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Abstract

This paper develops a hydro-economic optimization modeling framework to assess the economic consequences and potential trade-offs of various infrastructure development and policy pathways in the Nam Ngum Basin (Lao PDR). We considered whether large shifts in water resource demands in a relatively water abundant basin could induce meaningful economic trade-offs among water uses, including hydropower generation, irrigation expansion, flood control, and transboundary water transfer objectives. We constructed a series of sensitivity scenarios under dry, average, and wet hydrologic conditions with varying levels dam development, irrigated agricultural expansion, agricultural returns, flood control storage restrictions, and water diversions to Northeast Thailand. We also considered how flows into the Mekong would be affected by these collective developments. In general, results indicate that tradeoffs between hydropower production, irrigation, and flood control are modest. Hydropower and agricultural expansion are found to be complimentary under high levels of water availability, even with the most ambitious level of irrigation expansion. Allowing for flood control by maintaining reduced storage levels in the reservoir that is largest and furthest downstream on the Nam Ngum (NN1) has a minimal effect on economic output and decreases total system hydropower by less than 1%. However, economic outcomes are highly dependent on water availability and economic returns to irrigated agriculture. System hydropower was greatly reduced, and inter-basin transfer projects induced large economic costs under dry conditions. These results on seasonal impacts illustrate the importance of accounting for climate variability and potential hydrologic change in cost-benefit analysis of infrastructure projects, even in watersheds that are relatively water abundant.

Keywords: Optimization; water resources management, Mekong River, Lao PDR, hydropower, irrigation

1. Introduction

As rapid economic development continues in South East Asia and the Lower Mekong Basin, demands for both food and energy will continue to rise (FAO 2010; IEA 2012). With these rising demands come challenges associated with regional management of water resources, creating increased competition between different users and Mekong River riparians, and putting new and greater pressure on surrounding ecosystems (Ringler 2001; Friend et al. 2009; Ziv et al. 2012). Lao PDR, one of the least developed economies in the Mekong region, is also one of the most active in pursuing hydropower and agricultural development (Grumbine and Xu 2011; Matthews 2012). With its rivers contributing 35% of Mekong flows and its strategic location between the booming economies of China, Vietnam, and Thailand, Lao PDR is uniquely situated to deliver hydropower to both domestic and regional markets, and has ambitions of becoming the "battery of Southeast Asia" (Bardacke 1998; MRC 2005; ICEM 2010). The country has 10 dams now in operation, eight under construction, and 82 under license or in planning stages nationwide, together representing more than 20,000 MW (ICEM 2010).[1] Yet the basin-wide implications of such projects are a matter of some controversy (Molle et al. 2009; Bangkok Post 2011; Pearse-Smith 2012), and the degree to which hydropower-based economic development is consistent with other socioeconomic and environmental objectives in Lao PDR (e.g. irrigation, fisheries, flood control) has scarcely been explored.

In fact, the Lao government is also keen to utilize its water resources to pursue irrigation expansion. Much of the new irrigated area would be located in or would use water from the Nam Ngum Basin (DWR 2008). Covering 7% of the country's land area, the Nam Ngum Basin is home to roughly 500,000 people, representing approximately 9% of Lao PDR's total population (WREA 2008). Its flows contribute 4% of mean annual flows and up to 15% of dry season flows of the Mekong River (Lacombe et al. 2012). The vast majority of existing food production and expansion potential from the Nam Ngum occurs in the Vientiane Plain, which is home to one of the nation's most agriculturally viable land areas, with great potential for irrigation expansion (WREA 2008). Several new irrigation projects are in various stages of planning as part of a larger government strategy to turn the basin into a national and regional production area for rice and vegetables. The most ambitious of these proposals would increase irrigated area by more than 100,000 hectares (Geotech 2012). There have also been recent discussions of diverting flow from the Nam Ngum (or Mekong) River to water-scarce areas in northeast Thailand via a large inter-basin transfer just upstream of its confluence with the Mekong.[2]

However, like many rivers in Lao PDR, the Nam Ngum attracts the most economic interest for its hydropower potential. The basin already includes three dams built primarily for hydropower production. Two of these projects were completed in the last three years (representing 255 MW of

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[1] Lao PDR far exceeds any of the other lower Mekong countries, with Vietnam second in developing its hydropower potential, with seven currently operating projects and five under construction, but only two in planning stages.

[2] This proposal is not uncontroversial. However, due to the relative water stress of this region, water wealth in the Nam Ngum, and long-term efforts of the Thai government to significantly expand rice production, it is likely to resurface in future negotiations over water sharing.

installed capacity), another is under construction (120 MW), and seven more (373 MW) are in various stages of planning (EPD 2012; Lacombe et al. 2012). These developments are seen as critically important for meeting current and future energy demand in the rapidly growing cities and towns throughout the lower Mekong in Thailand and Vietnam, as well as Vientiane, the capital of Lao PDR.

Determining the viability of the dual strategy of irrigation and hydropower expansion requires careful analysis to understand whether energy generation objectives would be consistent with delivery of water required by additional irrigation development. As is the case with much of recent hydropower development in the developing world, however, the dam projects in the Nam Ngum are planned in piecemeal fashion and independently managed, with only minimal consideration of their cumulative and basin-wide economic and hydrological impacts (Jeuland 2010). The lack of coordination is evident in recent controversies and observed flood damages from poorly-managed water releases during high flow events (Bach et al. 2012). This is in part due to an insufficient understanding of the economic value of the country's vast water resources, with revenues from electricity generation at individual dams sometimes overshadowing potential trade-offs with other important economic sectors like agriculture, aquaculture, or with the nonmarket value generated by subsistence fisheries or other hydrological services (Grumbine and Xu 2011).

This paper develops an optimization modeling framework for assessing the economic consequences associated with various infrastructure development paths in the Nam Ngum Basin. The model is then parameterized with the latest hydrological, water use, and technical and economic project-specific data. Our goal is not to conduct a comprehensive economic analysis of different packages of potential infrastructures, but rather to understand whether different energy generation, irrigation, and flood control objectives can be achieved across alternative water availability scenarios, focusing specifically on potential economic tradeoffs among them. To do so, we use a hydro-economic model that optimizes the economic benefits from basin-wide power production and agricultural production, subject to constraints such as flood control and environmental flow requirements. The model allows us to measure the cost, in terms of lost power generation, that might emerge from constraints developed to protect assets and ecosystems located downstream from hydropower dams. We model dry, normal, and wet years as selected from the wide range of variability in historical flows, since this variability appears to include the range of projections of average climate change for this region (Lacombe et al. 2012). Importantly, the model assumes that operation of control infrastructures in the basin would be coordinated across dams and over time, and thus represents an upper bound on the economic production that would be possible. The Nam Ngum being such an important tributary to the Mekong, we also consider how flows into the larger river would be affected by these collective developments. We also study the degree to which downstream flow requirements or large-scale demands for water transfer to Northeast Thailand would reduce the economic benefits generated in the Nam Ngum Basin. Though such water transfers are not currently under serious consideration, they have been in the past, and could re-emerge in the future. Thus, we place our results for this basin in the wider context of Mekong Basin development (Ringler 2001; Lauri et al. 2012), without however attempting to evaluate the economics of changes in the Mekong hydrograph.

The remainder of the paper is organized as follows. In the next section, we provide additional background on the Nam Ngum Basin and the various development proposals advanced for increased utilization of its water resources. We then develop the model and discuss data sources and parameterization in Sections 3 and 4. Section 5 presents results, and a discussion follows in Section 6.

2. Background

2.1. Existing Literature

A large number of hydro-economic optimization modeling studies have been developed and applied to river basins around the world (Rogers and Fiering 1986; Harou et al. 2009; Jeuland 2010), but only two have focused on the Mekong or its sub-basins. In a basin-wide analysis, Ringler and Cai (2006) applied an optimization model to analyze trade-offs between dam development on the main stem of the Mekong and the value of downstream fisheries and wetlands located around the Tonle Sap Lake in Cambodia. The analysis revealed clear tradeoffs between consumptive and in-stream uses, with the largest occurring between fisheries and agriculture, and wetlands and municipal and industrial uses. Ultimately, due to the geographic scope of the study, the Mekong Basin model is fairly coarse in resolution, requires numerous assumptions due to significant data gaps, and is limited to considering development projects on the Mekong main stream. Nonetheless, the study is useful for describing the economics of competing sectors of production from water resources in the basin: hydropower, agriculture, and ecosystem services such as fisheries.

Similarly to ours, the second analysis was conducted for an important sub-basin of the lower Mekong. Ringler et al. (2006) use an economic optimization model for the Dong Nai catchment, a sub-basin located downstream in the Vietnamese Mekong Delta, to assess the impacts of changes in water management policies in the basin, including improvements in irrigation efficiency, changes in cropping patterns or reservoir operations, and the establishment of water rights trading mechanisms. Contextually, the Dong Nai is a very different basin than the Nam Ngum, however. In particular, the Dong Nai is already highly developed and densely populated, and competition among water users in irrigation, domestic water consumption, and hydropower generation is already acute. The authors do not therefore include new infrastructure projects in the analysis. The Nam Ngum, in contrast, was until recently fairly undeveloped, with the exception of the Nam Ngum 1 dam and the relatively limited irrigation located in the Vientiane Plain; it therefore provides an opportunity to consider somewhat different questions related to the economics of new infrastructure projects.

Though there have been few studies of the economics of different infrastructure development strategies in the Mekong Basin, studies of the drivers of hydrological and other changes affecting the river abound (Lauri et al. 2012; Räsänen et al. 2012). These studies point to important developments in hydropower and irrigation (King et al. 2007; Keskinen et al. 2012), climate change (Vastila et al. 2010; Kingston et al. 2011; Lauri et al. 2012), and land cover change, water diversion, and urbanization (Kummu and Sarkkula 2008). This collective work points to the important effects that would result from alterations of the natural flood pulse of the river, which would significantly perturb several of its key ecological functions (Kummu and Sarkkula 2008; Ziv et al. 2012).

