will face and an important basis for debate. However, the report also embodies many of the risks and challenges inherent in using models to inform policy. Quantification of the economic outcomes of scenarios is likely to be widely used as justification for policy decisions, but there is a risk that the errors and uncertainties set out in the report—particularly those relating to valuation of ecosystem services and non-market values—may become lost in the debate. There is concern that the analysis is inevitably skewed towards parts of the system that can be quantified (hydrology and economics) and that critical dimensions of ecology and livelihoods are underrepresented, particularly those relating to fisheries (Friend et al. 2009).

Hydrological models were developed under MRC's WUP to support formulation of rules for maintenance of flows on the Mekong mainstream. Particular emphasis was placed on the fact that the models were developed and endorsed by the four Lower Mekong Basin countries collaboratively, based on best available combined information and with agreed processes for calibration and validation (MRC 2005). The WUP models significantly improved the understanding of the Lower Mekong system. In theory, this improved understanding could have underpinned negotiation of an agreement on water sharing and rules for water use. In reality, the opposite happened. In 2005, at the same time as the publication of a landmark report "Overview of the Hydrology of the Mekong Basin" (MRC 2005), the MRC Council downgraded "Rules" to "Procedures". In 2006, the "Procedures for maintenance of flows on the mainstream" (MRC 2006) were agreed, but with only a generalised agreement that flows would be maintained at "acceptable" levels, and stating that "*the flows to be maintained at specified locations… are set out in a separate document entitled Technical Guidelines*". These have never been released. It seems that the opportunity to move the debate regarding quantification of flow rules into a technical space was consciously rejected; and procedures were framed so as to keep political options open. The models certainly informed the debate, but did not resolve it; and it can be argued that, rather than supporting the establishment of rules, the development of the WUP models pushed rules off the negotiating table by imposing a degree of technical rigour not then—or yet—matched by political will.

A number of studies have been conducted, or are underway, to quantify the potential impact of climate change on flow and water availability in the Mekong Basin as the basis for adaptation planning (Hoanh et al. 2004; Eastham et al. 2008; Kiem et al. 2008; TKK and SEA START RC 2009; Hoanh et al. 2010; Västilä et al. 2010). Results have been reviewed by TKK and SEA START RC (2009) and Johnston et al. (2010). In general, the studies concurred that rainy season runoff and discharge are likely to increase in the first half of the 21st century in response to projected increases in precipitation; but there were significant differences in projected magnitude of changes in the maximum water level and flooded area, and in estimates of dry-season changes. Since the studies used different climate scenarios, time periods and models, it is not possible to unravel the sources of these differences. In the context of policy and planning, until more certainty emerges, it is very important to take account of the full range of possible outcomes and take a 'no regrets' approach to policy development. A robust approach is needed, seeking solutions that address current problems and build resilience, regardless of the direction of change (McGray et al. 2007; World Bank 2004; Johnston et al. 2010).

Modelling in the Mekong has been dominated by the requirements of the MRC. Of the 23 models listed in Table 1, 11 were developed directly within MRC programs; and another six were developed by research agencies with some degree of collaboration with MRC. Only two (VRSAP and Lancang models) were developed or operated exclusively within national agencies. As large-scale development proceeds, national and local governments will need to progressively engage in the debate about basin-scale water use and allocation; and local and international civil society networks are also playing an increasing role in negotiating basin scale water policy. If models are to be used effectively in shaping policy, these groups must be included not just in interpreting results but also in determining which questions are asked, and which options and issues are modelled.

7 Discussion

7.1 Comparing Models—Diversity and Redundancy

International interest in the Mekong has meant that a wide range of models have been developed by different groups. While there has been a degree of coordination under the auspices of MRC, most groups have worked relatively independently and there is significant redundancy in the modelling effort. There are, for example, no less than seven hydrodynamic models used to study the Mekong floodplain and delta (see Table 1), in addition to older models no longer in use (DELTA-SOGREAH, the Mekong Delta Master model and MEKSAL). There is obviously an argument to be made that sufficient effort has gone into building models, and that the issue now is to make best use of existing tools to provide thorough, balanced assessments. It is clear that a greater degree of coordination and consistency is required. Effort needs to be directed to developing applications; and to capitalising on comparisons.

