Case Study

Model-Based Assessment of Water, Food, and Energy Trade-Offs in a Cascade of Multipurpose Reservoirs: Case Study of the Sesan Tributary of the Mekong River

Timo A. Räsänen[1]; Olivier M. Joffre[2]; Paradis Someth, Ph.D.[3]; Cong Tran Thanh[4]; Marko Keskinen, Ph.D.[5]; and Matti Kummu[6]

Abstract: The Mekong River Basin in Southeast Asia is undergoing rapid development in the exploitation of its water resources. Although hydropower is the most dominant driver for water development, the possibilities for multipurpose reservoirs have been increasingly discussed but not well studied. The authors assess the potential benefits and negative impacts of a multipurpose reservoir cascade facilitating hydropower and irrigation in the Sesan River, a transboundary tributary of the Mekong. A model-based assessment approach was developed where the hydropower operations of a cascade of reservoirs were simulated together with the irrigation water withdrawals. The assessment revealed that the reservoirs created considerable irrigation potential (28,348 ha), and the resulting losses for hydropower generation were relatively small (−1.6%). The river flow impacts were significant, but they originated mainly from the hydropower operations. The inclusion of irrigation led to an increased competition of water resources during the dry season. In addition, the assessed hydropower and irrigation development affected negatively protected areas, agriculturally valuable land, and forest cover. Gaps and shortcomings in the model-based assessments of water resources development were further recognized, including this one, concluding that particularly the connection to ecological and social domains remains often weak and needs, therefore, to be strengthened. **DOI: 10.1061/(ASCE)WR.1943-5452.0000459.**

Author keywords: Multi-purpose reservoirs; Trade-offs; Hydropower; Irrigation; River flow; Models.

Introduction

Several river basins in Asia are undergoing rapid development of their water resources, particularly in the form of hydropower. Such a situation exists also in the Mekong River Basin (Grumbine et al. 2012). Although the Mekong Basin has currently less than 40 large hydropower dams, in the future the basin could have up to 160 large dams if all development plans actualize (Grumbine et al. 2012; Räsänen et al. 2012). Such development would bring radical changes to the river system, as the total regulating capacity of all these reservoirs would be over 20% of the annual flow of Mekong River (Räsänen et al. 2012).

In addition to hydropower, water abstraction for irrigation is playing an increasing role in water resources exploitation. Presently, an area of 4 million hectares is equipped for irrigation in the Lower Mekong Basin (LMB; China and Myanmar excluded), corresponding to 5% of the total basin area (MRC 2010). The estimated irrigation water abstraction in the LMB is 41.8 km^3 (MRC 2010), of which half is being used at the Mekong Delta (MRC 2010) and impacts thus only on the flow to the South China Sea. However, the irrigation in the Mekong is expected to increase within the coming decades, especially during the dry season (MRC 2010).

Major drivers for hydropower and irrigation development in the Mekong are increasing energy and food demands, and the quest for economic growth (Grumbine et al. 2012; MRC 2010; Pech and Sunada 2008). During the period of 1993–2005, the energy demand increased at an average annual rate of 8%, which is one of the fastest in the world (ICEM 2010; MRC 2010). At the same time, the cereal demand may double in the region by the year 2050 according to Pech and Sunada (2008). Should the current rate of rice production and population growth continue, the basin is likely to produce enough rice for its population only up to 2030–2040 (Pech and Sunada 2008).

One of the major constraints for increasing crop production in the region has been limited access to water because of uneven seasonal distribution of water and inadequate irrigation infrastructure (Nesbitt et al. 2004). The agricultural sector has been dominated by the rainfed cultivation of a single rice crop during the wet monsoon months of May–October (Nesbitt et al. 2004). Yet, the access to supplementary irrigation during the wet season and irrigation during the dry season enables two or three crops, and can also lead to improved crop yields (Nesbitt et al. 2004; Shimizu et al. 2006). Currently 34% of the total rice production area of 10 million hectares in LMB is irrigated (MRC 2010). The constraints on access to water in the agricultural sector, together with the unequal distribution of benefits from hydropower projects, have increased the

[1]Water and Development Research Group, Aalto Univ., P.O. Box 15200, Tietotie 1 E, 02150 Espoo, Finland (corresponding author). E-mail: timo.rasanen@aalto.fi

[2]International Centre for Environmental Management (ICEM), No. 6A, Lane 49 To Ngoc Van St., 1000 Tay Ho District, Hanoi, Vietnam.

[3]Dept. of Rural Engineering, Institute of Technology of Cambodia, P.O. Box 86, Russian Federation Blvd., 12152 Boeungkak, Phnom Penh, Cambodia.

[4]Southern Regional Hydrometeorological Centre, 8 Mac Dinh Chi, 710494 District 1, Ho Chi Minh City, Vietnam.

[5]Water and Development Research Group, Aalto Univ., P.O. Box 15200, Tietotie 1 E, 02150 Espoo, Finland.

[6]Assistant Professor, Water and Development Research Group, Aalto Univ., P.O. Box 15200, Tietotie 1 E, 02150 Espoo, Finland.

Note. This manuscript was submitted on September 30, 2013; approved on April 17, 2014; published online on July 2, 2014. Discussion period open until December 2, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496/05014007(10)/$25.00.

discussion on multipurpose dams that could facilitate irrigation (MRC 2011b).

The rapid development in water resources exploitation requires careful planning and management, particularly because of the increasing competition of the resources and the increasing complexity of the managed systems. Various modeling tools are commonly used to manage these challenges and to assess the impacts of water resources development. In the case of reservoir management, there are several examples of these modeling tools and their applications, as reviewed for example by Labadie (2004), Rani and Moreira (2010), and Singh (2012). Many of these model applications address management situations where the reservoir operation has several objectives, such as hydropower generation, irrigation, domestic water supply, and flood protection.

Modeling tools are commonly used approaches in water resources related planning and decision making in the Mekong as well (Johnston and Kummu 2012). For example, the regional Mekong River Commission (MRC) uses decision support framework (DSF), which is largely based on hydrological and water management models (MRC 2005a). The research community has also used various models to assess the water resources development such as the impacts of hydropower development and climate change (e.g., Lauri et al. 2012; Räsänen et al. 2012), and many of these modeling approaches have been reviewed by Johnston and Kummu (2012).

Despite the extensive water resources related modeling efforts in the Mekong Basin, little is known about the potential benefits and possible impacts of multipurpose reservoirs. Particularly scarce are analyses of reservoir cascades at the catchment scale. Yet, the consideration of multipurpose reservoir development in that setting is important, as an assessment of an individual project may neglect the broader cumulative catchment scale impacts.

This paper aims to contribute to the discussion on multipurpose reservoirs by partially filling the research gap on the potential benefits and negative impacts of multipurpose dams in the Mekong using Sesan Catchment as a case study area. The focus of the paper is on: (1) the potential of a cascade of multipurpose reservoirs to increase agricultural production by increasing irrigation potential, and (2) the impacts of such development on stream flow. The methodological focus of the paper is on the model-based assessment of hydrology, hydropower production, and land cover related changes. To achieve these aims, a five-stage modeling approach was developed, a *what if* irrigation scenario for existing and planned reservoirs in a case study catchment, and the developed modeling approach was used in the case study area to assess the hydropower losses from irrigation and the related stream flow impacts.