Modeling efforts specific to the Nam Ngum, though much more limited, have also been carried out, with a particular focus on the effects of new infrastructure proposals. Broadly speaking, these studies fall into two basic categories: studies that describe or estimate the social and environmental impacts of specific projects, especially new dam proposals (ADB 1996; ADB 2007; Vattenfall Power Consultant AB 2008); and more comprehensive research that analyzes development scenarios to better understand the basin's water balance and future water availability (SCI 2004; WREA 2008; Agence Francaise de Developpement and Asian Development Bank 2009; WREA et al. 2009; Lacombe et al. 2012). The most comprehensive of these studies, Lacombe et al. (2012), finds that hydropower projects enable the full suite of irrigation expansion plans in the Vientiane Plain, while preserving required ecological flows and increasing dry season contributions from the Nam Ngum to the Mekong. The analysis shows that such expansion would not be feasible without dam storage; however, it is also worth noting that hydropower projects reduce the flood peak in the river by roughly 20% in an average year.

In general, the Nam Ngum Basin studies do not consider the effects that new water control infrastructures would collectively have on ecosystems, fisheries, and downstream flooding. In addition, to date, there has been no comprehensive economic assessment to understand the nature of synergies or tradeoffs between development options, and to understand the cumulative impacts on the basin from their optimal economic management.

2.2. The Nam Ngum Basin

The Nam Ngum River extends from its uppermost regions above the Plain of Jars in the Xiengkhouang plateau south into the expansive Nam Ngum 1 reservoir and the Vientiane Plain, and down to its confluence with the Mekong near the Lao capital of Vientiane (Figure 1). With the exceptions of these two large plains the basin is mostly hilly and mountainous, with elevations ranging from 2820 meters above sea level at the Phou Bia peak (the highest mountain in Lao PDR), to the lowest low point of 155m at the confluence with the Mekong. The basin is the fourth largest in Lao and covers an area of 16,700 km^2 (or 7% of the total area of the country). It comprises 18 development districts spread across five provinces in Lao, and represents 2% of the total area of the Mekong basin (and provides 4% of its mean annual flow). The climate of the basin is tropical, with two distinct seasons powered by the East Asian and Indian monsoons. The wet season begins in June and ends in October and the dry season spans from November to the end of May. Mean annual rainfall across the basin ranges from 1,500 to 3,000 mm, with an average of 2,000 mm per year (WREA 2008).

The hydrology of the downstream portions of the basin is heavily influenced by the regulation provided by the 155 megawatt Nam Ngum 1 (NN1) dam and its enormous 370 km^2 reservoir just upstream of the Vientiane Plain. Prior to construction of NN1, average flows in the mainstem of the Nam Ngum River through the Vientiane Plain ranged from approximately 150 m^3/s in the dry season to 3,000 in the wet. Today, though, flows range from roughly 300 m^3/s to 1,500 m^3/s; the hydrograph has thus significantly changed, which theoretically allows for greater water use during the dry season (Lacombe et al. 2012). Due west of the NN1 catchment, the large tributary system of the Nam Song and Nam Lik rivers flows around the dam, its confluence with the Nam Ngum River lying just downstream of NN1's outflows to the Vientiane Plain. A diversion completed in 1996 transfers a portion of flows (the capacity of this transfer is about 400 m^3/s) from the Nam Song River directly into the NN1 reservoir, for the purpose of increasing hydropower generation. There are also two major interbasin diversions into the Nam Ngum Basin from neighboring catchments outside the basin: the Nam Leuk, east of NN1 and completed in 2000, diverts flows into the NN1 reservoir via the Nam San River (roughly 100 m^3/s capacity) and the Nam Mang 3 dam, completed in 2005, which diverts flows into the Nam Khan River in the Vientiane Plain (Figure 1).

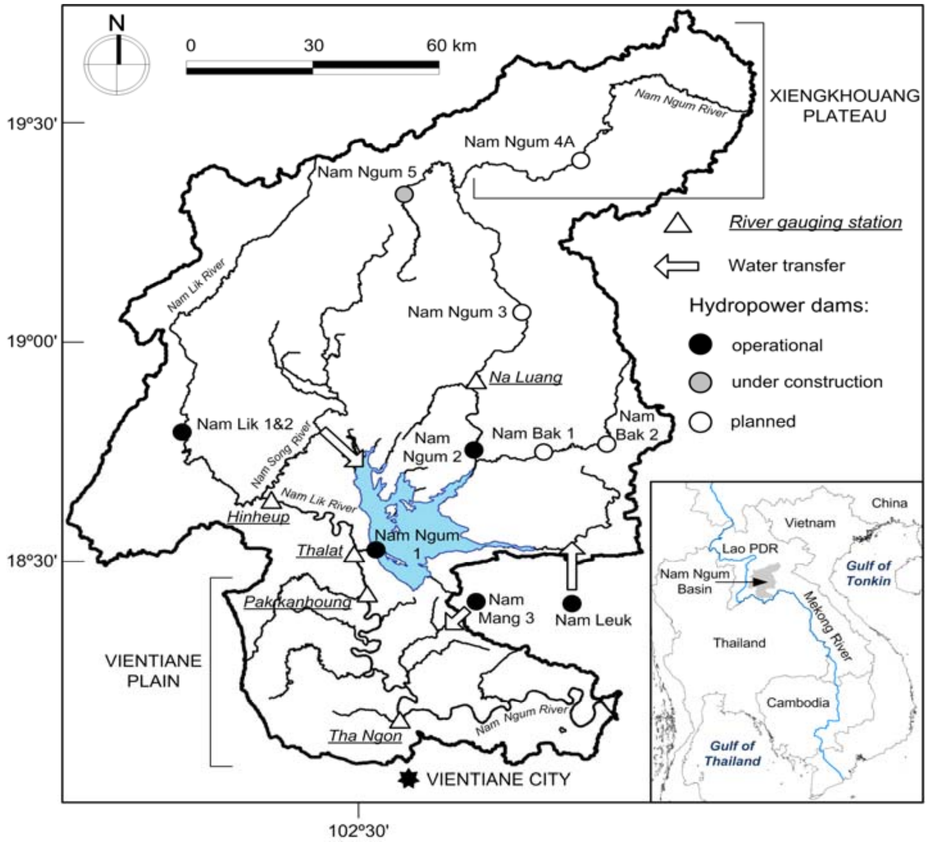


Figure 1. The Nam Ngum Basin, including current and planned hydropower dams

The Nam Ngum basin is largely rural: small villages and population centers are found along main roads and in the Xiengkhouang Plateau and Vientiane Plain, with some peri-urban areas and the majority of the population (300,000; about three fifths) found at the southern end of the basin in the city of Vientiane. Forest covers roughly 50% of the basin, with shrub land, bamboo, and re-growing forest covering roughly one third, and cropped areas about 10% (WREA 2008). Subsistence-based agriculture is the main form of livelihood generation, and 75% of the population in basin provinces report agriculture as their primary form of employment in the 2005 national census. The fifth province, which comprises Vientiane Municipality, is mostly urban; two thirds of people there reported non-farm income as their main activity in 2005. Industrial activity in the basin is very limited (WREA 2008).

The wet season irrigation present throughout much of the Lower Mekong region also occurs in the Nam Ngum Basin (Mekong River Commission 2010), with lowland and upland rice being the most cultivated crops, followed by maize and a mix of vegetables. Dry season irrigation is currently much more limited due to a number of factors, including insufficient returns on investment, limited infrastructure, high operation and maintenance costs, insufficient capital investment to expand irrigation networks, and probably also resistance to adoption of new modern farming practices (UNEP and AIT 2001; Setboonsarng et al. 2008). The main dry season irrigation areas are on the Xiengkhouang Plateau and in the Vientiane Plain, with the plain accounting for roughly 75% of the basin's dry season irrigation and the majority of its large-scale irrigation infrastructure. Forty-two pumping stations and a number of concrete, brick, and dirt canals were built in the Vientiane Plain along the main stem of the Nam Ngum River during the 1990s (Lacombe et al. 2012). Current government plans obtained from the Department of Irrigation call for an increase of roughly 5,000 hectares at three of these pumping stations during the next five years, with feasibility studies being carried out for much greater expansion in the coming decades, including 120,000 ha of new gravity-fed irrigation in the Plain (Geotech 2012). This large development plan would utilize diverted flows from the Nam Lik River and the Nam Ngum reservoir. The government also hopes to expand production in the Xiengkhouang Plateau, on a more limited scale (WREA 2008).

Table 1. Current and Future Dams in the Nam Ngum Basin

	Status	Type	Year Operational	Capacity (MW)	Intended Market
Nam Lik 1-2	Operational	Reservoir	2010	100	Lao PDR
Nam Ngum 1	Operational	Reservoir	1971	155	Lao PDR/Thailand
Nam Ngum 2	Operational	Reservoir	2011	615	Lao PDR
Nam Ngum 5	Under construction	Reservoir	2012	120	Lao PDR/Vietnam
Nam Bak 1	Proposed	Reservoir	Unknown	88	Thailand
Nam Bak 2	Proposed	Reservoir	Unknown	60	Lao PDR/Thailand
Nam Ngum 3	Proposed	Reservoir	2014	440	Thailand
Nam Ngum 4A	Proposed	Run-of-river	Unknown	45	Lao PDR/Vietnam
Nam Ngum 4B	Proposed	Run-of-river	Unknown	45	Lao PDR/Vietnam
Nam Ngum Downstream	Proposed	Run-of-river	Unknown	70	Lao PDR
Nam Ngum Downstream 2	Proposed	Run-of-river	Unknown	5	Unknown
Nam Lik 1	Proposed	Reservoir	Unknown	60	Unknown

Notes: Operational years and intended markets are currently unknown for some proposed projects, as they are still in feasibility assessment stages. Source: Compiled from ADB, 1996; International Rivers, 2009; EPD, 2012.

The other major component of current basin development plans is the construction of new hydropower facilities. There are a total of 13 dams in various stages of operation (3 dams; 870 MW), construction (1 dam; 120 MW) and planning (9 dams; 813 MW) in the basin (Table 1). Four of these planned projects are run-of-the-river dams that would not store water. There is very little irrigated area around the planned dam projects; thus the area of lost farmland due to construction of such infrastructures would likely be minimal.