However, model diversity can be useful on a number of counts. First, a range of different models is needed to cover different categories and issues: for example, hydrological models do not provide information on flood extent. Even within the same category a range of different models may be needed to deal with variation in spatial and temporal scales. Secondly, different configurations of models have different strengths and limitations. Adamson (2006) reviewed and compared the four main regional hydrological model suites for the Mekong and concluded that each is appropriate for different applications: for example, MRC-DSF is the preferred system for regional scale appraisal of impacts of resource development in the LMB; while MikeBasin has significant advantages in assessing specific infrastructure. Thirdly, the existence of independently developed models provides opportunities for cross-comparison and validation of model results.

Comparison of results from different models is not straightforward. Differences result not only from variations in the modelling platform, but also from a mix of other issues including underlying assumptions, input data and the way research questions are posed. Two examples illustrate the difficulties involved.

Kummu and Sarkkula (2008) compared the results from three major cumulative impact assessments (CIA) on the impact of basin development on Tonle Sap Lake (Table 2). All three predicted higher dry season water levels and lower flood peaks, but the predicted magnitude of the resulting change in dry season lake area varied from 6% to 30%.

Eastham et al. (2008) modelled hydrological impacts of climate change in the Mekong to 2030. Using a water accounting methodology, and based on the assumption (from the A1B SRES scenario) of an average increase in rainfall of 0.2 m (13%) they predicted a 21% increase in overall flow in the river and an increase in probability of “extreme wet” flood events from 5% to 76%. In contrast, Hoanh et al. (2004) modelled hydrological impacts of climate change in the Mekong to 2039, using the SLURP model. Based on an assumption (from the A2 and B2 SRES scenarios) of a minimal change in overall precipitation but with different sub-basins varying from −6% to +6%, they predicted a decrease in average

Table 2 Cross-comparison of results from three cumulative impact assessment studies of impacts of development on Tonle Sap Lake

	MRC DSF (World Bank 2004)	ADB - Nam Theun 2 (ADB 2004)	Adamson (2001)
Assumptions and methods			
Increase in storage	49.5 km^3	54.9 km^3	22.7 km^3
Increase in irrigation	+53%	–	–
Other developments	Increased domestic and industrial use, intra-basin diversions	Increased domestic and industrial use	–
Method/model used			
	DSF—hydrological and hydrodynamic model	MikeBasin—water balance and hydrodynamic model	Statistical analysis
Predicted impact on Tonle Sap water levels			
Wet season	−0.36 m	−0.54 m	NA
Dry season	+0.15 m	+0.60 m	+0.30 m
Min area (change from observed)[a]	2,532 km^2 (6%)	3,107 km^2 (30%)	2,712 km^2 (11%)
Max area km^2 (change from observed) [a]	12,559 km^2 (4%)	12,168 km^2 (7%)	NA

[a] Estimated by Kummu and Sarkkula (2008)

monthly flows of 7–11%, with a small increase (1%) in maximum flows, but large decrease in minimum flows.

In each case, the underlying assumptions (about the degree and nature of basin development in the first example, and about climate scenarios in the second) were fundamentally different, so the variance in results is not necessarily due to inaccuracies or inconsistencies in the models. However, it illustrates clearly the difficulties involved in comparison of model results, and the confusion that could potentially result for policy makers or planners attempting to use model results. These issues can only be addressed by very careful and transparent presentation and explanation of the assumptions and limitations inherent in the modelling process. A structured cross-comparison of models using the same starting assumptions and scenarios could provide valuable information on the overall reliability and comparability of model results.

