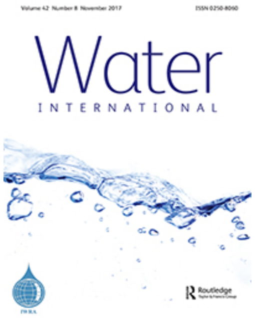

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A cooperative framework for optimizing transboundary hydropower development

Seemanta Sharma Bhagabati[a], Akiyuki Kawasaki[a,b] and Mukand Singh Babel[b]

[a]Department of Civil Engineering, The University of Tokyo, Japan; [b]School of Engineering and Technology, Asian Institute of Technology, Pathum Thani, Thailand

ABSTRACT
Hydropower development may result in water conflicts among the riparian nations, which, however, can be resolved by benefit sharing. An optimization framework is proposed for a transboundary sub-basin following a cooperative game theoretical approach. A broad range of factors at different levels of cooperation between the riparian countries has been used in the optimization model. As an illustration, the framework is implemented in the Sesan and Sre Pok sub-basins of the Lower Mekong Basin. Higher levels of cooperation lead to greater total net benefits as well as greater benefits to individual countries.

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Introduction

The global population is exploding: from 7 billion in the year 2011, it is expected to exceed 9.3 billion by 2050 (United Nations, 2010). Optimum usage of available resources is of paramount importance if the food, water and energy needs of a burgeoning global population are to be satisfied. Hydropower development presents a good alternative. Hydropower is the only renewable energy technology that is commercially viable on a large scale, and it plays an important part in global power generation. Global hydropower production in the year 2008 (3288 TWh) accounted for over 16% of power generation capacity and around 20% of energy produced. Hydropower could double its contribution by 2050, reaching 2000 GW of global capacity and over 7000 TWh (International Energy Agency, 2010). Hydropower has many advantages over traditional energy generation methods. However, in a transboundary context, it has produced some irreversible consequences, such as in the case of the Three Gorges Dam, the Hoover Dam and the Aswan Dam (Dunar & McBride, 1993; Fearnside, 1988; Qiu, 2011). Hence, it is essential to make the best from available resources to achieve maximum returns.

Although optimization may seem fairly easy to achieve in a simple system, in the context of a transboundary sub-basin – that is, where a river basin is shared among two or more countries – it becomes a complex matter. The issue of water resources allocation has triggered transboundary conflicts and critical debates throughout the world. Fair utilization of transboundary water resources is a major and significant

CONTACT Seemanta Sharma Bhagabati seemanta0605@gmail.com

challenge (Paisley & Henshaw, 2013; Tarlock, 2001). While many unilateral, bilateral and multilateral treaties and agreements have been struck on the use of international rivers, these agreements often leave many transboundary issues untouched (De Bruyne & Fischhendler, 2013). This raises concerns about water resources management (Toset, Gleditsch, & Hegre, 2000).

The aim of this article is to provide a framework to improve cooperation among countries for better transboundary watershed management. It includes an optimization model coupled with cooperative game theory. A number of different coalition scenarios, involving no cooperation, partial cooperation and full cooperation, are proposed. The article applies the framework to the Sesan and Sre Pok sub-basins of the Mekong River, to illustrate the benefits to Cambodia and Vietnam of transboundary sharing. Past studies in this field have focused mostly on a single country or sub-basin (Lee, 2012; Rogers, 1969; Suzuki & Nakayama, 1976). Moreover, these studies took into account only a limited number of factors, such as power generation, irrigation, flood control and navigation. In this study, 10 factors are considered, with the intention of optimizing a 'two-country, two-sub-basin' plot. The study includes scenarios with different levels of player participation, in line with formal game theory process. This makes the analysis more realistic, and useful in terms of supporting a basin-wide strategy. By contrast, studies by Xiao and Yang (2007) and Wei, Yang, Abbaspour, Mousavi, and Gnauck (2010) were based on scenarios where countries offered either full cooperation or none at all. Furthermore, this study used practical data, provided by the Mekong River Commission [MRC] or extracted from a GIS database. Never previously has research in the field of transboundary river management incorporated so many factors and levels of player participation.

This article mainly focuses on this new concept of 'scenarios developed with different levels of cooperation among riparian countries' rather than the method of estimating the benefits or cost (because most of the data are already published MRC data). The possibility of partial cooperation makes the framework more realistic for actual implementation of the results for policy making in the context of an international river.

Optimization models

Optimization is a mathematical tool, which uses linear and nonlinear formulations to solve complex problems concisely while analyzing solutions. In simple words, optimization provides the outcome that yields the best result at the highest profit and lowest cost. However, it can also solve complex problems by providing alternative solutions to a disputed issue. Such problems have been solved by using different optimization techniques (Bhagabati, Kawasaki, Babel, Rogers, & Ninsawat, 2014; Loáiciga, 2004; Rogers, 1969; Shah-Hosseini, 2012; Zhang & Huang, 2011).

There are a limited number of modelling packages that provide decision support systems for hydropower development. One is the MODSIM (Modelling and Simulation) model developed by Colorado State University. It can be used to develop a hydropower operations model, which in turn provides information regarding hydropower planning and basin management (Jamali, Abrishamchi, & Madani, 2013). However, this model involves only a single player/country, omitting the cooperation aspects of hydropower development in multiple-player systems. Anghileri, Castelletti, Pianosi, Soncini-Sessa, and Weber (2013) proposed a two-step model to design coordination mechanisms between hydropower producers upstream and irrigation water users downstream. Bhaduri and Liebe (2013) developed a framework for transboundary cooperation in the Volta Basin. This framework was based on a static Stackelberg game involving many scenarios. Although these models result in win-win solutions to the problems, partial-cooperation scenarios are lacking.