3. Modeling Framework

In this section, we describe the mathematical structure of the model used to assess potential economic and hydrologic trade-offs of various development pathways in the Nam Ngum Basin. This economic optimization model is a nonlinear mathematical programming model that maximizes net returns to regional economic activities that rely on water as a primary factor of production (principally, irrigated agriculture and hydropower generation).

3.1. Model Schematic

We characterize the Nam Ngum system as a series of links (river reaches corresponding to particular sub-catchments) connecting nodes that represent key water infrastructures or river confluence locations (Figure 2). Nodes were classified into four categories: river confluences; hydropower projects (reservoirs with hydroelectric turbines); surface diversion points; and irrigation pumping stations located along the river system. Node types were further separated into categories of "existing" and "proposed," depending on their current status, as determined from basin planning documents from the Department of Irrigation (DOI), the Ministry of Energy and Mines (MEM), and NGOs working in the Lao hydropower sector. Proposed project nodes were then assigned to different development scenarios based on these categorical classifications (see Section 4.5). The schematic only includes the most important surface diversions in the basin, and does not include connections to groundwater systems.

3.2 Model Objective

As with many other previous economic models applied to river basin management, water is allocated over space and time to optimize net economic returns to the combined agriculture and energy system. The time-step for the model is monthly. The objective function of the model maximizes the net returns to hydropower ($HydroBenefits_i$) and agricultural profits ($AgBenefits_i$) across all months (t) and modeled river "nodes" (i) within the system (expressed by Equation 1), over the course of a modeled year. Nodes refer to any modeled point or area along the watershed and can include confluence points between tributaries, or locations where water is regulated, consumed, stored, or diverted.

$$maximize\ \pi = \sum_{i=1}^{I}(HydroBenefits_i + AgBenefits_i) \qquad (1)$$

The model constraints are described below.

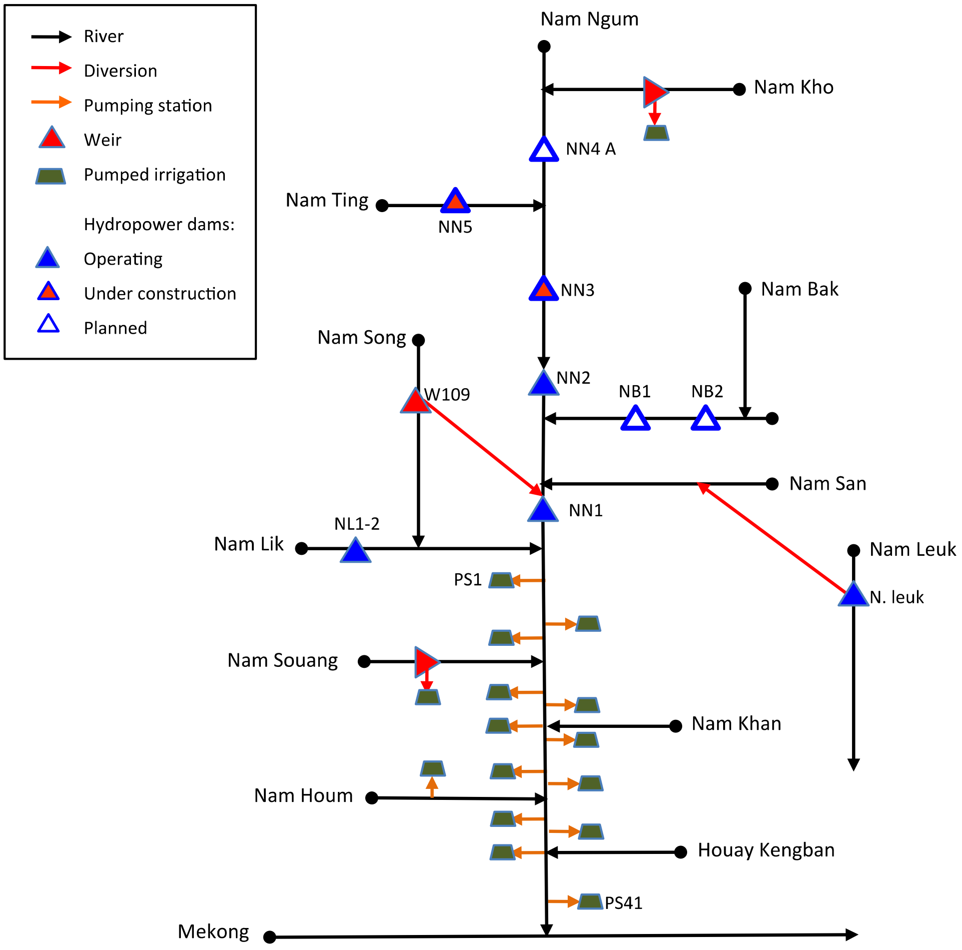


Figure 2. The Nam Ngum River basin node-link hydrological schematic

3.3. Flow continuity constraints

$$Inflow_{it} + W_{i-1\to i,t} = W_{i\to i+1,t} + (1-\delta)W_{it}^{Ag} \quad \forall\, i,t \tag{2}$$

$$Inflow_{it} + W_{i-1\to i,t} + NetRain_{it} + WS_{i,t-1} = W_{i\to i+1,t} + WS_{i,t} \tag{3}$$

The continuity constraints ensure proper accounting of the water quantities flowing through the system, from upstream reaches towards the downstream. Equation 2 depicts the continuity flow conditions for intermediate nodes without storage, whereas equation 3 dictates the continuity of flows at hydropower dams. The optimization procedure uses inflow data to initiate the flow of water within the system; node-specific virgin inflows ($Inflow_{it}$) were thus calculated for each node. The first constraint then requires that the sum of natural inflows ($Inflow_{it}$) and releases from upstream nodes ($W_{i\text{-}1i,t}$) equate to all releases ($W_{i\to i+1,t}$) and irrigation withdrawals (W_{it}^{Ag}), for intermediate nodes. The term δ in equation 2 accounts for the fraction of flow that returns to the river system from irrigated areas (a 30% return flow rate is assumed for this analysis, as in other similar analyses where irrigation canals are unlined – see for example Wu et al. (2012)). For hydropower dams, the flow continuity constraints also account for net rainfall (precipitation less evapotranspiration) over the storage reservoir ($NetRain_{it}$); and the ability to store water flows over time (as represented by time variation in the stock variable WS_{it}). Thus, for dams in the system, the sum of all inflows in *t* and storage in *t-1* must equate to total storage and releases in the current time step.

3.4. Hydropower production and turbine outflows

Net outflow from hydropower dams comes from two sources that are determined endogenously by the model: turbine outflow (which dictates energy output), and spillway outflow (for periods of water abundance, i.e. when dam storage exceeds the spillway level). Let *D* be the set of all nodes that are active hydropower nodes in the system, equation 4 illustrates the net outflow relationship for hydropower facilities:

$$W_{i\to i+1,t} = TurbineOutflow_{i\to i+1,t} + SpillwayOutflow_{i\to i+1,t} \quad \forall\, i\ \in D \tag{4}$$

Equations 5 and 6 govern hydropower production by month, which is a function of turbine outflow, plant efficiency (ϕ_{it}), gravity, and net head—the difference between the storage height variable and the turbine intake height (which is a fixed parameter specific to each dam):

$$Hydro_{it} = TurbineOutflow_{i\to i+1,t} \cdot NetHead_{it} \cdot \emptyset_{it} \cdot 9.81 \tag{5}$$

$$NetHead_{it} = StorageHeight_{it} - TurbineIntake_{it} \tag{6}$$

Linear functions with slope coefficients β_i and intercept terms were used to approximate the relationship between storage height and volume for each reservoir. This relationship is summarized in Equation 7:

$$StorageHeight_{it} = \ \alpha_i + \ \beta_i \cdot WS_{it} \tag{7}$$

Additionally, we impose minimum and maximum bounds on storage volume, storage height, net head, turbine outflow, and spillway outflow. The lower and upper bounds correspond to the characteristics of specific dams (such as storage capacity, maximum height, and turbine intake levels). Dam specific parameter values are show in Table A1 in the Appendix. In addition, minimum and maximum bounds are imposed on the proportion of hydropower produced, by dam, in any given month:

$$\theta^{min} \cdot Hydro_{it} \leq {}^{Hydro_{it}}\!\Big/\!{}_{\sum_{t=1}^{12} Hydro_{it}} \leq \theta^{max} \cdot MaxHydro_{it} \tag{8}$$

Equation 8 is a behavioral constraint on operations that ensures that an arbitrarily large (or small) amount of energy is not produced by specific dams during particular months. These parameters were formed using observed energy output data at the NN1 dam from 1999-2010. For each month, we calculated the average and maximum proportion of monthly energy output to total energy produced during the calendar year. The average proportion parameterizes the lower bound (θ^{min})

on the left-hand side of the equation, while maximum monthly proportions (θ^{min}) are used for the upper bound constraint. The minimum and maximum values vary by month, and serve as lower and upper bounds, respectively, on the proportion of energy each dam can produce in a given month. For simplicity (and due to a lack of observed data for additional dams), we assume the same relative monthly proportions hold for each dam.

Revenue generated at each dam is the product of hydropower generation (in megawatt hours) and the electricity price ($ per megawatt-hour). Eqation 9 shows the net benefits to hydropower, which are calculated as the sum of revenue over all months less annualized capital costs of dam construction and maintenance (assuming a discount rate equal to 5% and a lifespan of 50 years).

$$HydroBenefits_i = (\sum_{t=1}^{12} Hydro_{it} \cdot P^e) - CapCostsHydro_i \tag{9}$$

Where P^e is the unit price of energy and $CapCostsHydro_i$ are the annualized capital costs calculated for each dam.

3.5. Flood control constraints

To allow for flood control upstream of the Vientiane plain, we limit total storage in NN1 to be less than some threshold below full capacity. The purpose of this constraint is to allow for excess storage capacity at the largest dam in the system in case of a flood event, which would provide protection downstream farmers and inhabitants from extreme flows. Equation 10 depicts the flood control constraint for this system:

$$WS_{\mathrm{NN1},t} \leq \gamma * StorageCapacity_{NN1} \quad for\ t = Wet\ Season \tag{10}$$

Where γ is a user-defined proportion set to 1 when flood control constraints are not active. For this study, wet season months include May through October.