Both consistency and inconsistency can provide important information. In the Tonle Sap case above, the consistent projection of higher dry season and lower wet season lake levels resulting from upstream development is an important consideration for planning and management, regardless of the exact magnitude of the changes. In the case of differing projections for the impact of climate change on Mekong flows, the important message is that of uncertainty, and the need to factor uncertainty into planning.

7.2 Accuracy and Uncertainty

Because models are simplifications of reality, they are always inaccurate at some level. This does not necessarily detract from their usefulness, as long as the degree of uncertainty is documented and acknowledged. It is, however, difficult to report uncertainty in a meaningful way even for quantitative models, because of the problems in characterising and quantifying uncertainty from different sources; and it becomes almost impossible for qualitative results. Estimates of the uncertainty associated with model results are rarely reported, but without adequate description of the uncertainties involved, model results are (or should be considered as) unusable in a policy context.

In addition, there is often a tendency in reporting model results to disregard or downplay the assumptions and inaccuracies, particularly at a policy level, where caveats and qualification of results can be seen as undermining the credibility of results. In fact, in a policy context the degree of uncertainty associated with model results is useful information in its own right. Policy responses and priorities will differ depending on the degree of certainty with which a particular situation or issue is known. Where uncertainty is high the important policy message is the need to factor uncertainty into planning.

Many current hydrological models, and the planning and management frameworks built on them, rely on the assumption of 'stationary'—that is, the envelope of natural variability does not change, and the past can be used to simulate future conditions. A combination of climate change and human disturbance in river basins may push hydro-climate beyond the range of historical behaviours, with important consequences for planning and adaptation (Milly et al. 2008; Godden and Kung 2011). To predict the hydrological consequences of such changes in a context where small shifts in average climate may produce large changes in extreme hydrological events, increased emphasis will be needed on process based and probabilistic models.

7.3 Costs of Model Development

The costs of model development are difficult to estimate, since in most cases the models are one component of broader research and development programs. However, at MRC alone, the cost of developing basin-scale models is estimated at around USD 20 million since 2000 (Table 3). This is a very substantial component of total funds for the organisation: committed funding for models, assessment tools and data programs totalled USD 15.6 million from total committed funding of USD 111.7 million for the period 2006–2011. These very substantial costs underscore the need to ensure best use of resources by reducing redundancy through better coordination.

Table 3 Cost of model development in MRC since 2000

MRC programme	Committed funds (USD)
Water Utilisation Programme 2000–2008 (MRC 2008b)	
Basin modelling and knowledge base component	8.8 million
Environment and transboundary analysis component (including IBFM)	2.3 million[a]
Integrated Knowledge Management Programme 2006–2011 (MRC 2010b)	
Modelling component	5.4 million
Hydrometeorological data	5.9 million
GIS and databases	2.1 million
Environment Programme 2006–2011 (MRC 2008b)	0.9 million
Environmental decision support	
BDP2 2006–2011 (MRC 2008b)	1.3 million
Knowledge base and assessment tools	

[a] Includes all costs for the component, not only IBFM

7.4 Integrated Model Platforms—Pros and Cons

The requirement at a policy level for integration of impacts across domains has produced a strong focus on inter-disciplinary modelling platforms. The long-term aim of several modelling groups working in the Mekong is to produce seamless integrated information systems for sequential analysis of impacts in hydrological, environmental (including fisheries), economic and social domains. Analytical frameworks to facilitate this are being developed under the MRC BDP2, WUP-FIN and the Virtual Mekong (M-POWER 2010).

Modelling across disciplinary boundaries is notoriously difficult, in part because of the different intellectual frameworks and assumptions underlying different disciplines; and in part because of differences in availability and quality of data in the different disciplinary domains. The dependencies between different domains are only partially understood and very rarely quantified. As a result, the emphasis of all the major modelling platforms is still primarily on hydrology. In the social domain particularly, impact assessment is based mainly on analytical frameworks and data collection/surveys.