Study Area: The Sesan River Catchment

The study area of this paper is the transboundary Sesan River Catchment, part of the Mekong Basin and shared by Vietnam and Cambodia (Fig. 1). The Sesan River joins the Srepok River upstream of one of the assessed hydropower projects (Lower Sesan 2). Consequently, Srepok was also included in the study area, in order to be able to simulate the hydropower operation of Lower Sesan 2 dam. The Sesan-Srepok River further joins the Sekong River. Together these three rivers form one of the largest tributaries of the Mekong River, called collectively as 3S Rivers. The Sesan Catchment covers an area of 18,684 km^2, and the landscape varies from lowlands (60–300 masl; meters above sea level) located in Cambodia in the west to the highlands (300–700 masl) and Annamite mountain range (1,000–2,100 masl) located in Vietnam.

Climate and Hydrology

The climate in the study area is characterized by distinct wet (May–October) and dry seasons (November–April), caused by the monsoon climate (MRC 2005b; MRC 2010). The climate in the study region is closely connected at least to the North-Western Pacific component of the Asian monsoon (Delgado et al. 2012) and

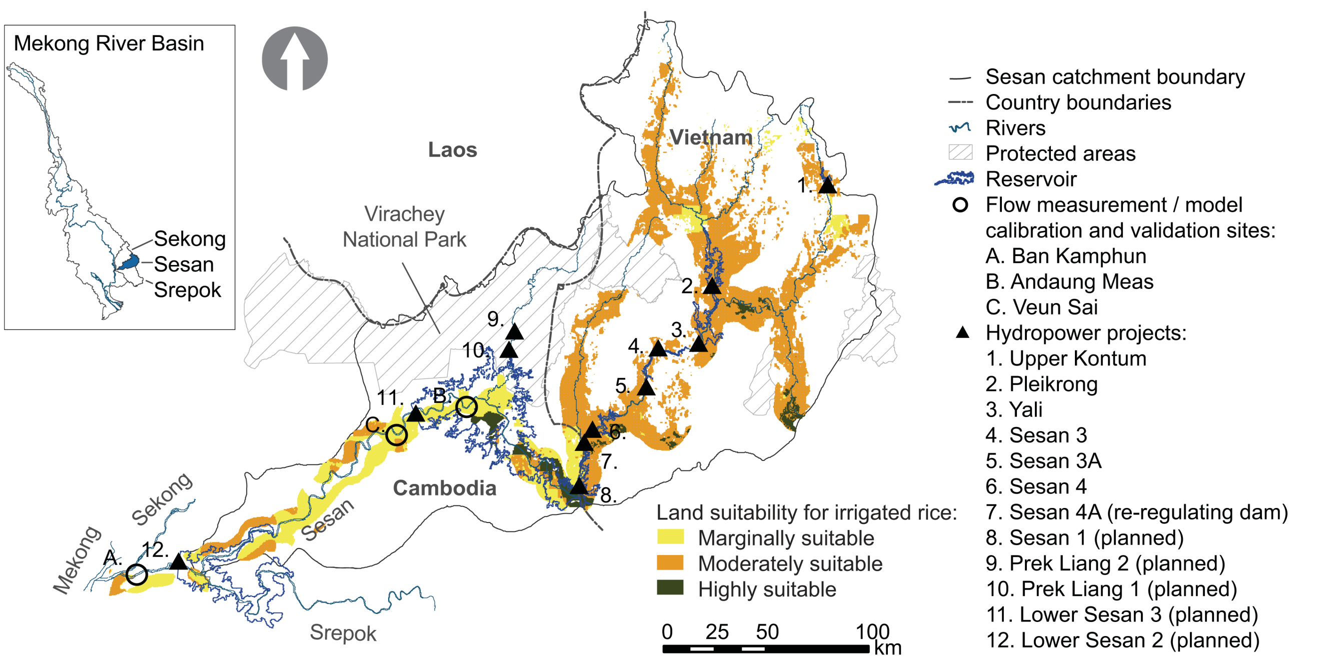

Fig. 1. 3S Catchment of the Mekong Basin with Sesan in the middle, Srepok in the south, and Sekong in the north; the map shows also the 12 dams included in this study, the main hydrological stations used in the calibration of the hydrological model, the estimated land use suitability for irrigated rice within a 5-km buffer from the main rivers, the protected areas that were excluded from the land suitability assessment, and the inundated areas of the existing and planned reservoirs (location data of hydropower projects, basin borders, rivers, and protected areas from MRC 2011c)

affected by tropical cyclones (Darby et al. 2013) and El Niño-Southern Oscillation (Darby et al. 2013; Räsänen and Kummu 2013). The monsoon climate results also in an annual flow regime with a pulsing nature where the majority of the flow occurs between wet season months.

Hydropower Development

Currently seven large dams (dam height >15 m) exist in the Sesan Catchment, all located in the upper part of the catchment in Vietnam. According to MRC future scenarios, there are plans to build one more in the Upper Sesan and four more in the Lower Sesan in Cambodia (MRC 2011a, c). This study focuses on the 12 largest dams and reservoirs, of which one is a re-regulating dam with no power plant (Sesan 4A; Table 1). Nine dams out of the twelve are designed or planned mainly for power generation and only three, Pleikrong, Yali, and Sesan 4, have been designed to facilitate irrigation (MRC 2011c). More of the hydropower development in the Sesan can be found from Wyatt and Baird (2007).

Past Research

Scientific research on the Sesan Catchment is relatively scarce, although some high quality research exists. Piman et al. (2012) assessed the flow changes potentially caused by 41 existing and planned dams in the 3S. They found that the operation of the dams would increase the dry season flows by +63% and decrease the wet season flows by −22% at the outlet. Takamatsu et al. (2013) forecasted the potential future land cover development in 3S and its impacts on water resources up to the year 2033. Their findings suggest that water demand will increase, which may result in −10 to −15% decrease in dry season flows of the Sesan. Ty et al. (2011) assessed the future land use/cover, population growth, and hydropower development on flow regimes in the upper parts of Srepok Catchment. Interestingly, Ty et al. (2011) found that the land use/cover change and population growth caused greater impacts on flow regimes than the dam operations. Ty et al. (2012) made future climate projections for Srepok Catchment up to the year 2050. They found that rainfall and temperature will increase, which will lead to increased runoff, but the increased runoff may not be adequate to compensate the increased water use. The future climate change projections of Ty et al. (2012) are in line with projected changes in the Mekong Basin (Lauri et al. 2012). In addition, the impacts of hydropower development in the 3S Rivers on the Tonle Sap Lake in Cambodia have been assessed by Arias et al. (2014b).

Kummu et al. (2010) estimated the sediment trapping efficiencies of existing and planned hydropower reservoirs in the Mekong Basin. In the Sesan River, the reservoirs were estimated to have the total trapping efficiency of 85–95%. The trapping efficiencies of the downstream reservoirs of Lower Sesan 3 and Lower Sesan 2 were estimated to be 86–92% and 35–61%, respectively.