3.6. Agricultural production

In optimizing overall net returns from water use, the model allocates water for irrigation (W_{it}^{Ag}), and solves for the corresponding total productive area for crop j (L_{ij}) associated with each withdrawal node in the system. Total irrigated area for all crops cannot exceed the initial land endowment (L_i^{max}) plus the expansion potential at node i ($LExp_i^{max}$):

$$\sum_{j=1}^{J} L_{ij} \leq L_i^{max} + LExp_i^{max} \tag{11}$$

We model crop production in areas irrigated with Nam Ngum water using three composite crop groups: rice, cereals (including maize), and fruits/vegetables. Area weighted prices and yields (exogenous model parameters which were specified at the district level) for each composite crop type were formed by dividing commodity-specific yields and prices by the total area for the crop group, as shown in equations 11 and 12. For example, if k represents the set of crops within composite crop group j, then the following equations were applied to generate a time series of yield ($\mathrm{Y_{ij}}$) and price P_{ij}^{Ag}.

These calculations were performed for all years in the time series for which we have provincial-level statistics. We took the mean and maximum values for yields and prices over the time series to produce high and low profit conditions. The "high returns" case is based on data from the year 2009, while "low returns" parameters were formed using average yield and price estimates over the full time series. High agricultural returns denote the baseline yield and price assumptions, which is justified given the trends in high global commodity prices that have been observed in recent years. Furthermore, use of high yield and price parameters encourages irrigation expansion, allowing one to evaluate potential trade-offs between uses, or effects of irrigation expansion on watershed hydrology.

$$Y_{ij} = \sum_{k=1}^{K} \frac{Yield_k}{Area_k} \quad \forall\, k \in J \tag{12}$$

$$P_{ij}^{Ag} = \sum_{k=1}^{K} \frac{P_k}{Area_k} \quad \forall\, k \in J \tag{13}$$

Similar to the yield and price parameters, an area-weighted procedure was used to generate crop water requirements for each composite crop type. Equation 14 then equates monthly irrigation withdrawals to these crop water requirements, where ϕ_{ijt} represents the theoretical crop water requirement for crop group j and μ is the irrigation canal efficiency (assumed to be 50% at all nodes):

$$W_{it}^{Ag} = \frac{\sum_{j=1}^{J} \emptyset_{ijt} \cdot L_{ij}}{\mu} \tag{14}$$

Equation 15 then denotes total profits (or economic benefit) generated from irrigated production at each node:

$$AgBenefits_i = \sum_{j=1}^{J} \left\{ \begin{array}{c} L_{ij} \cdot \left[P_{ij}^{Ag} \cdot Y_{ij} - C_{ij} \right] \\ \left[(L_i^{max} + LExp_i^{max}) - L_{ij} \right] \cdot [-\kappa - \eta] \end{array} \right\} \tag{15}$$

In this equation, C_{ij} represents cultivation cost, and the parameters κ and η represent per-hectare capital costs for land conversion and irrigation canal expansion, respectively (annualized at 5% discount rates, and assuming a lifespan of 25 years).

Crop area allocation at each node is restricted to avoid corner solutions (i.e. unrealistic conversion of all irrigable land to a particular type of crop) and to reflect appropriate area totals that are consistent with observed crop mixes. Following MAF (2010) and conversations with MAF officials, we assume that 80% of all new irrigated area is dedicated to rice production, while 20% is allocated to grain production. While this does not allow for flexibility in crop mix decisions for new irrigated area, it is consistent with expected development plans in the basin. Here, we calculated the minimum and maximum ratio of observed area by proxy crop to total observed irrigated area for the years of available data (see next section). The ratio of projected area (by crop) to total cropland use at each node was then constrained to lie between these minimum and maximum area proportions:

$$MinCropArea_j \leq \frac{L_{ij}}{\sum_{j=1}^{J}\left(L_{ij}^{max}-L_{ij}\right)} \leq MaxCropArea_j \tag{16}$$

3.7. Instream flow protection and terminal constraints

Finally, we impose three additional management constraints on river flows and/or dam operations. First, an instream flow constraint is implemented to preserve minimum levels of unregulated outflows from the basin. This constraint ensures that the minimum amount of flow flowing into the Mekong is at least equal to the historical low flow in the river. Consistent with Lacombe et al., 2012, this outflow constraint is set to 94 m^3/sec., or approximately 247 million m^3 per month:

$$W_{i\rightarrow \text{Mekong},t} \geq MinInstreamFlow_t \quad \forall\, t \tag{17}$$

Second, we specify a target withdrawal for the proposed water transfer to Northeast Thailand. To do so, we add an intermediate node to the schematic just upstream of the Mekong confluence. Water transfers at this point are required on a monthly basis. This essentially reduces net flows to the Mekong River by a constant amount on a m^3/sec. basis. This process augments equation 17, forming a new minimum outflow constraint given when the Thai transfer is active, as shown by equation 18.

$$W_{i\rightarrow \text{Mekong},t} \geq MinInstreamFlow_t + ThaiTransfer_t \quad \forall\, t \tag{18}$$

Finally, we restrict final reservoir storage conditions to protect against the model systematically depleting storage in the later months of the optimization period in an effort to maximize hydropower and/or other water use. This constraint requires that final storage at each reservoir must fall within +/- 5% of the initial storage condition. Initial storage is defined as the December storage condition obtained using simulated flow data for the year preceding the rainfall scenario year (Lacombe et al. 2012):

$$0.95 \cdot InitialStorage_i \leq WS_{it} \leq 1.05 \cdot InitialStorage_i \tag{19}$$

4. Data and analytical approach

This section presents the Nam Ngum model schematic and describes the data used to parameterize the model (Additional details are provided in the Appendix).

4.2. Flow data

Flow data were obtained from the Lao Direction of Meteorology and Hydrology (DMH) for two stations: Ban Naluang on the mainstream of the Nam Ngum River south of the Nam Ngum 2 dam (1985-2004); and Ban Hinheup on the Nam Lik River between the Nam Lik 1-2 and Nam Lik 1 dams (1967-1984). Inflows were then assigned to specific nodes in the model by apportioning historical flows recorded at the main hydrological gauging stations in the Nam Ngum Basin using the catchment method, similarly to the process described in Lacombe et al. (2012). We also use data from Lacombe et al. to define initial reservoir storage conditions. For additional details on the spatial delineation procedure used to calculate inflows at modeled nodes within these catchments, refer to the technical Appendix.

4.3. Hydropower dam characteristics and energy production

Model parameters for current and proposed dams were obtained from basin development reports, project profiles, dam developers, the electricity authority of Lao PDR, Electricité du Laos (EDL), and the Department of Energy Promotion and Development (EPD) of the Ministry of Energy and Mines (MEM). Actual electricity generation data from NN1 for 2009 and 2010, though not strictly necessary for the model, provide a useful comparison with our optimized production estimates for that dam (Electricite du Laos (EDL) 2010). These dam-specific parameters are summarized in Table A1 of the Appendix and are consistent with those used in Lacombe et al. (2012). Price data ($0.07/KW-hr) and electricity generation capacities for existing infrastructures are consistent with the figures presented in annual reports published by EDL (2010).

Capital costs for the dams included in the long-term scenario were obtained from EPD, dam feasibility and impact assessment reports, and NGOs with direct knowledge of the Lao hydropower sector (ADB 1996; International Rivers 2009; SD & XP Consultants Group and Nippon Koei 2009). These costs were normalized to be in constant year terms (2010).

4.4. Crop production data

The main irrigated crop grown in Lao PDR is rice (crop 1). We grouped other cereal crops (group 2) and high value fruits and vegetables (group 3) which are also widely cultivated in the Nam Ngum Basin. Our data for the crop parameters (yields, prices and areas) come from a time series of (2000-2009) of district- and provincial-level agricultural statistics. These parameters are formed at the district or provincial level using the observed agricultural statistics, which are then mapped directly to the node level.

Crop water requirements (per unit area) were estimated for individual crops using CROPWAT 8.0 (UNFAO 2009). CROPWAT calculates irrigation requirements based on climate, soils, and other environmental parameters for each crop, as well as a user-specified cropping calendar. Cropping calendars for Lao were obtained from the Ministry of Agriculture and Forestry (MAF) (MAF 2010; MAF 2010). Due to data limitations, the CROPWAT default parameter values for developmental stage time, crop coefficients and soils were maintained (MAF 2009; MAF 2010; MAF 2010).

Cultivation costs were derived from a survey of roughly 500 farmers in Vientiane Province and the Vientiane Plain (Setboonsarng et al. 2008). Due to data limitations in the survey data, cultivation costs do not vary by crop. For new irrigated areas, estimates of capital costs associated with building new irrigation canals were obtained from DOI. These estimates (in US$/hA) include costs associated with building new reservoirs, weirs, electric water pumps, and lining dirt canals with brick or concrete, but do not include other costs associated with developing new agricultural lands, such as clearing and leveling, which are likely to vary considerably depending on the nature of the lands that would be converted to irrigation.

Additional details on agricultural statistics and parameter development can be found in the Appendix.

4.5. Scenario analysis

Our base analysis consists of 39 different scenarios: three different climatic conditions representing “wet,” “dry,” and “average” hydrology in the basin for five agriculture and hydropower expansion scenarios, including current conditions and maximum expansion, and two different levels of agricultural returns (Table 2). These “wet,” “dry,” and “average” years (2002, 1998, and 1996) were determined by the max, min, and median of total annual flows for the entire basin, as indicated by the flows measured upstream of the confluence with the Mekong River (at Tha Ngon), following data from Lacombe et al. (2012). Agriculture and hydropower scenarios are reasonable best guesses of likely development trajectories in the basin. With regards to hydropower, our model includes three active dams for the current scenario (NN1, NN2, and NL12), and 8 active dams for all long-term scenarios (adding NN3, NN4, NN5, NB1, NB2). Thus, only five of the nine planned dams for the basin are represented; the remaining 4 projects have not been well studied at this time and critical design parameters needed for inclusion in the model are therefore unavailable.