This raises questions as to whether integrated modelling is feasible, or indeed desirable, in assessing the social impacts of hydrological change. A number of philosophical and technical reasons are evinced for this. The most fundamental is that impact assessment is about cultural and social values, which cannot be reduced in any meaningful way to a common currency for comparison with economic and other impacts. Moving the debate about social impacts into a technical space may obscure important—but unquantifiable—values. Friend and Blake (2009) have questioned the validity of basing the water resource development debate around trade-offs, arguing that the use of trade-offs limits the scope for shaping alternative visions of development, infers a technical rather than a political process of decision making, and limits involvement in the debate to technical experts. A similar argument can be made about quantitative modelling of social impacts and options: that the decision making process needs to remain explicitly in the political domain, and accessible to all stakeholders.

At a technical level, the sheer complexity of the systems remains an obstacle. The tendency to focus on aspects of systems that lend themselves to modelling and quantification may mean that other critical aspects are downplayed. Differences in the level of detail and accuracy between domains mean that important nuances from the physical models are lost by being lumped to a spatial or conceptual level for which social data can be used. In moving between domains, errors are very difficult to characterise and quantify, and propagate in unpredictable ways.

The major frameworks for social impact assessment in the Mekong (WUP-FIN, SIMVA, IBFM) all have a strong focus on participatory surveys to elucidate vulnerability and impacts. This is not simply because data are scarce, but because well-designed surveys are a reliable and simple method of gauging not only what impacts people anticipate, but also their attitudes to them. It is arguable that extension of participatory monitoring programs may be a better way to approach social impact assessment than technically based modelling. Perhaps the most productive approach is to focus on educating policy makers and the public in understanding the connections between environmental and social systems; acknowledge that models are not going to give a final answer; and keep the debate within the political arena.

7.5 Gaps in Mekong Modelling

Despite the high degree of sophistication and diversity of existing models, there are still areas in which models are lacking or inadequate for the Mekong Basin. Four such areas are listed and briefly discussed below; in all of the cases this is linked closely to paucity of data.

7.5.1 Groundwater and its Interaction with Surface Water

Groundwater and surface water are known to be closely linked in the Mekong floodplain and Delta, (CIAP 1999; Raksmey et al. 2009), and there are many other areas, such as the limestone provinces of central Laos, with major aquifer systems. None of the major modelling suites currently operating for the Mekong has a working groundwater model. Both MikeBasin and the WUP-FIN suite have the capability for such a component built in. Groundwater data in the Mekong region is very sparse, and building and calibrating a groundwater model at the regional scale for the Mekong would require a major research program.

7.5.2 Modelling the Ecological and Social Impacts of Flow Modification

Because of the complexity of ecological responses, ecological, livelihood and social impacts have generally been approached by concentrating on a single component, such as fish in the Tonle Sap (see for example Baran et al. 2004); flooded forests in the Tonle Sap (e.g. Kummu and Sarkkula 2008); and some studies assessing impacts in particular geographical areas (e.g. Keskinen et al. 2005; Friend et al. 2006). MRC's IBFM (Integrated Basin Flow Management) Program (MRC-IBFM 2006) aimed to provide a coherent framework for assessing ecological and livelihood impacts along the Mekong mainstream, but has been discontinued. International programs have developed methodologies for setting flow-based river ecosystem management targets (for example, King et al. 2003; Smakhtin and Anputhas 2006; Poff et al. 2010) but these have not been applied in the Mekong. Construction of integrated hydrological—ecological—social models has been hampered both by lack of data and by the complexity of the task. Identifying a basin-scale methodology capable of reflecting local ecological and social impacts adequately remains the greatest challenge in assessing impacts of hydrological change.