The Mekong Basin scale study by Ziv et al. (2012) assessed the potential impacts of hydropower development on fish biodiversity. They found that the Lower Sesan 2 dam may potentially reduce the total fish biomass of the whole Mekong basin by 9%. Overall, the 3S Rivers are known to be rich in biodiversity (Baran et al. 2011; Poulsen et al. 2004).

Wyatt and Baird (2007) reviewed impacts from the existing hydropower projects in the Sesan. They reported that the dam construction started to modify the river flow already in 1996. Since then approximately 55,000 people from 90 villages have been impacted resulting to losses of lives, property, livelihoods, and reduced income. The impacts of hydropower development in Sesan on the public health have been addressed by Polimenia et al. (2014).

Methodology

The developed approach for the assessment of irrigation potential of a cascade of multipurpose reservoirs and impacts on river flows were based on five stages: (1) the modeling of the catchment hydrology; (2) the assessment of land suitability for irrigated rice; (3) the estimation of crop water requirements; (4) the estimation of irrigation potentials of reservoirs; and (5) the simulation of hydropower and irrigation operations. The five stages of the modeling approach and their relationships are illustrated in Fig. 2 and briefly introduced subsequently, and refer to Section 1 of the Supplemental Data for more extensive information.

A distributed physically based hydrological model VMod (Koponen et al. 2010) was used to simulate catchment hydrology.

Table 1. Main Characteristics of Existing and Planned Large Hydropower Projects in the Sesan Catchment (Data from MRC 2011c)

Hydropower project	Commission year	Installed capacity (MW)	Active storage (Mm^3)	Reservoir area (km^2)	Announced hydropower generation (GWh)	Baseline annual hydropower generation (GWh)	Irrigation scenario (ha)	Annual hydropower loss [GWh (%)]
Upper Kontum	2011	250	122.7	7.4	1,056	1,057	600	20.3 (−1.9%)
Pleikrong	2008	100	948	53.3	417	497	2,817	7.1 (−1.4%)
Yali	2001	720	779	65	3,659	3,850	0	24.9 (−0.6%)
Sesan 3	2006	260	3.8	3.4	1,225	1,228	0	7.4 (−0.6%)
Sesan 3A	2007	96	4	8.5	475	454	6,490	7.8 (−1.7%)
Sesan 4	2009	360	264.2	58.4	1,420	1,478	3,474	30 (−2%)
Sesan 4A[a]	2008	—	7.5	1.7	—	—	5,091	—
Sesan 1	NA	90	3.4	10.6	480	641	0	20.6 (−3.2%)
Prek Liang 2[b]	NA	25	180	11.9	(186)	(238)	—	—
Prek Liang 1[b]	NA	35	110	7	(189)	(314)	—	—
Lower Sesan 3	NA	243	323	4,140	1,977	1,634	7,843	55.7 (−3.4%)
Lower Sesan 2	2016	480	379.4	394	2,312	2,218	2,033	28.7 (−1.3%)
Total	—	2,659	3,125	4,761	13,396	13,057	28,348	202.5 (−1.6%)

Note: The table shows also the simulated energy productions, estimated irrigation potential and, respective hydropower losses because of irrigation over the period 2002–2006.
[a]Sesan 4A is a re-regulating dam for Sesan 4 and does not have a power plant.
[b]Prek Liang 2 and 1 were excluded from the irrigation assessment as they are located inside a protected area. They were simulated to cover their river flow impacts but excluded from the energy assessment.

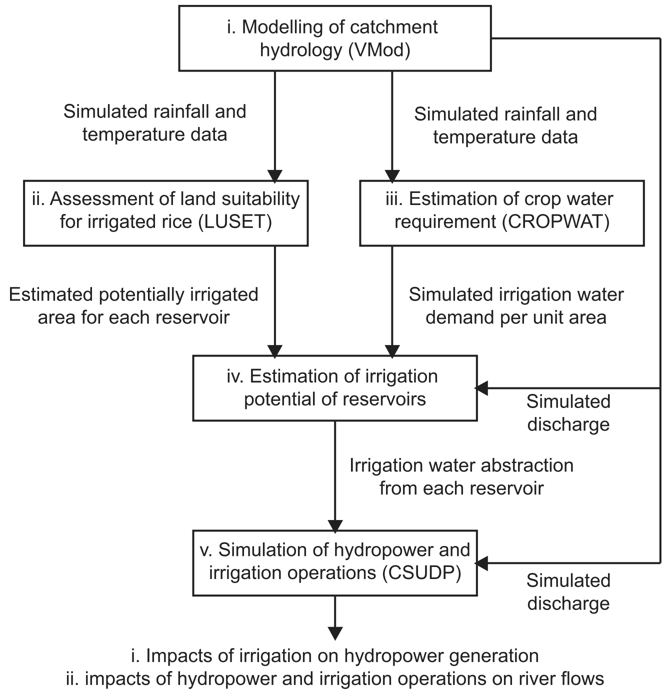

Fig. 2. Stages of the developed modeling approach and their relationships in the assessment of irrigation potential of a cascade of multipurpose reservoirs and their river flow impacts; a detailed description of modeling stages is presented in Section 1 of the Supplemental Data

VMod provided inputs, such as interpolated rainfall and temperature fields and discharge for the land suitability assessment, the crop water requirement modeling and in the simulation of hydropower and irrigation operations. The land suitability for irrigated rice was assessed using Land Suitability Evaluation Tool (LUSET; CGIAR-CSI 2006), which provided an estimate of the maximum area of potentially suitable land for irrigated rice within a 5 km distance from the main stem. The crop water requirements were estimated using CROPWAT (Allen et al. 1998; FAO 2013) that provided the amount of water and the irrigation schedule for the transplanted dry and wet season rice. The irrigation potential of each reservoir were then estimated according to dry season water budgets (i.e., water availability), suitable land for irrigated rice defined by LUSET, crop water requirements defined by CROPWAT, and a specific water allocation from the reservoirs. The dry season water budget consisted of reservoir active storage and dry season (December–May) river flow. The specific water allocation represents a percentage of dry season water budget allocated for irrigation. Thus the estimation of irrigation potential of each reservoir provided the actual irrigation scenario for the final simulations.

The final stage was the simulation of hydropower and irrigation operations using generalized dynamic programming tool CSUDP (Labadie 2003), into which the earlier stages fed the necessary inputs. The final assessment period was from 2002 to 2006, and it was limited by the availability and quality of the hydrological data. The impacts of irrigation on hydropower production were evaluated for each hydropower project while the hydrological impacts were evaluated at the border of Upper (Vietnam) and Lower Sesan (Cambodia) Catchment, and at the outlet of the Sesan River Catchment.

Because of the broad scope of the assessment and deficiencies in some of the used datasets, certain assumptions had to be made to focus the study: (1) the land suitability and irrigation potential assessment was limited to 5 km distance from the rivers; (2) for the specific water allocation from reservoirs, the single rate of 5% for all reservoirs was assumed; (3) in crop water requirement estimations, single soil type for the entire catchment was assumed; and (4) in hydropower operations, the maximization of the annual energy production was assumed as an operation strategy of each individual project. These assumptions are discussed and justified in Section 1.2 of the Supplemental Data.