Game theoretical optimization models are often used to find possible resolutions to issues of watershed management, especially in the transboundary context. This is explained in the next section.

Game theory

Game theory is the science of strategy and can be used for conflict resolution. It is a mathematical tool to model strategic decisions or interactions among rational or irrational agents. A game is defined as any activity involving two or more players. Players might be persons, firms, stakeholders or nations. Each player recognizes that outcomes depend on their actions and those of others (Myerson Roger, 1991). The fact that the game involves constraints on the actions of players means that game theory is a multi-person decision theory. Thus, it enables analysis of conflicts and rivalry.

With regard to game theory, observed decision behaviour can vary from that predicted by standard or traditional models. In a simple mathematical model the rational and self-interested player will try to maximize his or her payoff unilaterally. In practice, however, players might value reciprocity and equity, and hence choose alternative strategies (Güth, Schmittberger, & Schwarze, 1982). Game theoretical models provide various possibilities for cooperative outcomes based on the coalitions formed among players (e.g. partial cooperation instead of full cooperation), even where conflicting interests exist.

In broad terms, game theory is divided into two classes: cooperative games and non-cooperative games. Cooperative game theory focusses on agreements to allocate benefits and can analyze the cooperative synergy among individuals for equitable sharing of a resource (Madani & Hipel, 2011). In contrast, non-cooperative games consider strategic interactions between players who focus on their own objectives (Rashedi & Kebriaei, 2014).

These games can be further subdivided into transferable utility cooperative games and non-transferable utility cooperative games, zero-sum games, and Nash equilibria. This study is based on a transferable utility cooperative game. Such games, which rely on the principles of core stability and incentive compatibility, are well defined in the relevant literature.

Core stability and incentive compatibility

'Core' is the benefit that is achieved through cooperation among players. If the core is not empty, the scenario is successful, and the results are productive. The size of the core represents the additional benefit that might be gained by the players through cooperation. Mathematically, core is defined as the set of all benefit allocation vectors $\underset{x}{\rightarrow} \in R^N$ which satisfy two conditions (Maschler, Solan, & Zamir, 2013), efficiency:

$$\sum_{j \in N} x_j = v(N) \tag{1}$$

and coalition rationality:

$$\sum_{j \in c} x_j \geq v(c) \forall c \subseteq N \tag{2}$$

where N is the grand coalition including all players and j and v are the characteristic function values.

Efficiency (Eq. (1)) means that the sum of all the players' benefits is equal to the value of the grand coalition. Coalitional rationality (Eq. (2)) states that players are not incentivized to leave the grand coalition to form individual or partial coalitions.

Game theory in water resources management

Water is an essential resource for all life forms. Better allocation and management of water is at the crux of human development. Water resource allocation may sometimes lead to conflicts, which can develop at the individual, community or international level (Wang et al., 2008). In the case of a water conflict, stakeholders can make choices unilaterally or form coalitions among themselves, leading to Pareto-optimal outcomes. Game theory can be an effective language for discussing specific water conflicts. A systematic study of a strategic water dispute provides insights about how the conflict can be better resolved and offers innovative solutions (Madani, 2010).

Numerous methods have been proposed to handle strategic conflicts, including hypergame analysis (Huxham & Bennett, 1983), conflict analysis (Fraser & Hipel, 1984), drama theory (Howard, 1999), and the theory of moves (Brams, 1994), all of which are based on game theory concepts.

Many researchers have used game theory frameworks for water conflict resolution. Parrachino, Dinar, and Patrone (2006) reviewed studies in this field. Rosen and Sexton (1993) analyzed the response of water supply organizations in the western United States to rural-to-urban water transfers. Simon et al. (2007) modelled negotiations over irrigation quotas, water prices and reservoir sizes. Cooperative and non-cooperative studies have also been undertaken for sustainable ground water management (Gardner, Moore, & Walker, 1997; Loáiciga, 2004). Rogers (1969) demonstrated a game theoretic approach for conflict resolution between India and Pakistan (now Bangladesh) over the flooding of the Ganges and Brahmaputra Rivers. Kilgour and Dinar (2001) developed a flexible water allocation rule which guarantees efficient distribution of river flows to countries in a river basin. Teasley and McKinney (2011) developed a game theoretical model to analyze and verify the outcomes of a transboundary cooperative agreement between the four riparian countries of the Syr Darya Basin. Kucukmehmetoglu, Sen, and Ozger (2010) used game theory and fuzzy logic models, while Kucukmehmetoglu (2012) used game theory and Pareto frontier concepts to resolve transboundary issues in the Euphrates and Tigris Basin. Becker and Easter (1995) and Fisvold and Caswell (2000) modelled how water negotiations between the United States and its neighbours can minimize conflict over water usage. Studies on wastewater management and water quality management were completed by Fernandez (2002, 2009) and Sauer, Dvorak, Lisa, and Fiala (2003), while Yaron and Ratner (1990) and Ansink and Rujis (2008) analyzed the economic potential of regional collaboration in water use and the stability of agreements on river water allocation between riparian countries.

Hipel (1992) and Hyde, Maier, and Colby (2005) suggested that with ever-increasing demand on water resource systems, improved cost-benefit analysis can have positive effects on water resource planning, management and policy making. Multi-criteria decision analysis can help in handling water resource planning and management problems.

This literature review shows that cost-benefit allocation and cooperative game theory applications have become the most common applications and/or methods used by researchers in the field of water resources management. A possible reason for this trend is that bargaining and cost sharing in cooperative game theory are familiar concepts for water engineers. As with solutions to simple optimization problems, water resource issues can be solved by having a single objective function that addresses conflicting goals within systems, and a set of constraints.