7.5.3 Links Between Hydrology, Ecosystems and Economy

In the case of links between hydrology, ecosystems and economy, it is the paucity of data and very complex causalities, rather than lack of a modelling platform, that is of most concern. Ringler (2001) and Rowcroft (2005) made preliminary attempts to model the economic impacts of flow changes. MRC BDP2 is establishing a methodology and framework to assess economic, environmental and social impacts of basin-wide water development (MRC-BDP2 2009). However, all these efforts are hampered by the lack of information on the economic valuation of ecosystems and ecosystem services. Where reliable objective valuation data are lacking for cost-benefit analysis, there is a risk that the valuation process can be used to justify the desired outcome (Bowers 1990).

7.5.4 Optimisation of Hydropower Operation Rules

This crucial part of modelling hydropower impacts is not very well covered by any of the current basin-wide models. Most optimisation models available are based on a monthly time step. They may predict seasonal fluctuations well, but are not able to simulate daily and weekly operational rules which drive very significant short-term fluctuations in flows. Better collaboration with the dam operators and power companies is needed to include the actual operation rules into the models. Further, the impact of changing climate on the rules should be also examined in detail.

7.5.5 Data Issues

As part of developing the DSF, MRC put considerable effort into collating and validating a regional hydro-meteorological database and on the whole, hydrological data quality is not a major limitation for modelling in the Mekong at the basin scale (Adamson 2006, World Bank 2004). However, hydrodynamic modelling of the Mekong floodplain is limited by the quality of available digital elevation models; and development of basin-wide water quality and sediment transport models has been hampered by paucity of water quality data. Remotely sensed data on land surfaces (DEM, landcover, evapotranspiration) has improved dramatically over the last few years, as very sophisticated data has become available from global datasets collected from satellites—for example, the Shuttle Radar Topography Mission (SRTM) digital elevation models. These are being incorporated into the Virtual Mekong initiative and made available on-line (Richey, *pers. comm.*).

Data issues become even more critical when moving beyond hydrology to describe impacts in the environmental, economic and social domains. In general, data are simply not available to drive ecological and social models at the basin scale; hence much of the modelling effort in these domains has been limited to developing conceptual frameworks. Accurate valuation requires precise economic data that are rarely available for environmental systems in the Mekong, and lack of comprehensive and reliable data for valuation of ecosystem services (including fisheries) is a significant constraint in applying economic models.

8 Conclusions and Recommendations

A wide range of water resources related models and tools have been applied in the Mekong to address questions including basin planning, water allocation, impact assessment and flood forecasting. The models have been very effective in building understanding of the system, and identifying and describing the issues and trade-offs involved in basin-scale water planning, and in that context have made an important contribution to the policy debate. The extent to which this can form the basis for forging consensus on directions for development is yet to be seen. More effort is needed in building the understanding and involvement of decision-makers and other stakeholders in using the models to explore development options.

In the hydrological domain, the range of tools available is comprehensive, with different models available covering most of the needs of hydrological studies within the Mekong region. Future efforts would be better placed in developing applications of existing models than in developing new models. The exceptions are groundwater models, which remain a yawning gap in expertise; and water quality, where limited progress has been made. With a range of hydrological models available, there is an opportunity to select the most appropriate modelling tools to address specific questions; and to cross-check and compare results from different model platforms. A structured review and comparison of the basin wide models in the Mekong is required to assess their strengths and weaknesses in different applications, identify the optimum suite of tools for different applications and help to quantify the error associated with different models.

In the ecological and social domains, quantitative modelling of the impacts of water resources development in the Mekong has not progressed very far despite significant efforts. Geo-spatial analysis and qualitative frameworks remain the most commonly used tools. Progress has been hampered partly by lack of data to describe critical links; but also by the sheer complexity of the task. Quantitative models for specific aspects of ecological systems (such as fish population models) are being developed with some success; but linking these into broader assessments remains a daunting task. Approaches using streamflow-based targets may provide appropriate methods for synthesising ecological impacts. A debate is emerging about whether approaches based on participatory surveys and monitoring may be more feasible and better able to capture social and cultural values.