Results

Catchment Hydrology

The hydrological model VMod reproduced the measured flows well at the calibration and validation sites of Ban Kamphun and Andaung Meas (see locations in Fig. 1), despite the somewhat scarce network of meteorological data used to force the model and the impact of Yali dam on measured flow. The Nash and Sutcliffe Efficiency (NSE) between daily measured and simulated flows at Ban Kamphun was for the calibration period 2001–2003 0.87 and for the validation period 2004–2007 0.85. The NSE for validation at Andaung Meas over the period 2001–2007 was 0.72. Water balance error at Ban Kamphun for the calibration period was +4.8% and for the validation period +12%. In Andaung Meas, the water balance error for calibration period was +1.1%, and for the full data period 2001–2005 −2.9%. The daily measured and simulated flows are shown in Figs. S2(a and b). The simulated annual discharges at the main stem dam sites were further validated against the announced annual average flow (MRC 2011c). The differences varied from −16% to +7% and were on average +1%. The hydrological model produced also interpolated rainfall and temperature fields [examples in Figs. S2(c and d)] for land suitability assessment and crop water requirement modeling.

Land Suitability for Irrigated Rice

On the basis of the land suitability assessment, the size of the potentially suitable land area for irrigated rice downstream of each reservoir varied greatly. Fig. 1 shows the map of areas estimated suitable for irrigated rice within 5 km buffer from the main river (excluding urban and protected areas), and Table S2 shows the suitable land for irrigated rice per reservoir (areas inundated by reservoirs are excluded). The highest potential was at Upper Kontum, Sesan 3A, and Lower Sesan 3, whereas it was the lowest at Sesan 3 and Yali. The irrigation potential of Sesan 1 was reduced to zero because of extended reservoir area of Lower Sesan 3 reservoir that submerged its suitable irrigation land. Prek Liang 1 and 2 were excluded from the irrigation potential assessment, as they reside inside a protected area. Prek Liang 1 and 2 were, however, simulated to consider their river flow impacts. It is important to acknowledge that the estimations in Table S2 are based on a rather coarse method, and they should be, therefore, taken only as preliminary indication on potential for irrigated rice downstream the reservoirs. For example, the estimated potential may be reduced by spatially smaller scale factors, such as, residential areas (e.g., around Kontum) and microtopography (e.g., Upper Kontum, Pleikrong, Sesan 3A, 4, and 4A). The assessment also did not consider the technical feasibility of diverting water into the areas defined as suitable for irrigated rice.

Crop Water Requirements

According to CROPWAT simulations, the estimated irrigation demands in the Upper (Vietnam) and Lower (Cambodia) Sesan were on average for the dry season 12,450 m^3/ha/year and 13,251 m^3/ha/year, respectively, whereas the demands for the wet season were 2,223 m^3/ha/year and 2,718 m^3/ha/year, respectively. The slightly higher irrigation demand in the Lower Sesan resulted mainly from the warmer and drier climate compared with the Upper Sesan. The weekly irrigation patterns for dry and wet season rice are shown in Fig. 3(a).

Irrigation Potential of Reservoirs

According to dry season water budgets (i.e., in terms of water availability), all reservoirs could facilitate irrigation. Yet, only the Upper Kontum, Pleikrong, Yali, Sesan 4, Lower Sesan 3, and Lower Sesan 2 have active storages large enough to store and regulate water for the irrigation of the whole potential of suitable land area (Table S1). However, the Yali reservoir had a limited area of suitable land for irrigation, and therefore, Yali reservoir could thus be used to provide irrigation water for the Sesan 3A that has significant potential for irrigation in terms of suitable land area for irrigated rice (Table S2). Thus, in the final multipurpose reservoir simulations, Yali was considered to provide irrigation water for Sesan 3A, which itself had large irrigation potential but inadequate reservoir storage.

For the final irrigation scenario, 5% was assumed for the specific water allocation from the dry season water budget for irrigation from the reservoirs with adequate storage capacity. Cooperation was also assumed between Yali–Sesan 3–Sesan 3A as well as between Sesan 4 and Sesan 4A, so that irrigation potential downstream of Sesan 3A and Sesan 4A could be used. This approach yielded altogether potentially irrigable area of 28,348 ha, of which 18,472 ha is located in the Upper Sesan and 9,876 ha in the Lower Sesan (Table 1).

Hydropower and Irrigation Simulations

The simulated annual mean energy productions corresponded relatively well with the announced energy productions (MRC 2011c) for most projects with few exceptions (Table 1). The energy production of Sesan 1 and Prek Liang 1 and 2 were overestimated, which may have resulted from the data used to define the characteristics of the projects. The overestimation may have resulted also from inaccuracies in subcatchment delineation in the hydrological model causing larger river flows at dam sites as announced by MRC (2011c). The impacts of irrigation on hydropower generation are estimated only in the case of the nine impacted main stem hydropower projects. Thus the small tributary dams, Prek Liang 1 and 2 and re-regulating dam Sesan 4A without its own power plant were excluded from the energy assessment.

Impacts of Irrigation on Hydropower Generation

The total simulated annual hydropower production of nine hydropower projects was on average 13,056 GWh without irrigation (Table 1). The irrigation of 28,348 ha resulted on average in total of −1.6% (or 203 GWh) reductions in the annual total hydropower generation. The largest impacts were experienced in downstream projects Sesan 1 (−3.2%) and Lower Sesan 3 (−3.4%) because of accumulating water abstraction for irrigation along the river (Table 1). The majority of the reductions in hydropower generation occurred in the dry season [Figs. 3(b) and S3]. On average, the total dry season hydropower generation was reduced by −4.2%, from 4,427 to 4,241 GWh. Again the largest impacts were experienced in downstream projects Sesan 1 and Lower Sesan 3, where dry season reductions were on average −7.5% and −8.6%, respectively. The highest short-term reductions occurred early in the dry season at the start of the dry season irrigation in week 48, where the total energy production was reduced by −10.1%.

Impacts of Hydropower and Irrigation Operations on Flow Regimes

The hydropower operations generally affected flow regimes by increasing the dry season flows and decreasing the wet season flows (Table 2 and Figs. 4 and S5). At the border of Vietnam and Cambodia and the outlet of the Sesan Catchment, the largest flow increases (+175% and +201%, respectively) occurred in March. The largest flow decreases in the same locations occurred in August (−31% and −21%, respectively). The average seasonal flow changes at the outlet of the Sesan were for the dry season (December–May) +53% and wet season (June–November) −11%. These estimates suggest smaller seasonal flow changes than the ones of Piman et al. (2012), who estimated a dry season increase of +79% and a wet season decrease of −25%. The differences between the two estimates originate most likely from the different methods and assumptions that were used to describe the hydropower operations.