Development of the framework

The optimization model

An optimization model is a mathematical model designed to help individuals/players allocate scarce resources while making the most of their circumstances. With regard to the optimization of hydropower benefits and costs, a simple mathematical model has been used (Rogers, 1969). Each player (country) has two options: to construct or to not construct extra hydro-electric power plants (HEPs). The principal objective of the model is to maximize the total net benefits in the study area. The grand coalition case seeks to maximize total benefit (Eq. (3)). The model and its various parameters and variables are shown below.

Sets	I	HEPs, identified by project ID
	J	Countries
Parameters	$group_i$	groups based on different stages of HEP
	$country_i$	the riparian countries
	$b_{i,j}$	benefits of HEP i for country j
	$c_{i,j}$	costs of HEP i for country j
Variables	$x_i = \{0,1\}$	HEP decision variable
Constraints	$budget_j$	country's hydropower investment fund
	BCR_i	benefit-cost ratio of the HEP

Objective function:

$$\text{Maximize} \sum_{j \in c} \left\{ \sum_{i \in I} x_i \left[b_{i,j} - c_{i,j} \right] \right\} \forall c \in C \tag{3}$$

where C is a particular coalition scenario from the set of all possible coalitions.

Parameters

In an optimization model, a parameter is a characteristic feature or a measureable factor which can assist in defining the system. Four different parameters were considered in this model:

Group. All HEPs are divided into four groups based on their current status: (1) HEPs currently in operation; (2) HEPs currently under construction; (3) HEPs in the design stage; and (4) HEPs in the master planning stage.
Countries. All HEPs are categorized according to their location, i.e. by country.
Benefits. The benefit components of hydropower activity are evaluated for each HEP. These include benefits from (1) energy production, (2) fisheries, (3) irrigation, and (4) flood control.
Costs. The cost components of all HEPs are calculated. The components are (1) project cost, (2) socio-economic cost, (3) cost of transmission lines, (4) fish loss, (5) environmental loss, and (6) navigational cost.

Economic valuation of benefit and cost components

The selection of these benefit and cost components is based on their importance and data availability.

The following section explains how these benefit and cost components were calculated.

Benefits from energy production. The calculation of benefits from energy production, although seemingly easy, is difficult in the transboundary context. This is because each country has different costs per unit of energy (e.g. $0.213 million/GWh for Cambodia and $0.073 million/GWh for Vietnam). A variety of methods are available for calculating benefits from energy production, including net present value (Hanafizadeh & Latif, 2011), discounted cash flow, replacement cost (Jackson, Finn, & Scheepers, 2014; Teasley & McKinney, 2011), and internal rate of return (Bejbl, Bemš, Králík, Starý, & Vastl, 2014). Since the unit cost of energy differs for each country, we chose the valuation method based on replacement cost, which calculates the benefits from alternative energy production if the country were to produce an amount of energy equivalent to that provided by a HEP (Jackson et al., 2014; Mekong River Commission [MRC], 2011a).

Benefits from fisheries. Benefits from fisheries were calculated using the prices of cultured fish in 2010 (MRC, 2011b). A linear relation between this benefit and the total catchment area was established (based on the individual HEP catchment area) and these benefits assigned according to Eq. (4) (B_f, in USD millions):

$$B_f = \frac{\text{benefit from fisheries}}{\text{total catchment area of the study area}} \times \text{catchment area of the HEP} \qquad (4)$$

Benefits from irrigation. The MRC has estimated the annual net increase in benefit from irrigated crops for countries in the Lower Mekong Basin (Mekong River Commission [MRC], 2011b). Individual country benefit was evenly distributed among the HEPs which have provisions for irrigation. This is represented as B_{i} (in USD millions) (Equation (5)):

$$B_{\mathrm{i}} = \frac{\text{total irrigation benefit of each country}}{\text{number of HEPs constructed for irrigation purposes in that country}} \tag{5}$$

Benefits from flood control. These benefits were estimated by the MRC for Cambodia and Vietnam (Mekong River Commission [MRC], 2011b). The result was evenly divided among the HEPs which have provisions for flood control (B_{fc}, in USD millions).

$$B_{\mathrm{fc}} = \frac{\text{benefit from flood control}}{\text{number of HEPs with provision for flood control}} \tag{6}$$

Project cost. The project cost (per year) was estimated using total cost figures and the capital recovery factor (CRF):

$$\text{Capital Recovery Factor (CRF)} = \frac{\left[(1+r)^{L}\right] \times r}{\left[(1+r)^{L}\right] - 1} \tag{7}$$

where r = discount rate

L = time period

The lifespan (L) of a hydropower project is normally estimated at 50 years, with a discount rate (r) of 10%. On average, annual operation and maintenance costs are approximately 1–2.5% of the total investment (IRENA, 2012). For this analysis we set the annual operation and maintenance costs at 2.5% of the total investment cost. Hence, the annual cost of the project can be calculated:

$$C_i = \text{total investment cost} \times (\text{CRF} + 0.025) \tag{8}$$

For simplicity it is assumed that this cost is borne by the country in which the project resides.

Socio-economic costs. The costs of resettlement, watershed management policies, livelihood and wildlife programmes, compensation for local communities, and public training, are all socio-economic costs of hydropower projects. In the case of the Nam Theun 2 Dam, these costs were estimated at USD 88 million (MIH, 2004). The dam has an installed capacity of 1070 MW, with annual electricity generation of 6000 GWh. The reservoir's capacity is 450 km^2, with active storage of 3680 million m^3. For this study we drew on the socio-economic costs of the Nam Theun 2 Dam for reference. We used a linear relationship between active storage and socio-economic costs:

$$C_{\mathrm{se}} = \frac{88}{3680} A(i) \tag{9}$$

where $C_{\mathrm{se}}(i)$ is the total socio-economic cost of HEP i in USD millions, and $A(i)$ is the active storage of HEP i in million m^3.