Economic models have been used to assess the costs and benefits of water resources development and to describe the trade-offs between different sectors and users. These analyses are likely to play an important role in the policy and planning debate, but the large uncertainties inherent in valuation of ecosystem services and other non-market values must be taken into account in interpreting and using the results.

Levels of uncertainty associated with models are often poorly articulated, or ignored. Understanding and explaining the level of uncertainty associated with modelling of trade-offs between sectors will be critical to ensuring the credibility of basin-scale planning models and it is important that decision-makers and stakeholders demand this information. In a policy context, the degree of uncertainty is useful information in its own right, since it can underpin precautionary approaches to policy and planning. Transparency of the model engine, scenario building and model results are an important part of ensuring that uncertainty is understood. Calibration and validation results of the model, as well as the development scenarios of the impact assessment procedures should be independently reviewed, openly presented and disseminated, with a greater focus on publication in the open literature.

Communication between modellers, planners and decisions makers and other stakeholders has been a challenge for a long time in multidisciplinary work. Nancarrow (2005) identified basic differences in the approaches of modellers and social scientists: modellers simply assume a problem and start by defining and collecting data needed to solve it, while social scientists start by identifying the different stakeholders and how they see and define the problem. There is a need to find a common language for discussing definitions of issues and the formulation of questions to be modelled, as well as modelling results. Modellers need to pay more attention to presenting their results in understandable ways to different actors and end users.

Model development to date has been driven mainly by international agencies, particularly MRC. Initiatives led by MRC have considerably improved simulation modelling capacity within the national agencies of the MRC partner governments, but it is important that stakeholders beyond national governments are included, since civil society, local and international NGOs and local governments all have a stake in the results of the assessments. MRC's programs, particularly BDP, have an increasing focus on stakeholder consultations (MRC 2010b), which can foster interaction between the technical modelling community and stakeholders. Involvement of stakeholders is needed at three stages: conceptualising the scenarios to be tested by the models and the questions to be posed; validation of results and alignment with local knowledge; and discussion of the significance of results in terms of policy outcomes. Promoting participation of regional universities and research centres more actively in both technical modelling and the broader impact assessment process will help building local understanding, ownership and capacity.

Four main recommendations for water resources related modelling in the Mekong emerge from this analysis:

- **Develop applications of existing models and model comparison**: future efforts should be focused on optimising the use of existing model platforms, rather than developing new models. A structured comparison of existing models is needed to quantify errors and identify an optimum set of modelling tools for different applications. It is essential that model structure, calibration and validation procedures, and the uncertainties and assumption in the modelling process are reported transparently and in full.
- **Reassess modelling of social impacts**: an assessment of options for identifying and describing the social and livelihood impacts of hydrological change is needed before major investments are made in extending and developing integrated model platforms. Participatory social survey methods should be evaluated as part of an integrated assessment framework.
- **Groundwater modelling**: inclusion of comprehensive models of groundwater and groundwater/surface-water interactions into existing hydrological models is an urgent priority for regional planning. Suitable modelling platforms already exist, but calibration and validation at the regional scale will require a major research effort and funding from international donors.
- **Building local ownership and capacity:** enhanced involvement of regional universities and research agencies in water resources modelling and impact assessment, to act as a focal point for fostering broadly-based local participation in water resource policy and planning.

Models are an essential component of planning and managing change in the complex, inter-related water resources systems of the Mekong. The increasing sophistication and diversity of available models provides a crucial toolbox for impact assessment, but they must be used in a context where the underlying assumptions and limitations of the models, input data and the resulting projections are clearly spelled out for users. In the end, hydrology is not the main decision domain: managers and policy makers work in political, economic and social spheres. The utility of water resources models depends not so much on their sophistication as on how well results can be linked to decision making.

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