The inclusion of 28,348 ha of irrigation into the simulations generally reduced the dry season flows, but the impacts were relatively small in comparison with the hydropower impacts (Fig. 4 and Table 2). For example, the cumulative flow increase resulting

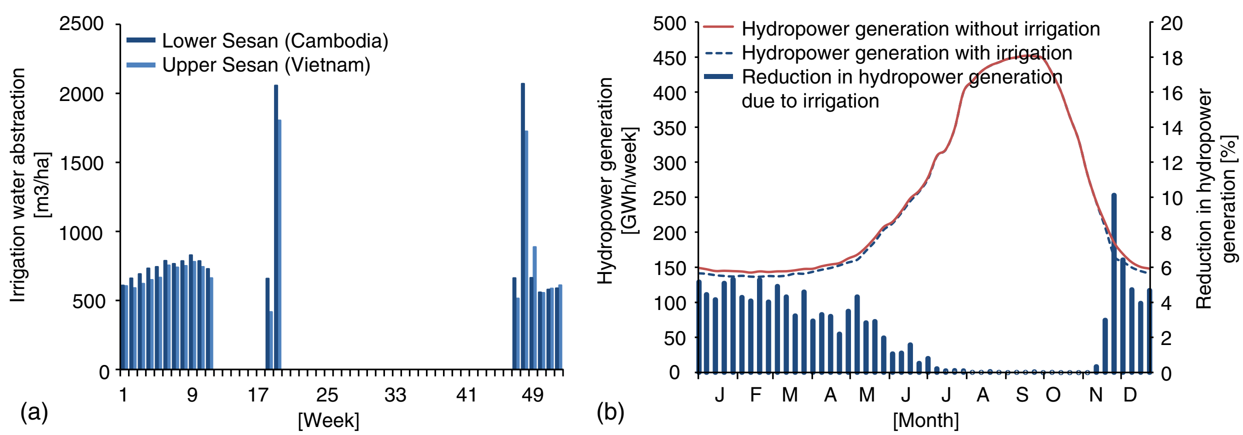

Fig. 3. Irrigation schedule and the hydropower losses due to irrigation: (a) estimated average weekly irrigation water abstraction requirements for Upper (Vietnam) and Lower (Cambodia) Sesan Catchment for transplanted irrigated dry and wet season rice and; (b) weekly average hydropower generation of nine hydropower projects (Prek Liang 1 and 2 and Sesan 4A excluded) without irrigation (continuous line) and with 28,348 ha irrigation (dashed line) and corresponding hydropower reductions (columns) over the period 2002–2006

Table 2. Hydropower and Irrigation Impacts on River Flow at the Border of Vietnam and Cambodia (Immediately Downstream of Sesan 1 Dam) and at the Outlet of Sesan Catchment on Monthly and Annual Scale Over the Period 2002–2006

	Border of Vietnam and Cambodia				Outlet of Sesan Catchment			
Month	Baseline (m^3/s)	Hydropower (%)	Hydropower + irrigation (%)	Irrigation (%)	Baseline (m^3/s)	Hydropower (%)	Hydropower + irrigation (%)	Irrigation (%)
January	108	+61	+45	−19	158	+68	+54	−20
February	79	+115	+90	−29	113	+130	+111	−32
March	63	+175	+160	−14	84	+201	+176	−15
April	72	+168	+162	−4	93	+172	+149	+6
May	174	+55	+50	−7	226	+46	+41	+9
June	306	+26	+25	0	445	+2	+1	0
July	596	−5	−5	0	846	−19	−20	0
August	1,163	−31	−31	0	1,791	−21	−21	0
September	1,099	−14	−14	0	1,798	−9	−9	0
October	640	−6	−6	0	1,044	−4	−4	0
November	276	+1	−6	−7	435	+2	−4	−7
December	165	+16	+5	−12	243	+17	+7	−12
Annual	395	0	−2	−2	606	0	−2	−2

Note: The impacts are presented as percentage changes from baseline flows (i.e., natural nonregulated flows).

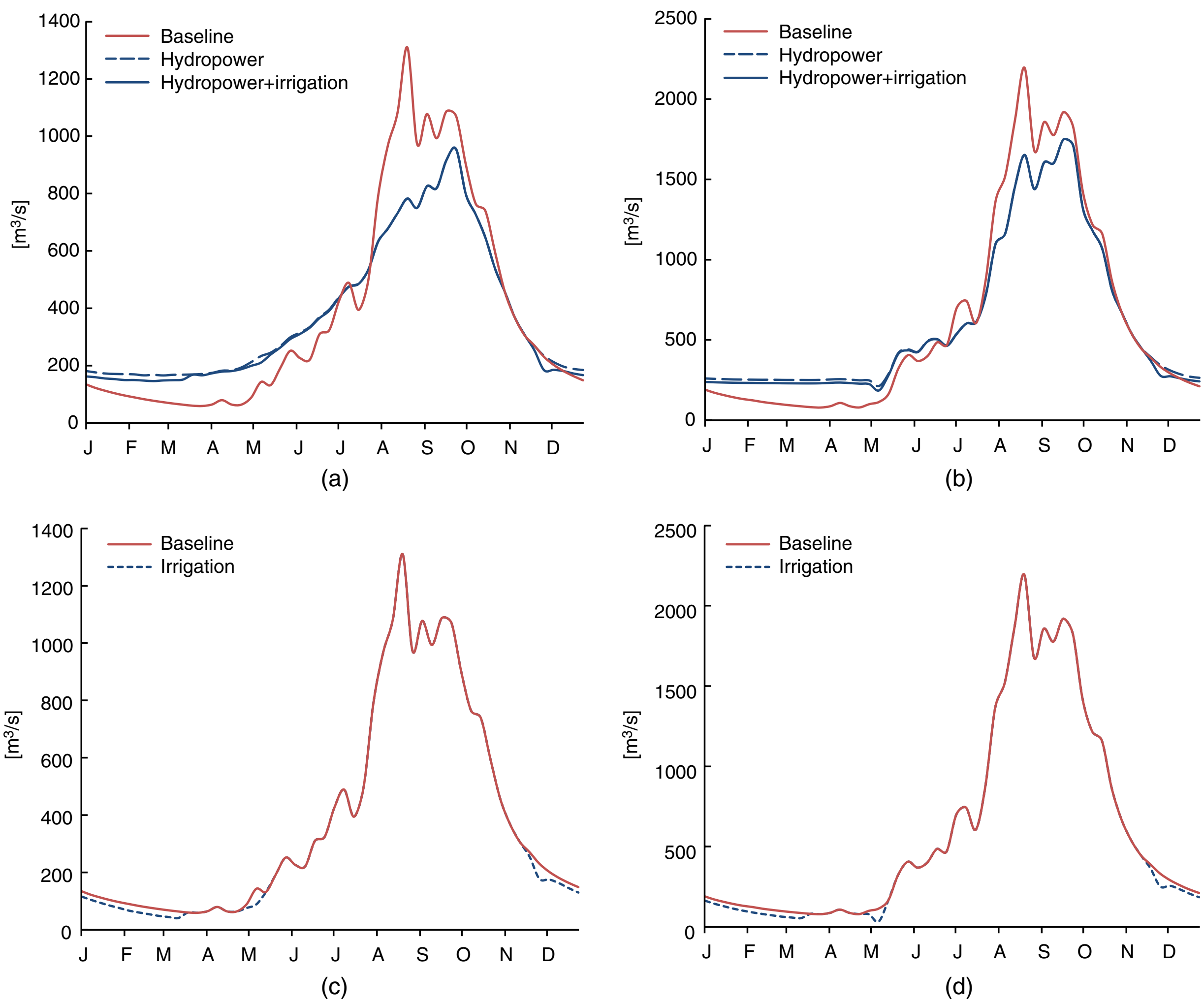

Fig. 4. Average river flow impacts at the border of Vietnam and Cambodia (immediately downstream Sesan 1 dam) and at the outlet of Sesan Catchment over the period 2002–2006: (a, b) impacts of hydropower and combined hydropower and irrigation; (c, d) impacts of irrigation on baseline flows (i.e., natural nonregulated flows)

from hydropower operation and irrigation in March at the border of Vietnam and Cambodia and the outlet of the Sesan were +160% and +176%, respectively, whereas the flow decreases in August was the same as in the simulation with only hydropower operations.