Using CRF, we calculated the annual socio-economic costs as:

$$C_{\mathrm{se,annual}}(i) = C_{\mathrm{se}}(i) \times \mathrm{CRF} \tag{10}$$

Cost of transmission lines. Using a simple GIS analysis, the cost of transmission lines was calculated. This calculation was based on the distance between the dam site and the destination grid of the importing country. In terms of the average cost of transmission lines per kilometre, we referred to figures from the Na Bong-Udon Thani Power Transmission Project (ADB, 2007). The estimated cost of the transmission line was USD 28,150 per kilometre. This cost is borne by the country importing electricity.

Fish loss. The MRC has conducted extensive studies in this regard throughout the Lower Mekong Basin (Mekong River Commission [MRC], 2011b). With the catchment area of each HEP in mind, estimates were made of the loss of fish per unit catchment area. From these results, the annual loss of fish for each HEP was estimated.

Environmental loss. Here only the degradation and loss of wetlands and species were considered. The MRC has estimated such losses for the Lower Mekong Basin (MRC, 2011c). A linear relationship between total active storage and total environmental loss was formed, with annual loss then assigned to each HEP based on active storage, C_{e} (in USD millions):

$$C_{\mathrm{e}} = \frac{\text{total environmental loss}}{\text{total active storage}} \times \text{activestorage of HEP} \tag{11}$$

Navigational costs. The loss of navigation due to construction of dams was calculated based on the sub-basin area. The loss was then distributed equally among all HEPs in respective countries to establish the navigational cost of each HEP (C_{na}).

$$C_{\mathrm{na}} = \frac{\text{navigational cost of the country}}{\text{number of HEPs of the country}} \tag{12}$$

Constraints

In an optimization model, a constraint is the condition that the solution must satisfy. In the above optimization model, two constraints have been used: investment funds; and benefit-cost ratio.

Investment funds

The investment fund is the amount each country allocates for investment in hydropower activity. The investment fund is country-specific and is calculated according to the average cost of past and future construction projects in the country. In this study, the higher of the two values (past or future) was rounded-off and fixed as the country's investment fund figure.

Benefit-cost ratio (BCR)

BCR is an indicator that summarizes the overall efficiency of the project. BCR takes into account the total benefit gained by the project versus its total costs. The higher the BCR, the better the investment. With regard to optimization, the top priority was to select the HEPs, within the available fund limits, with the highest BCR. Then the second-best HEP in terms of BCR was selected, and so on.

Scenario development

The scenario approach is a technique used to obtain solutions to robust optimization (RO) problems through the randomization of constraints and involved parameters. RO provides a flexible structure for analyzing stochastic optimization models. In RO, no matter what the constraints turn out to be, the outcome is always feasible and optimal for worst-case objective function. In simple words, RO attempts to find a solution that performs well for any realization taken by the unknown coefficients (Ben-Tal, El Ghaoui, & Nemirovski, 2009; Mulvey, Vanderbei, & Zenios, 1995). RO has been successfully applied in the field of water resources management (Kang & Lansey, 2013; Ray, Watkins, Vogel, & Kirshen, 2014; Watkins & McKinney, 1997). All countries/players have two choices: (a) to construct or not to construct additional HEPs, and (b) to share or not share investment funds (should they pursue construction). Based on these options, the logical combinations (in brackets) that can be proposed are:

- Operational HEPs. The HEPs in operation (Group 1) are selected. [*no construction, no sharing*]
- Complete and under-construction projects. The HEPs in operation (Group 1) and those under construction (Group 2) are considered. [*construction, no sharing*]
- Individual maximization. The countries/players take turns pursuing individual maximization by building HEPs from Groups 3 and 4. This is done with investment fund constraints in mind. While one country/player is maximizing, other countries/players do not build extra HEPs. [*construction, no sharing*]
- Simultaneous maximization. Countries and players maximize simultaneously by sharing their investment funds in varying ratios: no sharing; 25% sharing; 50%; 75%; or 100%. [*construction, different levels of sharing*]

These five levels of sharing, although experimental, give a better idea how partial sharing of funds affects the final output of optimization.

Illustration: a two-country hydropower development model

This study tried to implement a game theoretic model for transboundary hydropower development between two countries, in this case Cambodia and Vietnam. Both of these countries are involved in hydropower development, but not with each other. Vietnam has almost fully utilized its hydropower potential, while Cambodia has only recently started to develop hydropower plants. Despite its efforts in hydropower development, Vietnam produces insufficient energy for its needs, so it has to import electricity from neighbouring countries: Laos and Cambodia. Thus, there is real possibility for a joint hydropower venture between Cambodia and Vietnam.

The Sesan and Sre Pok sub-basins of the Mekong River were selected as the study area. Together, these sub-basins form a large tributary system in the Lower Mekong Basin, with a total area of 49,830 km^2 (Sesan, 18,890 km^2; Sre Pok, 30,940 km^2). This area covers the border regions of the 'Indochina junction'. Around 41% (20,410 km^2) of