Potential new irrigated areas for agricultural development were divided into three main expansion scenarios: ID1, ID2, and ID3 (Table 2). The ID1 scenario roughly corresponds to roughly a doubling of the detailed expansion plans described by the MAF in its 5 year investment plan (2011-2015), which identified three specific pumping stations to be expanded by a total of roughly 5,000 hectares in the Vientiane Plain (MAF 2010). This scenario expands on the 5 year expansion plan by adding all currently dry paddy fields within 2 kilometers of a water source and whose elevation is lower than that of existing canals. The ID2 scenario further includes nonagricultural bush areas, grasslands, and ponds that are below the elevation of existing canals and within 2 kilometers of existing irrigated areas. Lastly, the ID3 scenario includes a doubling of the irrigated area under production in the ID3 scenario, which approximates long-term plans to expand irrigation in the Vientiane plain by 100,000 hectares (Geotech 2012). The scenarios represent increases in irrigated area of approximately 12,000, 50,000, and 100,000 hectare, respectively, and were modeled using the same spatial delineation procedure as that used by Lacombe et al. (2012).

We also tested the sensitivity of results to alternative assumptions of agricultural returns. Specifically, we examined cases with “low” returns (mean price and yield from 2000-2009) and “high” returns (max price and yield from 2000-2009, which typically corresponds to 2009 values). Our base assumption is “high” agricultural returns, which is justified given recent trends in agricultural commodity markets (OECD/FAO 2012).

To test additional trade-offs between hydropower and agricultural production, we also model the diversion to Thailand and flood controls on NN1 dam in the ID2 and ID3 expansion scenarios. We run separate analyses that include two levels of diversion to Thailand: 150 m^3/s, which SCI (2004) determined could be transferred to Thailand while still meeting irrigation requirements in Lao in an average hydrological year; and 300 m^3/s, which represents the proposed design discharge capacity of the diversion tunnel to northeast Thailand SCI outlines in its feasibility study of the transfer. We also study the tradeoff between economic benefits and flood control. To do so we limit total storage at Nam Ngum 1 during normal and wet years to 90% and 95% of the maximum storage capacity, instead of 100% used for the default scenarios. Note that we do not evaluate flood control under dry hydrologic conditions, as flood control measures are not necessary under dry year conditions when reservoirs are likely already maintained at low levels. Additionally, the 300 m3/sec. transfer to Thailand is infeasible under the driest hydrologic conditions according to model results, so we focus on the implications of this diversion under average and wet conditions.

Table 2. Summary of model scenarios

		Current Conditions	**HP Expansion Only**	**HP + ID1 Expansion**	**HP + ID2 Expansion**[2]	**HP + ID3 Expansion**[2]
	Potential Irrigated Land Area (ha)[1]	**20,759**	**20,759**	**32,064**	**70,172**	**119,147**
	Total dams	**3**	**8**	**8**	**8**	**8**
	Capacity (MWh)	870	1228	1228	1228	1228
Scenario Specifics	**Climate Scenario**					
Agricultural Returns – High & Low[3,4]	Dry	X	X	X	X	X
	Average	X	X	X	X	X
	Wet	X	X	X	X	X

Notes:

[1] Irrigated potential is not fully developed if net returns do not justify capital expansion.

[2] Diversion to Thailand and flood control at NN1 are also considered in separate sensitivity analyses in the ID2 and ID3 expansion scenarios.

[3] High agricultural returns are based on 2009 prices and yields and are therefore used for the sensitivity analyses on flood control and the Thailand water diversion.

[4] Low agricultural returns are also considered in separate sensitivity analyses in the ID2 and ID3 expansion scenarios.

5. Results

Our results provide insights into the potential economic and hydrologic impacts of alternative development pathways in the Nam Ngum Basin across the different hydrological conditions described above. The following sections provide the key results for hydropower production, agriculture and irrigation expansion, net economic benefits, and total basin outflows; additional tabular summaries can be found in the Appendix.

5.1. Hydropower Production

Figure 3 displays the potential increase in system hydropower as the basin moves from a current (three dam) scenario, to a future with eight dams (under average annual flow conditions). The addition of the five dams leads to a substantial increase in hydropower production and net revenue. Average monthly energy production expands from approximately 570 MWh to slightly more than 820 MWh, representing a 44% increase per month on average. While the addition of new dams to the system increases total energy output, hydropower at existing dams does not increase. In fact, average monthly hydropower output at NN1 and NN2 decreases from the current scenario by 15 and 11.6 MWh, respectively, implying greater system flexibility and reduced reliance on individual dams for hydropower.

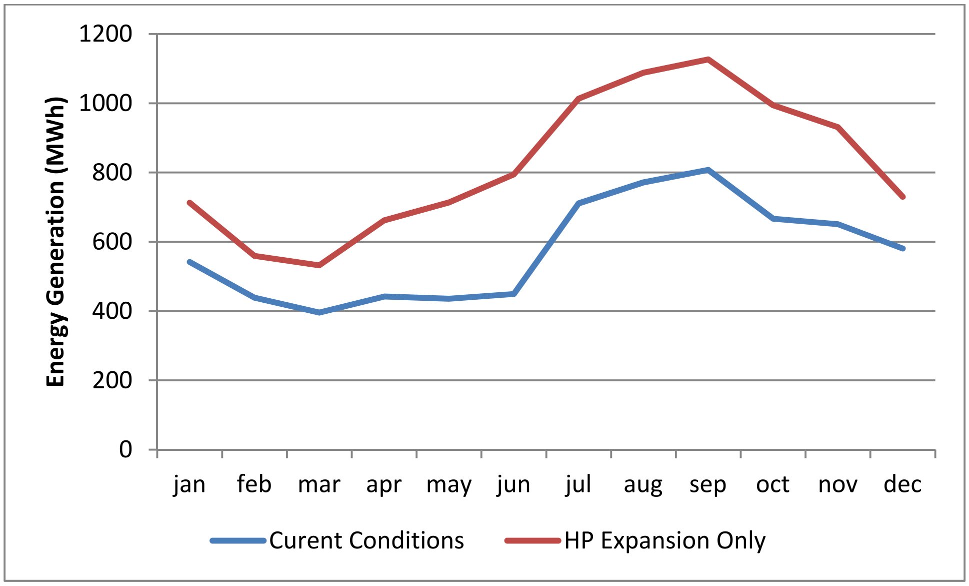


Figure 3. Hydropower expansion from current baseline to 8 dam future scenario

While hydropower potential is dramatically improved with the addition of new dams, total output is highly dependent on climate conditions. Figure 4 displays the variation in optimal hydropower output across the three climate scenarios (assuming no agricultural expansion). In wet years, monthly hydropower output is approximately 9% higher than in the average year (ranging from 600-1150 MW over the course of the year), reflecting additional water availability in the system. Under dry conditions the system is much more constrained by water availability, and hydropower decreases by 61% when all 8 dams are included (to 400-600 MW during the year). This is similar to the 59% decrease obtained with the 3 existing dams. The implication of this result is that adding additional dams increases total hydropower production but that long-term reductions in flow could still reduce hydropower production to levels below historical generation.

While hydropower output varies greatly with water availability, irrigation expansion and other development scenarios do not substantially affect energy output, implying little to no trade-off between irrigated agriculture and hydropower. Figure 5 shows the percent change in total annual hydropower output, by climate condition, across irrigation expansion scenarios. Even under dry conditions, increased irrigation withdrawals do not alter total energy output significantly (less than 1%, even with the greatest area expansion scenario). For the average and wet scenarios, the percent change in total hydropower is less than 1% across all irrigation expansion cases.