The impact from irrigation is, however, different than the one from the hydropower operation, as it reduces the total flow of the river whereas hydropower only transfers the flow regime from one season to another (if evaporation and seepage from the reservoir is excluded). In the simulations, the irrigation of 28,348 ha required an annual average water abstraction of 0.43 km^3, which corresponds to 2.1% of the Sesan River's annual flow of 20.5 km^3. This water volume was taken mainly from the dry season flow. In reality, however, part of the water percolates into the soil and returns to the river. If the average percolation rates reported in Thailand, Vietnam, and Cambodia by Phengphaengsy and Okudaira (2008) are used in this case, 8.8% of water diverted to the fields would percolate. And if further assumed that the percolated water returns to the river in the same year of abstraction, the annual flow reduction would be 0.39 km^3 instead of 0.43 km^3.

The annual water loss of 1.9%–2.1% because of the irrigation of 28,348 ha may seem small, but if the same irrigation water abstraction rate is assumed in a situation where the water would be taken directly from the river, and there would be no hydropower operation, the water abstraction resulted in notable depletion of dry season flows [Table 2, Figs. 4(c and d)]. For example, the irrigation water abstraction reduced the flow of February by −29% and −32% at the border of Vietnam and Cambodia and outlet of the Sesan, respectively. Furthermore, on weekly scale, significant water depletion was experienced in the first week of May at the outlet of the Sesan when the baseline flow was reduced by −71% [Fig. 4(d)].

Discussion

The modeling approach developed during this study proved to be successful in simulating a cascade of multipurpose reservoirs, and describing their hydropower generation, potential water abstraction for irrigation, as well as the impacts on flow regimes. Thus as such, the research objectives of the study were able to be fulfilled. Yet, in order to draw a more comprehensive picture of the impacts of multipurpose reservoir development and the usefulness of the developed modeling approach, the view is broadened in this section by discussing additional findings discovered during the modeling process.

Further Findings

During the modeling process, it became apparent that the development of irrigation jointly with hydropower requires good planning and management because of increasing water related interdependencies between the two. For example, downstream projects are dependent on the upstream operations. Both the planning and management should also be transboundary by its nature, as the Sesan Catchment is shared by Vietnam and Cambodia. It was further found that approximately 70% of the dry season flow originates from the Upper Sesan (Vietnam), thus making the Lower Sesan dependent on development and operations in the upper part of the catchment.

It should also be emphasized that the considered hydropower and agricultural development would lead to significant land cover changes. While the existing reservoirs inundate 19,800 ha (198 km^2) of land, the total inundated area would be approximately 103,500 ha (1,035 km^2), if all the planned reservoirs were built. Moreover, if the considered agricultural expansion would be developed, it would cause an extra land cover changes of 28,000 ha (280 km^2). Together, these land cover changes would impact an area equivalent of 7% of the total land area of the Sesan Catchment. Many of the impacted areas are at the moment fully or partly under forest cover. The combined analysis of the project locations, land cover maps (GLC 2000 2003), and satellite images (Google Earth 2013) indicates that the construction of Lower Sesan 3 and Lower Sesan 2 reservoirs and the agricultural expansion downstream of Sesan 4, Sesan 4A, Lower Sesan 3, and Lower Sesan 2 would very likely lead to deforestation. However, more detailed studies would be needed to clarify the exact impact and extent of such changes. The forests in the area have already been progressively transformed into agricultural land (Meyfroidta et al. 2013).

It was further found that the reservoirs of Lower Sesan 3 and Lower Sesan 2 would inundate 16,450 ha and 730 ha, respectively, of highly and moderately suitable land for agriculture (Fig. 1). Thus, although the hydropower reservoirs would provide irrigation potential, at the same time they reduce the overall agricultural potential in the catchment. Lower Sesan 3 reservoir and Prek Liang 1 and 2 projects were also found to impact the Virachey National Park in Cambodia (Fig. 1).

Limitations of the Study

The major limitations of the developed modeling approach are related to the very nature of the approach itself. The models in general are selective conceptualizations of the assessed phenomena, and the composition of the model determines which aspects are included in or excluded from the model, and at which level of accuracy the modeling exercise can be performed.

In this modeling approach, the focus was on technical and hydrological aspects, such as power generation, irrigation potential, and river flows. Because of limitations related to the modeling approach as well as availability of resources and reliable information, broader social, economic, and ecological aspects were not considered. As a result, this approach provides only a limited view on the study area, and as such is not sufficient to understand the broader nature of the dam development impacts (e.g., Wyatt and Baird 2007). Similarly, the institutional, political, and social aspects of proposed irrigation projects and their possible implementation could not be considered. Further, some key aspects related to irrigation were left out from the analysis, including, for example, issues related to water use efficiency and water productivity.

Several other simplifications had to be done during the modeling process in order to keep the study focused. The modeling was carried out with rather coarse resolution data, and the simulation of multipurpose reservoirs was simplified. For example, the land use suitability assessment was performed with spatially coarse data, the simulated hydropower operations were based on the assumption of maximizing annual power generation, and the feasibility of diverting water from reservoirs to agricultural areas was not examined in detail.

In the assessment of the impacts of multipurpose reservoirs on the Sesan's flow regime, all existing water resource developments in the catchment could not be considered because of lack of reliable data. There exists, for example, a large number of small irrigation dams with at least 28,000 ha of irrigated rice in the Upper Sesan in Vietnam (GSO 2013), which were not considered in this study. The cumulative effect of the irrigation of this study and the existing irrigation would probably be larger than the results from the modeling approach suggested, and it is likely that natural, nonregulated dry season flows would be seriously depleted.

Given the uncertainties and simplifications discussed above, the analysis presented in this paper should not be considered as a comprehensive assessment of multipurpose reservoirs' impacts, a development suggestion for the Sesan Catchment, nor a detailed assessment of specific hydropower and irrigation projects. Instead, the modeling approach and its results should be considered as a basis for further discussions.

Future Research Directions

This argues that several modeling approaches applied in the Mekong Region have suffered from the same challenges as this study, being often poor in coupling detailed hydrological analysis with broader social and ecological domains. Despite such shortcomings, the models have been commonly used in water resource related planning and decision support (Johnston and Kummu 2012; Keskinen et al. 2012). The models are further criticized to produce nontransparent information (Käkönen and Hirsch 2009), which has been found difficult to connect with the actual planning and policy making (e.g., Brugnach et al. 2007).

Based on the findings and the past experiences in the Mekong Basin (e.g., Johnston and Kummu 2012; Sarkkula et al. 2007), three future research directions are suggested that would enhance the applicability and appropriate use of the water management models. First, the increasing water resources exploitation and water sharing challenges between different water users require further development in the assessment methods: the use of multiobjective assessment approaches would be needed to promote sustainable and equitable water sharing.