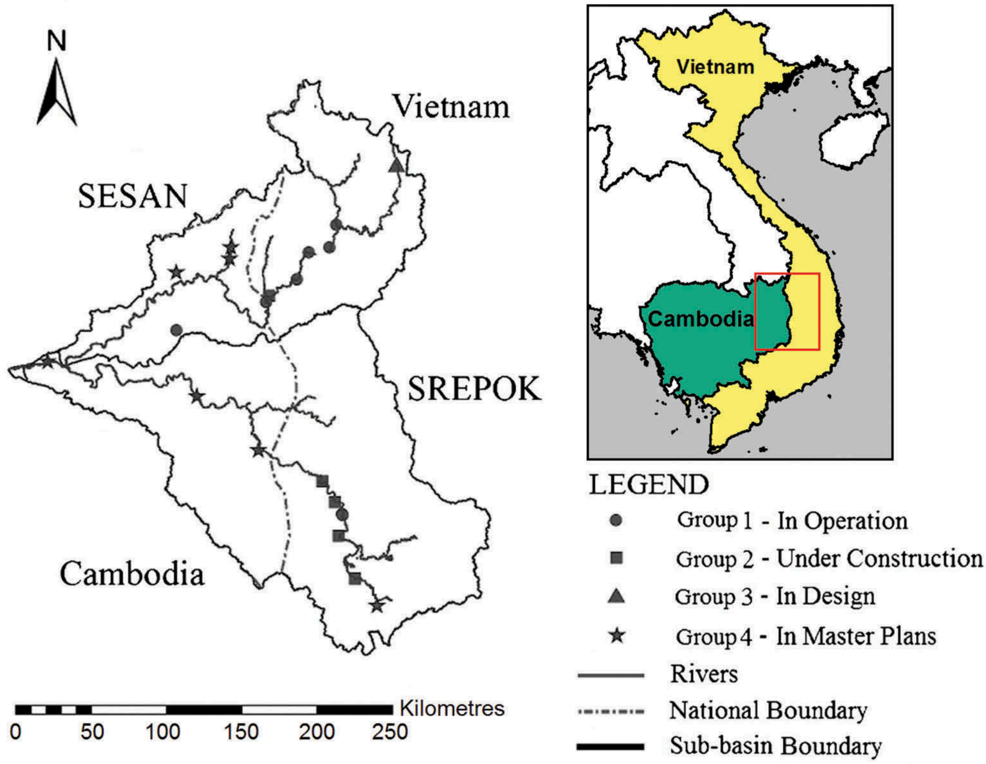

Figure 1. Hydropower plants in the study area.

the study area lies in Cambodia, and the remaining 59% (29,420 km^2) in Vietnam (Ty, Babel, Sunada, Oishi, & Kawasaki, 2009).

Hydropower development is occurring at a rapid pace in both sub-basins. A number of HEPs are already in operation, with a few under construction, and many in the design or master planning stage. As of April 2009, the total number of HEPs was 21 (ADB 2009). HEPs are classified into four groups: Group 1, under operation; Group 2, under construction; Group 3, in the design stage; and Group 4, in the master planning stage. Figure 1 shows these HEPs and the group to which each belongs. More information is provided in Table 1 (MRC, 2009).

This section uses the same data as cited in the previous sections.

Table 1. Status of hydropower plants in the study area.

		Total annual production (Number of HEPs), 10^3 GWh					
	Land area (10^3 km^2)	Group 1	Group 2	Group 3	Group 4	Total	Total reservoir area (10^3 km^2)
Cambodia	25.9	0.003 (1)	0 (0)	0 (0)	6.5 (6)	6.5(7)	106.3
Vietnam	30.1	5.9 (7)	4.6 (5)	1.0 (1)	0.1 (1)	11.8(14)	94.3
Total	56.0	5.9 (8)	4.6 (5)	1.0 (1)	6.7 (7)	18.3(21)	241.1

Source: Mekong River Commission, 2009

Model parameters and constraints

Parameters used

(a) Groups: 1, HEPs in operation; 2, HEPs under construction; 3, HEPs in the design stage; 4, HEPs in the master planning stage.
(b) Countries: Cambodia and Vietnam.
(c) Benefits: (1) energy production; (2) fisheries; (3) irrigation; (4) flood control.
(d) Costs: (1) project cost; (2) socio-economic cost; (3) cost of transmission lines; (4) fish loss; (5) environmental loss; (6) navigational cost.

The total cost and total benefit components for each HEP are presented in Table 2.

Constraints used

(a) Investment funds: these have been estimated at USD 950 million and USD 300 million for Cambodia and Vietnam, respectively.
(b) BCR: as stated in the model, the top priority was to select the HEPs with the highest BCR from the available fund; thereafter, the second-best HEP (in terms of BCR) was selected, and so on.

Scenarios

Four main coalition scenarios (with several sub-scenarios) were selected. The sub-scenarios included: no cooperation, partial cooperation and full cooperation between individual investment funds. The main scenarios are:

(A) HEPs in operation: status quo
(B) Complete and under-construction projects
(C) Individual maximization: (a) Cambodia, (b) Vietnam
(D) Simultaneous maximization: Cambodia and Vietnam maximize simultaneously by sharing their investment funds: (a) no sharing; (b) 25% sharing; (c) 50% sharing; (d) 75% sharing; (e) 100% sharing.

Results and discussion

Results of optimization

As per the results of optimization presented in Table 3, Cambodia currently faces a loss of USD 4.2 million (Scenario A). This loss results from the downstream costs of HEPs constructed by Vietnam along the Cambodia–Vietnam border. Once all the HEPs currently under construction are built (Scenario B), this cost for Cambodia will rise by a further USD 3.2 million. The situation is very different for Vietnam. At present (Scenario A), Vietnam derives a benefit of USD 246.4 million from hydropower activity. This will increase greatly (by USD 176.3 million) as the five HEPs under construction (V06, V09, V10, V12 and V13) are completed (Scenario B). Moreover, with Vietnam

Table 2. All HEPs with results of economic valuation of cost and benefit components.