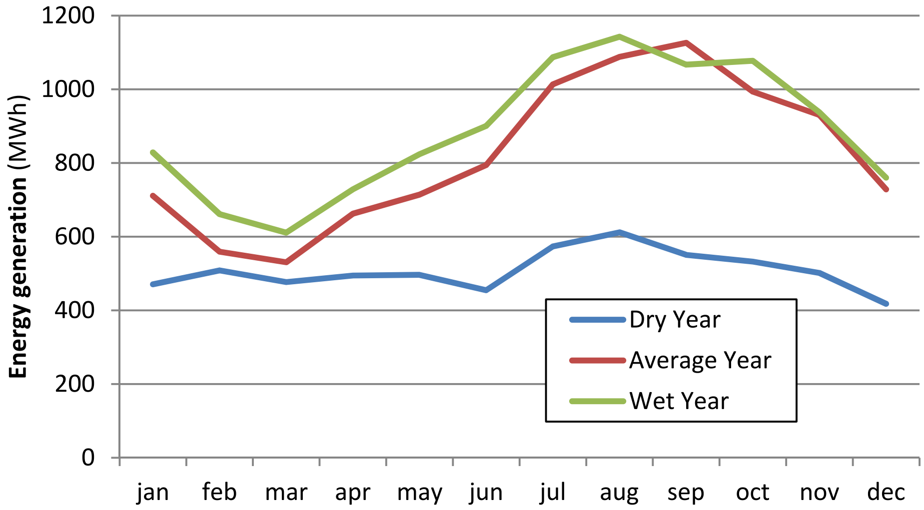


Figure 4. Hydropower generation variation by hydrological condition

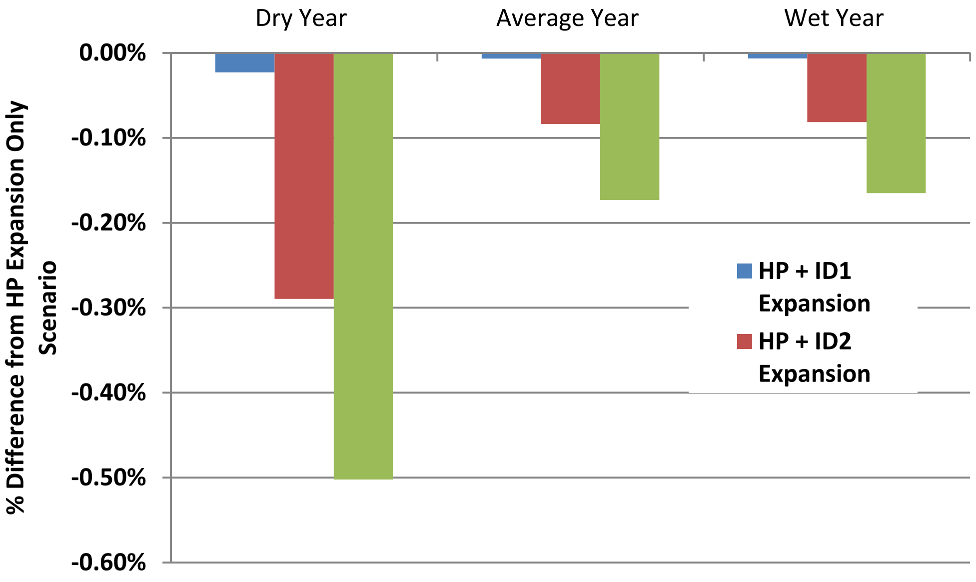
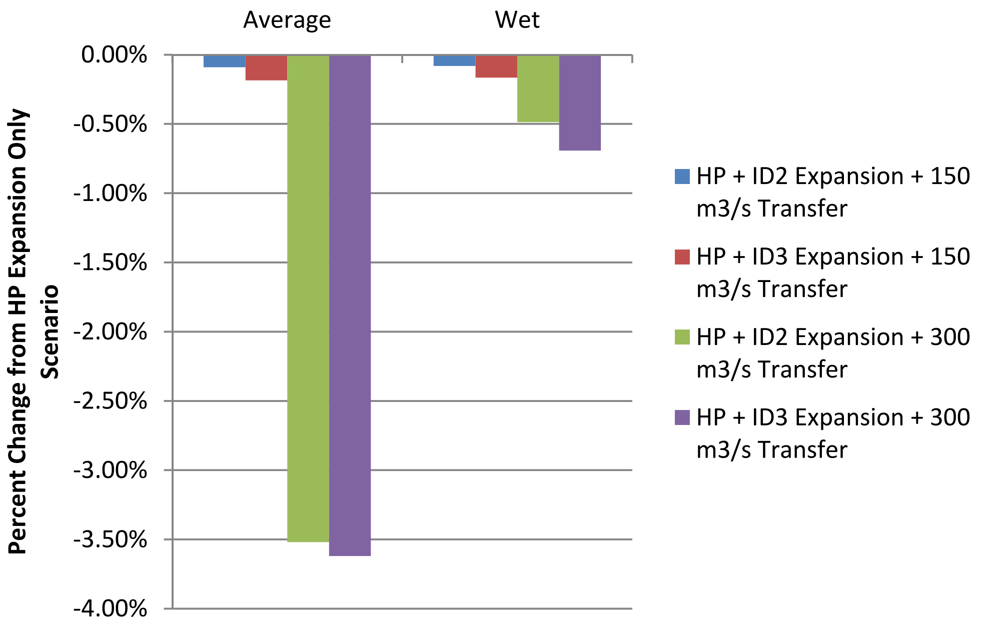


Figure 5. The effect of agricultural expansion on hydropower generation

The water transfers to Thailand and flood control scenarios have a greater impact on net hydropower than irrigation expansion, as shown by Figure 6. A transfer of 300 m^3/s induces a 3.5% and 1% decrease in total hydropower under average and wet conditions, respectively, relative to the 30-year agricultural expansion scenario with no transfer. This reduction in output occurs because temporal flows must be augmented to supply monthly diversion requirements (hence, greater outflows in the dry season which reduces total storage, storage height, and net electricity generation over the course of the year). Flood control also reduces total hydropower, though this effect is very small (less than 1%). Flood control at NN1 changes reservoir management patterns, and inhibits the system's ability to maximize storage height at NN1 for greater hydropower output. This effect increases with the level of flood control required. Additionally, flood control induces a larger hydropower trade-off as irrigation withdrawals increase; as water demands increase in the system, the opportunity costs of flood control constraints increases and the reservoir water storage systematically decreases. To assess the value of flood control at NN1, one would have to compare the reduced hydropower generation with the benefits from enhanced flood control.

5.2. Agricultural Expansion and Irrigation Water Use

To analyze the effects of irrigation expansion, we allow the total land area available for irrigation to expand incrementally in the Vientiane Plain and the Xiengkhouang Plateau, from 20,000 hectares under current conditions to about 120,000 hectares in the ID3 scenario. As detailed in section 3, our methodology does not require that all irrigated area potential be used in all scenarios, but rather allows the model to increase or decrease total irrigated area endogenously depending on water availability, water demands, net returns from irrigation, and other constraints on water use that are specific to a scenario. The crop-mix in irrigated areas is also constrained, to avoid unrealistic crop-production solutions (such as conversion of all land to vegetable farming).



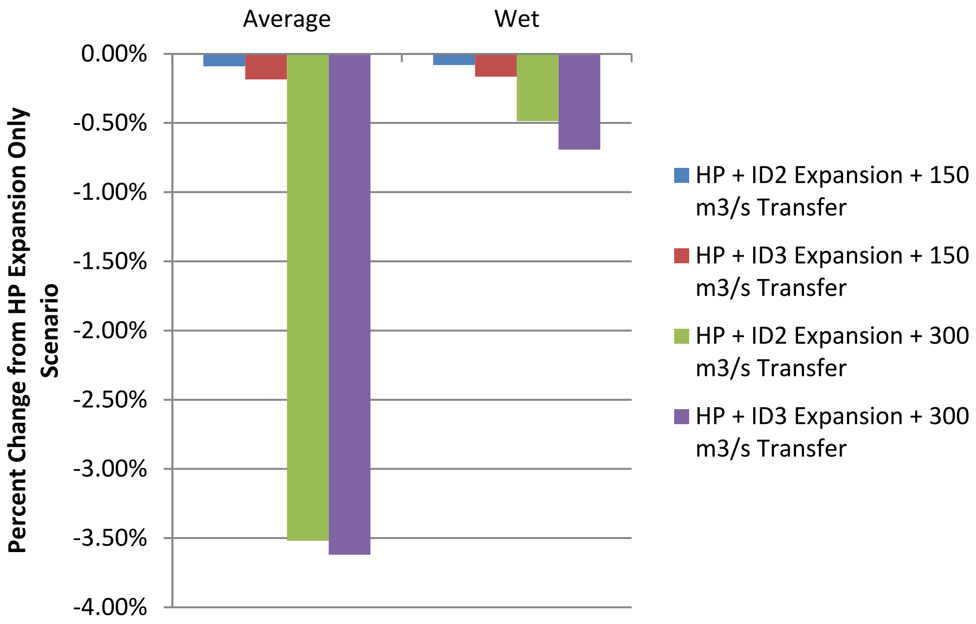
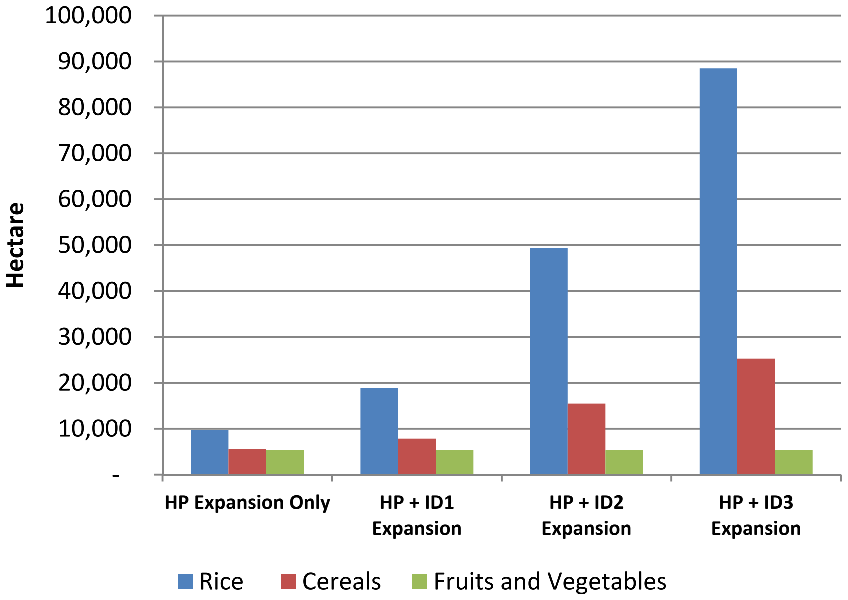


Figure 6: Hydropower production losses with inter-basin transfer to Thailand and flood control scenarios

In most cases, irrigated potential is fully realized. Figure 7 shows total irrigated area, by crop, under average climate conditions. In each case, irrigated area is maximized, rising from approximately 20,000 ha in the baseline to 119,000 under the ID3 expansion scenario. The same result is found for wet year conditions. However, under dry year conditions when irrigation supplies are constrained, area expansion decreases below the maximum bound. For the ID2 and ID3 expansion scenarios, total irrigated area under dry year conditions falls 0.6% and 7.6%, respectively, relative to the average year totals.



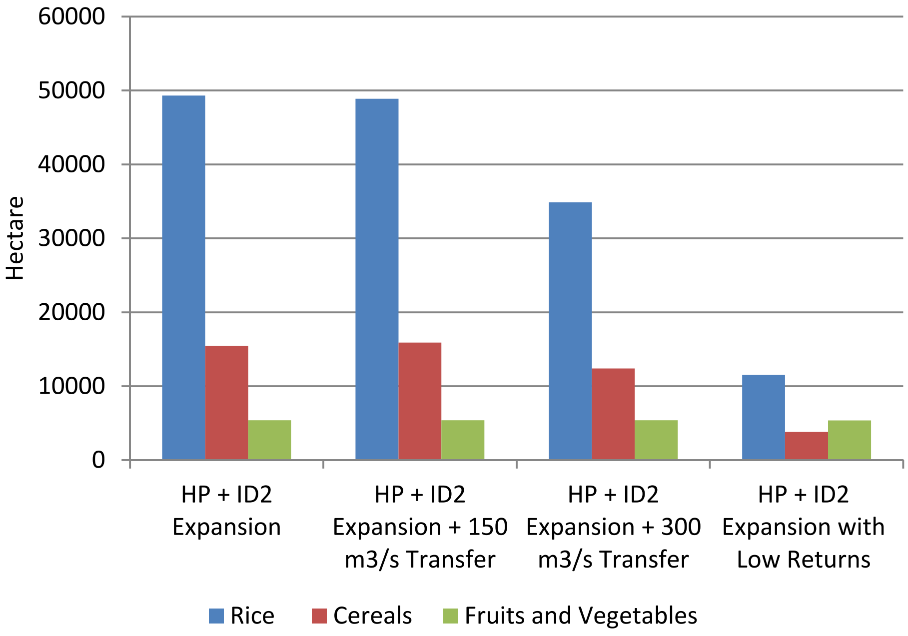


Figure 7. Total irrigated area by irrigation expansion scenario (top) and alternative scenario (bottom)

Furthermore, as the right-hand side of Figure 7 indicates, total irrigated area is not fully realized under all scenarios. In the ID2 expansion scenario, total irrigated area declines when large water transfers are required, or when expected agricultural returns are low. Relative to the ID2 case without the transfer, total irrigated areas with the 300 m^3/s transfer declines by approximately 25%. The 150 m^3/s transfer scenario does not impact irrigated area under average climate conditions, but (if prioritized) decreases agricultural expansion by approximately 60% under dry conditions relative to the ID2 expansion with no transfer. Supplying increased irrigation demands and water transfer requirements under dry conditions would thus be difficult. As the transfer quantity is mandated, this induces a clear trade-off with lost agricultural production in the Nam Ngum. Under wet conditions, transfer requirements do not affect agricultural expansion.