Second, because of the discussed limitations of the modeling approaches, their role in the assessments of development choices and impacts should be actively discussed, and the limitations clearly defined. It is suggested that it would be beneficial to critically discuss what kind of models should be used and what kind of roles the models should play in the assessment processes. For example, performing modeling in participatory context involving various stakeholders (Hage et al. 2010; Liu et al. 2008) would help modeling efforts to focus on the most important aspects.

Third, the knowledge gaps in the relationship of hydrology with ecological, economic, and social domains should be bridged more actively. Although models indicate altered flow regimes, the linkages of such alteration to aquatic and riparian ecosystems have remained poorly understood in the Mekong Basin (some exceptions exist e.g., Arias et al. 2014a). Similarly, although there are several studies and reports about the importance of water systems to local livelihoods in the Mekong and the Sesan (Baird et al. 2002; IUCN 2005; Lazarus et al. 2011; Molle et al. 2009; Wyatt and Baird 2007), their linkage to more technical aspects is often very limited or even nonexisting. Pursuing these three research directions would likely push the water resources–related impact assessments to a more holistic direction in the Mekong.

Conclusions

In this paper, the aim was to assess the potential benefits and negative impacts of a cascade of multipurpose reservoirs, facilitating hydropower and irrigation, in the Mekong by using a model-based approach. The developed approach was applied to the Sesan River, a transboundary tributary of the Mekong. The approach provides a methodology for understanding the relation of multipurpose reservoir development to the water, food, and energy trade-offs, and can be applied in river basins in various regions. The results themselves are characteristic of a tropical monsoon–driven river basin and can therefore benefit the water resources assessment in the Mekong Region and potentially broader in the monsoon Asia.

The results indicate that the development of multipurpose reservoirs would potentially increase rice production and the overall benefits of hydropower projects in the Sesan River Catchment with minor losses in hydropower generation. In this case study, the irrigation of 28,348 ha resulted in the reduction of −1.6% in the total annual hydropower generation of nine dams. However, the results revealed that the development of multipurpose reservoirs would have major impacts on flow regimes and land cover. The dry season flows increased as much as +176%, and the impacts on the river flows originated mainly from hydropower operations. Moreover, reservoir inundation and potential new agricultural areas impacted a land area equivalent to 7% of the Sesan Catchment. These land areas include protected areas, agriculturally valuable land and forest areas. The changes in river flows and land cover are likely to have negative impacts further on the aquatic and terrestrial ecosystems.

In general, the Sesan case study emphasizes that the development of irrigation in conjunction to hydropower results in increasingly complicated management systems and competition between the water users. The multipurpose reservoirs are thus likely to contribute to increasingly complex trade-offs, where ecosystems and their contribution to local livelihoods and food security are put against the broader economic and societal needs. The results provide a technically orientated starting point for further discussion and more detailed studies on the multipurpose reservoirs in the Mekong and more general in monsoon climate conditions. More comprehensive assessments are urgently needed in the Mekong region to fully understand the potential benefits and costs of rapidly progressing water resources development.

Acknowledgments

The work presented in this paper was part of the MK3 Project of the CGIAR Challenge Program on Water and Food in the Mekong (CGIAR 2011) led by ICEM. For transforming the project work into this research article, TR received further funding from the RYM-TO Graduate School, PS from Institute of Technology of Cambodia, MKe from the Academy of Finland (#133748, #269901), and MKu from the postdoctoral funds of Aalto University and the Academy of Finland (#267463). The authors would like to thank the Mekong River Commission, particularly Erland Jensen, for kindly providing the hydrological data for the study. The authors are grateful to Prof. Olli Varis, Peter-John Meynell, and Tarek Ketelsen for their support. The comments and suggestions of editor and reviewers are warmly acknowledged.

Supplemental Data

Tables S1 and S2, Figs. S1–S5, Eqs. (S1) and (S2), and a detailed description of the methods used are available online in the ASCE Library (http://www.ascelibrary.org).

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration—Guidelines for computing crop water requirements." *Irrigation and Drainage, Paper 56*, Food and Agriculture Organization (FAO) of the United Nations, Rome.

Arias, M. E., et al. (2014a). "Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland." *Ecol. Model.*, 272, 252–263.

Arias, M. E., Piman, T., Lauri, H., Cochrane, T. A., and Kummu, M. (2014b). "Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia." *Hydrol. Earth Syst. Sci. Discuss.*, 11, 2177–2209.

Baird, I., et al. (2002). "Community-based study of the downstream impacts of the Yali Falls Dam along the Se San, Sre Pok and Sekong Rivers in Stung Treng province, Northeast Cambodia." Rep. for the Sesan Protection Network Project, Oxfam America, Phnom Penh, Cambodia, 78.

Baran, E., Samadee, S., Shwu Jiau, T., and Tranh Cong, T. (2011). "Fish and fisheries in the Sesan River Basin. Catchment baseline, fisheries section." *Project rep. Mekong Challenge Program Project MK3. Optimizing the Management of a Cascade of Reservoirs at the Catchment Level*, WorldFish Center, Phnom Penh, Cambodia, 61.

Brugnach, M., Andrew Tagg, A., Florian Keil, F., and de Lange, W. J. (2007). "Uncertainty matters: Computer models at the science–policy interface." *Water Resour. Manage.*, 21(7), 1075–1090.

CGIAR. (2011). "CGIAR challenge program on water & food, Mekong Basin challenge, project MK3." ⟨http://www.waterandfood.org/page/Mekong/type:basin⟩ (May 26, 2014).

CGIAR-CSI. (2006). "LUSET—Land use evaluation tool." ⟨http://csi.cgiar.org/CGIARGeoSpatialTools.asp#LUSET⟩ (Jun., 2011).

Darby, S. E., Leyland, J., Kummu, M., Räsänen, T. A., and Lauri, H. (2013). "Decoding the drivers of bank erosion on the Mekong River: The roles of the Asian monsoon, tropical storms, and snowmelt." *Water Resour. Res.*, 49(4), 2146–2163.

Delgado, J. M., Merz, B., and Apel, H. (2012). "A climate-flood link for the lower Mekong River." *Hydrol. Earth Syst. Sci.*, 16(5), 1533–1541.

FAO. (2013). "CROPWAT. Land and water development division of FAO." ⟨http://www.fao.org/nr/water/infores_databases_cropwat.html⟩ (Jan. 15, 2013).

GLC 2000. (2003). "Global land cover 2000 database." *European Commission, Joint Research Centre*, ⟨http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php⟩ (Jun. 15, 2011).

Google Earth. (2013). "Google earth satellite images." ⟨http://www.google.com/earth/index.html⟩ (Dec. 18, 2013).

Grumbine, R. E., Dore, J., and Xu, J. (2012). "Mekong hydropower: Drivers of change and governance challenges." *Front. Ecol. Environ.*, 10(2), 91–98.

GSO. (2013). *GSO online database*, General Statistics Office of Vietnam, Hanoi, Vietnam.

Hage, M, Pieter Leroy, P., and Petersen, A. C. (2010). "Stakeholder participation in environmental knowledge production." *Futures*, 42(3), 254–264.

ICEM. (2010). *MRC strategic environmental assessment (SEA) of hydropower on the Mekong mainstream*, Hanoi, Vietnam.