Country	Basin	Code	Project	Stage	Purpose	Commencement date (year)	Catchment area (10^3 km^2)	Mean annual production (GWH)	Active storage (km^3)	Project investment cost ($US million)	Total annual costs ($US million)	Total annual benefits ($US million)	Annual net benefits ($US million)	Benefit-to-cost ratio
Cambodia	**Sesan**	C01	O Chum 2	4	Power	1992	0.04	3.00	0.00	7	1.2	0.6	-0.6	0.5
		C02	Lower Se San 2 +Lower Sre Pok 2	1	Power, Flood Control, Fishery	2016	49.2	2,312	379	960.9	133.3	266.9	133.6	2.0
		C09	Lower Se San 3	1	Power	-	15.6	1,977	3,120	1,423.3	188.9	420.3	231.4	2.2
		C10	Prek Liang 1	1	Power	-	0.8	189	110	280.7	35.8	40.2	4.4	1.1
		C11	Prek Liang 2	1	Power	-	0.6	186	180	238.4	30.6	39.5	8.9	1.3
	Sre Pok	C12	Lower Sre Pok 3	1	Power, Flood Control, Fishery	-	26.2	1,102	5,310	1,641.7	223.7	235	11.3	1.1
		C13	Lower Sre Pok 4	1	Power, Flood Control	-	13.8	772	2,700	1,019	137.1	164.1	27	1.2
Vietnam	**Sesan**	V01	Upper Kontum	2	Power	2011	0.3	1,056	123	380.8	49.6	77.1	27.5	1.6
		V02	Plei Krong	4	Power, Agriculture, Fishery	2008	3.2	417	948	226.6	32.8	34.7	1.9	1.1
		V03	Yali	4	Power, Agriculture, Fishery	2001	7.4	3,659	779	741.6	96.8	271.6	174.8	2.8
		V04	Se San 3	4	Power	2006	7.8	1,225	4	300.6	39.7	89.4	49.7	2.3
		V05	Se San 3A	4	Power	2007	8.1	475	4	129.2	19	34.7	15.7	1.8
		V06	Se San 4	3	Power, Agriculture, Fishery	2009	9.3	1,420	264	403.5	54.8	108.2	53.4	2.0
		V07	Se San 4A	4	Flood Control	2008	9.4	0	8	17.5	6.1	0.02	-6.08	0.0
	Sre Pok	V08	Duc Xuyen	1	Power, Agriculture, Fishery	-	1.1	181	413	97.4	15.0	17.4	2.4	1.2
		V09	Buon Tua Srah	3	Power, Agriculture, Fishery	2009	2.9	359	523	155	22.6	30.5	7.9	1.3
		V10	Buon Kuop	3	Power, Agriculture, Fishery	2009	7.9	1,455	15	369.4	48.1	110.7	62.6	2.3
		V11	Dray Hlinh 2	4	Power	2007	8.9	85	2	19.4	4.3	6.2	1.9	1.4
		V12	Sre Pok 3	3	Power, Fishery	2009	9.4	1,060	63	325.1	42.7	77.7	35	1.8
		V13	Sre Pok 4	3	Power	2009	9.6	329	10	58.9	9.9	24	14.1	2.4
		V14	Dray Hlin 1	4	Power	1990	8.9	94	2	0	1.9	6.9	5	3.6

Source: Mekong River Commission (2009, 2011a, 2011b, 2011c).

Table 3. Results of optimization.

Coalition scenarios			Net benefits (USD millions)		
			Cambodia	Vietnam	Total
A	In operation		−4.2	246.4	242.3
B	Complete and under-construction projects		−7.4	422.7	415.3
C	Individual maximization	Cambodia	5.8	422.7	428.5
		Vietnam	−7.4	425.0	417.6
D	Simultaneous maximization (% cooperation)	0%	5.8	425.0	430.9
		25%	5.8	425.0	430.9
		50%	1.5	452.5	454.0
		75%	5.8	450.1	456.0
		100%	111.5	446.3	557.8

being upstream from Cambodia, it can never be affected by hydropower activity in Cambodia. Cambodia is at a significant disadvantage in this regard.

In terms of the individual maximization scenario (C), maximizing for Cambodia reaps the highest total benefit (USD 428.5 million). The benefit for Cambodia in C(i) (USD 13.2 million) is much greater than that for Vietnam (USD 2.4 million) in C(ii). The reason for this trend is that Vietnam is operating at almost full hydropower potential, with little scope for further growth, while Cambodia is just beginning to explore the benefits of hydropower. A large number of HEPs in Cambodia are in Groups 3 and 4. For the no-cooperation Scenario D(i), the two countries maximize together, within individual investment fund constraints. The result is an increase in net benefits of USD 15.6 million (selected HEPs C10, C11 and V08, along with the other Group 3 and 4 HEPs). It should be noted that, even after maximization, some funds are left.

When the countries share 25% of their funds (Scenario D(ii)), the outcome is the same (USD 5.8 million and USD 425.0 million), as the shared fund is not enough to construct additional HEPs (selected HEPs – C10, C11 and V08). When 50% funds are shared (scenario D (iii)), there is a much higher increase in net benefits ($US 38.7 million). This increase is 2.5 times that observed in the earlier case (selected HEPs C11, V01 and V08). In the case of 75% fund sharing (selected HEPs C10, C11 and V01), and although different HEPs will be constructed, net benefits only increase marginally (by USD 2.0 million).

For the 100% cooperation Scenario D(v), completely different sets of HEPs have to be constructed, but this leads to a huge increase in total net benefits (USD 142.6 million). The selected HEPs are C02 and C11 (along with the other Group 3 and 4 HEPs). These HEPs have a much better BCR and therefore yield higher benefits, but the cost of their construction is considerably higher (greater than the previous individual/joint funds). Under the other scenarios these HEPs are not constructed. Under the complete-cooperation scenario, with a higher fund threshold of USD 1250 million, these HEPs are constructed.

As the level of cooperation increases from none to 100%, the change in net benefits increases from USD 15.6 million to USD 142.6 million. In other words, the higher the level of cooperation, the greater the positive change in net benefits. Figure 2 shows the changes in net benefits for the different coalition scenarios.