Lower agricultural returns have the largest effect on irrigated area, as total production declines to levels consistent with the baseline condition. These lower returns deliver insufficient economic benefits to justify the additional per-hectare costs for land conversion and irrigation canal expansion. If these additional costs were covered from external public or private sources, then additional irrigated area could still provide positive net economic benefits to farmers, even with reduced agricultural revenues, though the economic case for such financing would likely be weak. Finally, the flood control measures have no impact on irrigated area expansion.

Figure 8 displays total water withdrawals for irrigation (in million cubic meters, or mcm) use across agricultural expansion scenarios for average year conditions. Irrigation withdrawals increase proportionally with the amount of area expansion, rising from approximately 262 mcm with no area expansion to almost 1,400 mcm under the ID3 expansion case. Results show minor changes to total withdrawals between the dry, average, and wet year scenarios under the ID2 and ID3 scenarios. These differences are caused by slightly reduced irrigation withdrawals in the Xiengkhouang Plateau, where flows are very low under dry conditions.

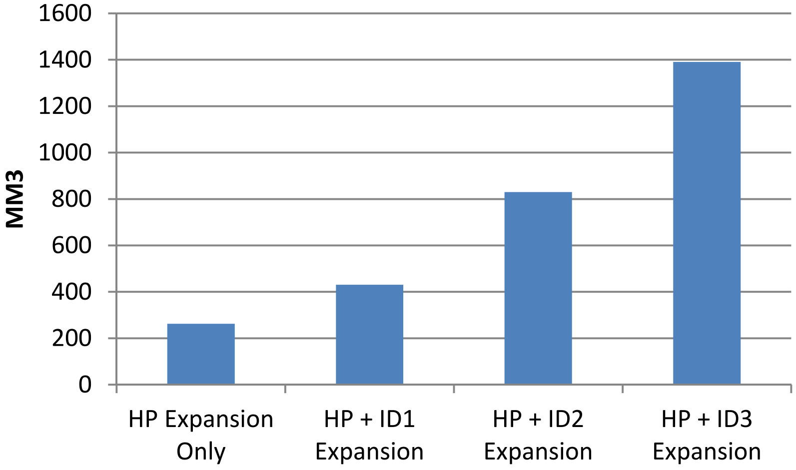


Figure 8. Agricultural Water Use across Agricultural Expansion Scenarios

Figure 9 displays the proportion of irrigation withdrawals to total basin outflows on an annual basis. This figure illustrates how irrigation expansion could potentially reduce total outflows to the Mekong annually, and how this varies with water availability (with the largest proportions found for dry years). Under future baseline conditions with no agricultural expansion, this proportion is less than 2% for all climate scenarios. This range expands to 3%-6% for the ID2 expansion, and 5%-10% for the ID3 case.

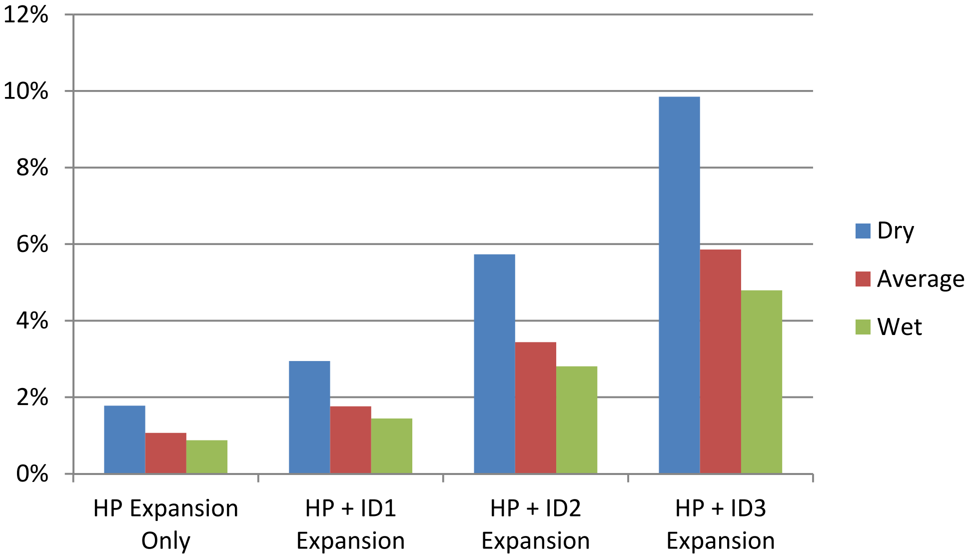


Figure 9. The proportion of irrigation withdrawals to total basin outflows (annual)

5.3. Economic Benefits

A detailed summary of total economic benefits for the modeled development scenarios is provided in tables 3-5, which represent dry, average, and wet hydrologic years. These results reveal several key findings. First, there is a substantial difference between the net economic benefits derived under dry, average, and wet conditions, suggesting that both hydropower and agricultural profits are highly sensitive to changes in watershed hydrology (though these sensitivities may be overstated since economic returns have been assumed to be the same across scenarios, which ignores the potential for price adjustments to mitigate these variations). Total economic benefits are 30%-38% lower under dry conditions than under average conditions, with the majority of this difference attributable to reductions in hydropower output. The difference in economic benefits between average and wet conditions is smaller, but not inconsequential, ranging from 3.5% to 7.5%.

The net economic benefit of hydropower development in the basin is found to be approximately $28 million, $98 million, and $112 million, respectively, under dry, average, and wet conditions. These projects would therefore provide a significant boost in economic activity from energy generation and consumption. Using a current GDP measure of approximately $8.3 billion per year in Lao PDR, the macroeconomic benefit of dam development under average conditions would equate to a 1.2% increase in annual economic output if all benefits accrued in Lao, though it is likely that some export power would be exported (World Bank, 2012). Of course, these estimates do not include the economic costs associated with resettlement or reduced livelihoods for activities displaced by the reservoir construction, for which data currently are not available.

Agricultural expansion would also deliver net benefits in the region. In contrast to hydropower, irrigation benefits only increase modestly with water availability, since there is relatively limited irrigation potential in the Nam Ngum, and it can be developed even under dry conditions. The difference in net benefits of irrigation expansion under different water availability scenarios is driven by subtle changes in the optimal crop mix and water release schedule from hydropower dams. The net benefits to ID1 expansion range $5.3-5.6 million relative to a no expansion case. This range expands to $15-16 million under ID2 expansion, and $30-32 million under ID3. The divergence in additional economic benefits to irrigation expansion between dry and average/wet conditions expands with the level of irrigated area potential. This implies that with increased economic opportunities for water consumption and lower water availability, there is a slightly increased trade-off between hydropower and agricultural expansion as temporal flows are adjusted and upstream flows are diverted for irrigation.

However, net benefits from agricultural expansion are dramatically reduced under the "low returns" scenario. In this case, the capital costs of land conversion and irrigation canal expansion would lead to negative profits for production activities on new land, so the expansion, assumed to have a constant cost per unit area, does not occur. In addition, profits on existing lands are reduced in this case via lower yields as well as reduced prices Total economic losses under a "low returns" scenario (measured relative to "high returns") thus range $91-$92 million per year. This result holds across all hydrologic scenarios with low returns, though the optimal crop mix shifts slightly in response to water availability. Note, however, that once land conversion and canal expansion costs are covered (that is, setting these cost parameters to zero in the model), land expansion potential is once again maximized, and net economic benefits to expansion are much closer to the "high returns" case. If government support were provided for land and canal development, agricultural expansion would in all cases deliver net economic benefits to farmers across a range of agricultural market conditions (though net social benefits would probably remain negative).

Water transfers to Thailand and implementation of flood control measures can also induce economic trade-offs. The costs of implementing 95% flood control are approximately $640,000 and $780,000 per year under wet and average conditions, respectively. This is a modest cost compared to total economic benefits from the system (1%-2% per year), and represents the opportunity cost of forgone economic activity (mostly due to reduced hydropower production) once flood control measures are implemented. Flood control costs increase with lower water availability. The 90% flood control case leads to lost economic benefits ranging $2-$2.3 million per year for the average and wet scenarios, respectively. High water transfer rates to Thailand also impose costs on the system. While the 150 m^3/s induces no costs for the average and wet hydrologic scenarios, a 300 m^3/s transfer leads to significant economic losses (approximately $2.3 and $22 million for the wet and average cases, respectively, with ID2 expansion). This equates to an average opportunity cost of transferring water of approximately $0.2 and $2.4/1,000 m^3 (before accounting for the capital costs of developing the transfer infrastructure). In addition, the 300 m^3/s case was found to be infeasible under dry conditions, so we do not include that scenario in this analysis.