IUCN. (2005). "Thai Baan research on the ecology and local history of the seasonally-flooded forest in the Lower Songkhram River Basin." *Mekong wetlands biodiversity conservation and sustainable use programme*, International Union for Conservation of Nature (IUCN), Bangkok.

Johnston, R. M., and Kummu, M. (2012). "Water resource models in the Mekong Basin: A review." *Water Resour. Manage.*, 26(2), 429–455.

Käkönen, M., and Hirsch, P. (2009). "The anti-politics of Mekong knowledge production." *Contested waterscapes in the Mekong Region—Hydropower livelihoods and governance*, F. Molle, T. Foran, and M. Käkönen, eds., Earthscan, London.

Keskinen, M., Kummu, M., Käkönen, M., and Varis, O. (2012). "Mekong at the crossroads: Next steps for impact assessment of large dams." *Ambio*, 41(3), 319–324.

Koponen, J., Lauri, H., Veijalainen, N., and Sarkkula, J. (2010). "HBV and IWRM watershed modelling user guide." *MRC Information and Knowledge Management Programme, DMS—Detailed Modelling Support for the MRC Project*, ⟨http://www.eia.fi/⟩ (Jan. 15, 2014).

Kummu, M., Lu, X., Wang, J., and Varis, O. (2010). "Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong." *Geomorphology*, 119(3–4), 181–197.

Labadie, J. (2003). "Generalized dynamic programming package: CSUDP." *Documentation and user guide, version 2.44.*, ⟨http://modsim.engr.colostate.edu/csudp.shtml⟩ (Sep. 15, 2010).

Labadie, J. (2004). "Optimal operation of multireservoir systems: State of the art review." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2004)130:2(93), 93–111.

Lauri, H., Moel, H. D., Ward, P., Räsänen, T., Keskinen, M., and Kummu, M. (2012). "Future changes in Mekong River hydrology: Impact of climate change and reservoir operation on discharge." *Hydrol. Earth Syst. Sci.*, 16(12), 4603–4619.

Lazarus, K., Badenoch, N., Dao, N., and Resurreccion, B. P. (2011). *Water rights and social justice in the Mekong Region*, Earthscan, London.

Liu, Y., Gupta, H., Springer, E., and Wagener, T. (2008). "Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management." *Environ. Model. Software*, 23(7), 846–858.

Meyfroidta, P., Phuong Vub, T. P., and Anh Hoang, V. A. (2013). "Trajectories of deforestation, coffee expansion and displacement of shifting cultivation in the Central Highlands of Vietnam." *Global Environ. Change*, 23(5), 1187–1198.

Molle, F., Foran, T., and Käkönen, M. (2009). *Contested waterscapes in the Mekong Region—Hydropower, livelihoods and governance*, Earthscan, London.

MRC. (2005a). *MRC decision support frame work*, Mekong River Commission, Vientiane, Lao PDR.

MRC. (2005b). *Overview of the hydrology of the Mekong Basin*, Mekong River Commission, Vientiane, Lao PDR.

MRC. (2010). *State of the basin report 2010*, Mekong River Commission, Vientiane, Lao PDR.

MRC. (2011a). *Assessment of basin-wide development scenarios—Main report*, Mekong River Commission, Vientiane, Lao PDR.

MRC. (2011b). *Integrated water resources management-based basin development strategy*, Mekong River Commission, Vientiane, Lao PDR.

MRC. (2011c). *MRC database*, Mekong River Commission, Vientiane, Lao PDR.

Nesbitt, H., Johnston, R., and Solieng, M. (2004). "Mekong River water: Will river flows meet future agriculture needs in the Lower Mekong Basin?" *Water in agriculture*, V. Seng, E. Craswell, S. Fukai, and K. Fischer, eds., Australian Centre for International Agricultural Research, Canberra, Australia, 86–104.

Pech, S., and Sunada, K. (2008). "Population growth and natural-resources pressures in the Mekong River Basin." *AMBIO*, 37(3), 219–224.

Phengphaengsy, F., and Okudaira, H. (2008). "Assessment of irrigation efficiencies and water productivity in paddy fields in the lower Mekong River Basin." *Paddy Water Environ.*, 6(1), 105–114.

Piman, T., Cochrane, T. A., Arias, M. E., Green, A., and Dat, N. D. (2012). "Assessment of flow changes from hydropower development and operations in Sekong, Sesan and Srepok Rivers of the Mekong Basin." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000286, 723–732.

Polimenia, J. M., Iorgulescub, R. I., and Chandrasekaraa, R. (2014). "Trans-border public health vulnerability and hydroelectric projects: The case of Yali Falls Dam." *Ecol. Econ.*, 98, 81–89.

Poulsen, A. F., et al. (2004). "Distribution and ecology of some important riverine fish species of the Mekong River Basin." *MRC Technical Paper No. 10*, Mekong River Commission, Vientiane, Lao PDR.

Rani, D., and Moreira, M. (2010). "Simulation-optimization modelling: A survey and potential application in reservoir system operations." *Water Resour. Manage.*, 24(6), 1107–1138.

Räsänen, T. A., Koponen, J., Lauri, H., and Kummu, M. (2012). "Downstream hydrological impacts of hydropower development in the Upper Mekong Basin." *Water Resour. Manage.*, 26(12), 3495–3513.

Räsänen, T. A., and Kummu, M. (2013). "Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin." *J. Hydrol.*, 476(7), 154–168.

Sarkkula, J., et al. (2007). "Mathematical modelling in integrated management of water resources—Magical tool, mathematical toy or something in between." *Democratizing water governance in the Mekong region*, L. Lebel, J. Dore, R. Daniel, Y. S. Koma, eds., Mekong Press, Chiang Mai, Thailand, 127–156.

Shimizu, K., Masumoto, T., and Hai Pham, T. (2006). "Factors impacting yields in rain-fed paddies of the Lower Mekong River Basin." *Paddy Water Environ.*, 4(3), 145–151.

Singh, A. (2012). "An overview of the optimization modelling applications." *J. Hydrol.*, 466–467, 167–182.

Takamatsu, M., Kawasaki, A., Rogers, P., and Malakie, J. (2013). "Development of a land-use forecast tool for future water resources assessment: Case study for the Mekong River 3S Sub-basins." *Sustainability Sci.*, 9(2), 157–172.

Ty, T. V., Sunada, K., and Ichikawa, Y. (2011). "A spatial impact assessment of human-induced intervention on hydrological regimes: A case study in the Upper Srepok River Basin, Central Highlands of Vietnam." *Int. J. River Basin Manage.*, 9(2), 103–116.

Ty, T. V., Sunada, K., Ichikawa, Y., and Oishi, S. (2012). "Scenario-based impact assessment of land use/cover and climate changes on water resources and demand: A case study in the Srepok River Basin, Vietnam—Cambodia." *Water Resour. Manage.*, 26(5), 1387–1407.

Wyatt, A. B., and Baird, I. B. (2007). "Transboundary impact assessment in the Sesan River Basin: The case of the Yali Falls Dam." *Int. J. Water Resour. Dev.*, 23(3), 427–442.

Ziv, G., Baran, E., Nam, S., Rodriquez-Iturbe, I., and Levin, S. (2012). "Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin." *PNAS*, 109(15), 5609–5614.