Table 3 shows that cooperation can lead to greater benefits from hydropower development. The highest individual benefit for Cambodia (USD 119.0 million) is

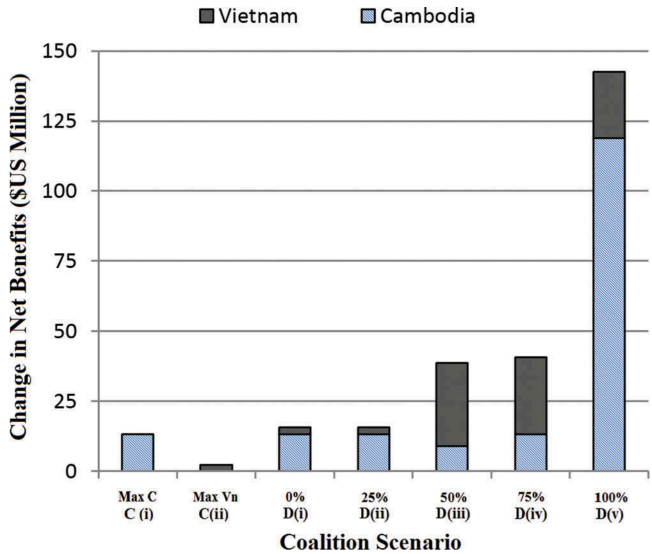

Figure 2. Change in net benefits compared to Scenario B for different levels of cooperation.

achieved through 100% cooperation, yet under this scenario Vietnam receives only USD 23.6 million, which is USD 6.2 million less than its maximum benefit under the 50% cooperation scenario. Vietnam reaps the highest individual net benefits (USD 29.8 million) from the 50% cooperation scenario, under which Cambodia receives only USD 8.9 million, one of the lowest benefits of any scenario. Given that Cambodia and Vietnam favour different levels of cooperation, for the cooperation schemes to be successful there must be economic incentives for individual players to remain in particular coalitions (in this case the 100% cooperation scenario). It has been shown that full cooperation with shared budget planning promises much higher benefits than the other scenarios. A non-empty core indicates the possibility of various benefit allocation strategies. To incentivize all the players to cooperate, benefit sharing must be implemented.

The analysis shows the hydropower potential of Cambodia. Cambodia has many HEPs in the design and master planning stages (Groups 2 and 1, respectively), but a lack of investment funds is hindering these plans and restricting potential benefits. Conversely, Vietnam has funds but no capacity for further hydropower development: its potential in this regard is almost fully exploited, and it is unable to construct more HEPs. Cooperation and benefit sharing between the two countries will allow them both to reap greater benefits, as more cooperation leads to higher total net benefits. In this regard, the 100% cooperation scenario promises the greatest benefit (Table 3).

Core stability and incentive compatibility

Figure 3(a) plots the change in net benefits for Vietnam and Cambodia under the individual maximization and 50% cooperation scenarios. The values are normalized with respect to the total change in net benefits for the 100% cooperation scenario.

On the *y*-axis, the first line (at 6.5) shows the normalized value of the change in net benefits obtained by Vietnam for individual maximization. The second line (at 24.8) is

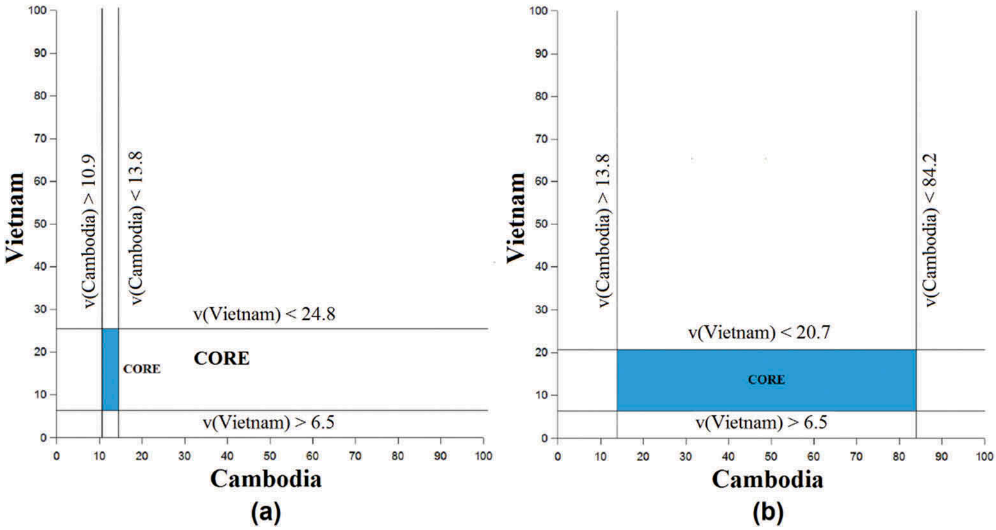

Figure 3. (a) Core for 50% cooperation scenario; (b) core for 100% cooperation scenario. All values are normalized.

the change in net benefits for Vietnam under the 50% cooperation scenario. The values for Cambodia (10.9 and 13.8) are plotted on the *x*-axis. The box thus formed is the core, which is non-empty.

Figure 3(b) plots the change in net benefit for Vietnam and Cambodia under the individual maximization and 100% cooperation scenarios. Normalized values have been used for this graph as well. On the *x*-axis, the first line (at 13.8) is the normalized value of the change in net benefits for Cambodia under the individual maximization scenario, while the second line (at 84.2) represents the change for Cambodia under the 100% cooperation scenario. The values for Vietnam (6.5 and 20.7) are plotted on the *y*-axis. The box formed is the core, which again is non-empty.

The existence of a core means that allocation of benefits between the two countries is feasible, where there are sufficient economic incentives for both to cooperate. The core in Figure 3(b) is much bigger than that in Figure 3(a). This reveals that the possibility of benefit sharing is higher in the case of 100% cooperation.

Sharing the benefits of cooperation

A fair and rational distribution of benefits is essential for the stability of different coalition scenarios. Per the concept of propensity to disrupt (PD) (Gately, 1974), for iii and iv, Cambodia is either incurring some loss or is not gaining any additional benefits (Table 3), and hence, the country's PD is very high. Contrary to this is the situation for v, where Vietnam gains a marginal increase in net benefits compared with huge benefits for Cambodia, resulting in Vietnam's much higher PD. Hence, some rational options of benefit sharing among the countries must be found. Some possible ways of sharing the total additional net benefits from cooperation are:

(a) equal sharing: both countries obtain half of the increase in the total net benefits

(b) based on percentage of investment: Cambodia (USD 950 million) receives greater benefits than Vietnam (USD 300 million)
(c) based on energy requirement: Vietnam, with much higher energy needs (13,340 GWh/y), receives lower benefits than Cambodia (4922 GWh/y).
(d) Based on PD: the country with the higher PD receives greater benefits.

Table 4 lists the net benefits received by both countries following the above sharing options for 50%, 75%, and 100% cooperation scenarios. These results provide some interesting ways to share benefits. Of the four, however, sharing based on percentage of investment and on energy requirements seem the most reasonable.

Policy implications

The results of this research were shared with some of the stakeholders and policy makers in the region, such as the Ministry of Energy and Mines (MEM), Laos; the MRC, Laos; the International Water Management Institute (IWMI), Laos; the Stockholm Environment Institute (SEI), Bangkok; and the International Finance Corporation (IFC), Laos.

According to MEM, the corresponding departments of energy of each country believe that their hydropower development plans are optimized for their own country. However, basin-wide, it is always sub-optimal, which results in high transboundary costs that are often overlooked. Some of the stakeholders (such as MEM and SEI) believe that the results of this research provide a glimpse of the benefits and costs of dams in other countries, and form a basis for advancing relevant and informed discussions. This provides a very significant opportunity to other stakeholders and NGOs to share their knowledge and provide guidance, advice and solutions to mitigate some of the problems. Using these opportunities, structural changes should be made in the current development policies.

Some stakeholders (such as MEM and IWMI) were sceptical about the quality of the data as well as the assumptions used, whereas others (such as MRC, SEI and IFC) believe that the data quality is fine, as it provides a starting point for negotiations. If treaties are formed, specific data can be acquired as needed.

Table 4. Possible ways of sharing the benefits (in million USD).

	Percentage cooperation								
	50%			75%			100%		
	Cambodia	Vietnam	Total	Cambodia	Vietnam	Total	Cambodia	Vietnam	Total
No sharing	1.5	452.5	454.0	5.8	450.1	456.0	111.5	446.3	557.8
Equal sharing	17.4	436.6	453.9	18.4	437.6	455.9	69.3	488.5	557.7
Based on the percentage of investment	23.4	430.5	453.9	24.9	431.0	455.9	102.2	455.5	557.7
Based on the energy requirement	22.7	431.2	453.9	24.1	431.8	455.9	98.4	459.3	557.7
Based on the propensity to disrupt	28.2	425.7	453.9	30.1	425.8	455.9	10.9	546.8	557.7

The officials at MEM and SEI appreciated that all the individual benefits and costs were shared separately rather than only the total net benefit (Table 3). This give policy makers a better understanding of the situation as they can formulate different strategies to negotiate one sector for another sector.

Mitigation planning in the Mekong, especially the Lower Mekong Basin, has a poor record. Even when these results were shared with different stakeholders, they had mixed opinions about the data model as well as the results. These stakeholders held different perspectives and interests. The only way to proceed is through mutual communication and planning that leads to joint investments. The significant question is how to optimize hydropower production while still in mutual agreement with other riparian countries. Such a situation can be resolved by transformative action by pursuing a sustainable development agenda. In the earlier stages of the development of hydropower plants, periodic interventions by other riparian countries should be permitted to achieve the Sustainable Development Goals. Hence, a holistic approach in developing hydropower policies for sustainable hydropower development is of utmost importance.

Conclusion

The article has presented a framework for optimizing hydropower development in transboundary watersheds. Different coalition scenarios were proposed, and optimization performed. A wide range of results, such as individual maximization, and joint maximization with partial and full investment funds sharing, were examined. Although full cooperation is the ideal scenario in that it promises the highest total net benefit, it is difficult to achieve such cooperation between two or more countries: the reality is that few countries are willing to construct or invest in projects beyond their own borders. More likely are partial investments that test the effectiveness of the concept and the possibilities for cooperation. Accordingly, it is important to consider alternative cooperation scenarios and model their potential benefits. A wide range of results will provide policy makers with diverse options, enable better decision making, and increase the possibility of actual cooperation.

This framework uses strong and reliable data, calculated by MRC. As individual HEP-specific data were not always available, however, some assumptions and simplifications were necessary. Such simplifications may generate results that are not perfectly accurate for individual HEPs. Were improved data to become available, the model could be recalibrated without difficulty. Also important to note is that NGOs have been raising concerns about downstream costs in the Sesan and Srepok sub-basins for over a decade. As it stands, there is little to no information about changes in the hydrology of the area and other environmental impacts.

This study shows us the different levels of benefit that result from varying levels of cooperation, thereby providing different benefit-sharing possibilities A number of different benefit-sharing options were also discussed.

Different stakeholders responded differently to these results. While some were more interested in the modelling aspect, others were concerned about the data used. This provides a good insight into the current situation and helps us identify the softer aspects of this study. These topics can act as the starting point for discussions among the stakeholders. The analytic approach used in this article may assist the governments of riparian countries to communicate with each other about transboundary watersheds, and to develop policies and schemes to protect their river basins. In the context of hydropower development, the outcomes of this study may provide a basis for equitable economic development in the region.

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