Table 3. Development Scenarios and Net Economic Benefits (Dry Year)

Outcome	Current Conditions	HP Expansion Only	HP + ID1 Expansion	HP + ID2 Expansion	HP + ID3 Expansion
Hydropower (GW-hr/yr)	2.5	6.1	6.1	6.1	6.1
Irrigated area ('000 ha)	20.8	20.8	31.6	69.7	110.4
Irrigation water used (mcm)	262	262	431	823	1,375
Incremental hydropower net benefits (millions of $)	n.a.	$35.1	$35.1	$35.1	$35.1
Incremental agricultural net benefits (millions of $)	n.a.	n.a.	$5.3	$15.4	$30.1
Total Benefits; 'high' ag. Returns (millions of $)	$297	$332	$337	$347	$362
Total Benefits; 'low' ag. Returns (millions of $)				$256	$256

5.4. Total Basin Outflows

Lacombe et al. (2012) provide a comprehensive assessment of the hydrologic impacts of dam development in the Nam Ngum Basin. Here, we focus on the combined effects of additional dams and the alternative irrigation development scenarios on total basin outflows to the Mekong in order to characterize the potential hydrologic impacts of these developments. As discussed, there is a substantial difference in temporal and spatial water availability across hydrological scenarios. Figure 10 illustrates how these differences translate into basin outflows over the course of a year.

Table 4. Development Scenarios and Net Economic Benefits (Average Year)

Outcome	Current Conditions	HP Expansion Only	HP + ID1 Expansion	HP + ID2 Expansion	HP + ID3 Expansion
Hydropower (GW-hr/yr)	6.9	9.9	9.9	9.9	9.8
Irrigated area (‘000 ha)	20.8	20.8	32.1	70.1	119
Irrigation water used (mcm)	262	262	431	830	1,390
Incremental hydropower net benefits (millions of $)	n.a.	$97.6	$97.6	$97.6	$97.6
Incremental agricultural net benefits (millions of $)	n.a.	n.a.	$5.6	$16.1	$32.0
Total Benefits; ‘high’ ag. Returns (millions of $)	$427	$525	$530	$541	$557
$449Total Benefits; ‘low’ ag. Returns (millions of $)				$449	
Costs (millions of $) of… 150 m^3/s Thai diversion 300 m^3/s Thai diversion	n.a.	n.a.	n.a.	$0.35 $22.3	$0 $36.2
Costs (thousands of $) of… 95% Flood control 90% Flood control	n.a.	n.a.	n.a.	$777 $2,260	$777 $2,260

Table 5. Development Scenarios and Net Economic Benefits (Wet Year)

Outcome	Current Conditions	HP Expansion Only	HP + ID1 Expansion	HP + ID2 Expansion	HP + ID3 Expansion
Hydropower (GW-hr/yr)	7.45	10.63	10.63	10.62	10.61
Irrigated area (‘000 ha)	20.8	20.8	32.1	70.1	119
Irrigation water used (mcm)	262	262	431	830	1,398
Incremental hydropower net benefits (millions of $)	n.a.	$121	$121	$121	$121
Incremental agricultural net benefits (millions of $)	n.a.	n.a.	$5.6	$16.1	$32.2
Total Benefits; ‘high’ ag. Returns (millions of $)	$442	$564	$570	$580	$596
Total Benefits; ‘low’ ag. Returns (millions of $)				$488	$488
Costs (millions of $) of… 150 m^3/s Thai diversion 300 m^3/s Thai diversion	n.a.	n.a.	n.a.	$0 $2.0	$0 $3.1
Costs (thousands of $) of… 95% Flood control 90% Flood control	n.a.	n.a.	n.a.	$643 $2,061	$643 $2,061

A key result from the model is that agricultural expansion has a minimal impact on monthly outflows, even while changes in water availability lead to high variance in total basin outflows. The greatest difference between the irrigation development scenarios and the status quo condition occurs in February-April (at the peak of the dry season when irrigation demands are greatest in comparison to river flows). Table 6 displays the percent change in annual basin outflows, relative to the no irrigation development case. For IP1 this reduction is less than 1% across all water availability cases. For IP2, this reduction in outflows ranges from 1.3%-2.7% (from wet to dry—the change in total outflows is greatest when flows are reduced). Finally, for IP3, the reduction in total basin outflows ranges 2.7%-5.3%. There is thus a small, but potentially meaningful hydrological trade-off between flows into the Mekong and expansion of irrigation in the Nam Ngum basin, and this tradeoff is greatest at the peak of the dry season water.

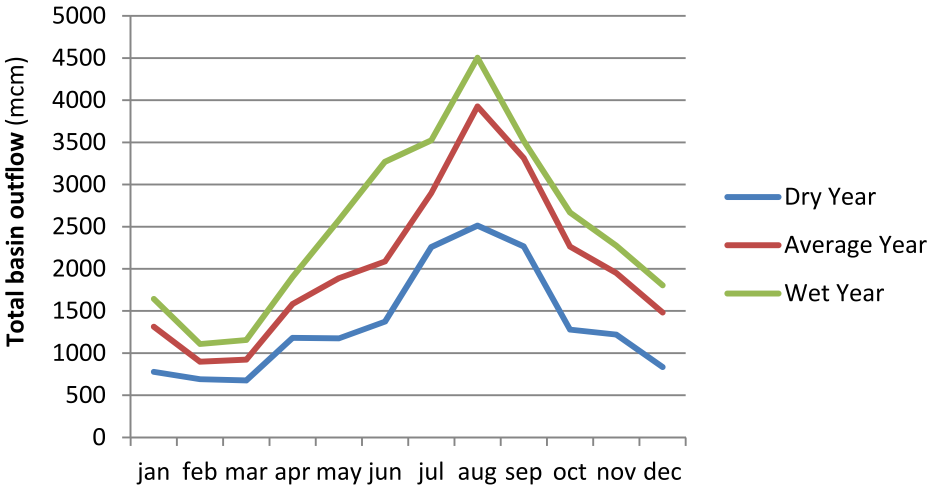


Figure 10. Comparison of hydrographs across hydrologic conditions

Transfers to Thailand have a more substantial impact on annual outflows to the Mekong. For the 150 m^3/s case, reductions in annual basin outflow range 17%-32% (ranging from wet to dry), and these increase to 33%-39.3% under average and wet conditions, respectively. As the Nam Ngum supplies 4% of the total annual Mekong inflows and 15% of dry season flows, this transfer would reduce total flow to the Mekong River, and could affect economic activities and ecological processes downstream in that system. Flood control does not have a significant impact on annual outflows, though we find subtle changes in monthly outflows.

6. Discussion

This paper developed and applied a hydro-economic optimization model for assessing the economic consequences associated with various infrastructure development and water management strategies in the Nam Ngum Basin. A voluminous literature has applied similar hydro-economic optimization models to address an array of policy and environmental issues in various watersheds world-wide. These modeling techniques are most often used in regions suffering from water scarcity and/or over-allocation of existing water resources, where marginal changes in water availability or demand induce important economic trade-offs. The contribution of this study is to assess the implications of various levels of development that would increase water resource demands in a relatively water abundant watershed by a large amount (e.g, up to a six-fold increase in irrigated area, or large inter-basin transfers). We consider whether such increases could induce meaningful economic trade-offs among water users.

Table 6. Percentage change in annual basin outflows relative to future 8 dam scenario

	Dry	Average	Wet
HP + ID1 Expansion	-0.76%	-0.48%	-0.39%
HP + ID2 Expansion	-2.66%	-1.62%	-1.33%
HP + ID3 Expansion	-5.28%	-3.22%	-2.65%
HP + ID2 Expansion + 150 m3/s Transfer	-32.32%	-20.89%	-17.11%
HP + ID3 Expansion + 150 m3/s Transfer	-32.34%	-22.49%	-18.44%
HP + ID2 Expansion + 300 m3/s Transfer	n.a.	-39.37%	-32.91%
HP + ID3 Expansion + 300 m3/s Transfer	n.a.	-39.40%	-34.23%
HP + ID2 Expansion + 95% Flood Control	n.a.	-1.62%	-1.33%
HP + ID3 Expansion + 95% Flood Control	n.a.	-3.22%	-2.65%
HP + ID2 Expansion + 90% Flood Control	n.a.	-1.62%	-1.33%
HP + ID3 Expansion + 90% Flood Control	n.a.	-3.22%	3.54%
HP + ID2 Expansion with Low Returns	-0.10%	-0.06%	-0.05%
HP + ID3 Expansion with Low Returns	0.00%	0.00%	0.00%

Specifically, the primary objective of the analysis was to quantify the potential economic tradeoffs among energy generation, irrigation, flood control, and transboundary water transfer objectives. We constructed a series of sensitivity scenarios under dry, average, and wet hydrologic conditions, with varying levels dam development, irrigated agricultural expansion, agricultural returns, flood control storage restrictions, and water diversions to Thailand.

In general, results indicate that tradeoffs between hydropower production, irrigation, and flood control are modest. Hydropower and agricultural expansion are found to be complimentary under high levels of water availability, as even the most ambitious level of irrigation expansion (ID3) would reduce total hydropower production by only a modest amount (less than 2% annually for all hydrologic conditions). This suggests that energy expansion and expanded food production could go hand in hand in the Nam Ngum Basin. The tradeoffs between hydropower and flood control also appear to be relatively small in the Nam Ngum Basin. Allowing for flood control by maintaining reduced storage levels in the reservoir that is largest and furthest downstream on the Nam Ngum (NN1) decreases hydropower by less than 1%. Similarly, addition of the water transfer to Northeast Thailand does not greatly affect hydropower generation. All of these results generally follow from the fact that the dams would optimally be operated to maximize storage during the flood season and to slowly release water during the dry season, which is also beneficial in terms of irrigation requirements, ecological low flows, and downstream flood control. We note, however, that critical information on the impact that dam development would have on freshwater biodiversity and fish populations in the basin is lacking, so assessing the effects of hydrological changes on ecosystems requires additional research. We did also find that the amount of water flowing out of the Nam Ngum and into the Mekong could decrease by up to 5% with full development of irrigation.

Results also suggest that economic outcomes are highly dependent on water availability. System production (of hydropower) was greatly reduced under dry hydrologic conditions, and irrigation consumed relatively more basin water. For example, hydropower decreased by 60% from the average, and irrigation requirements reached 5% of total basin flow under the most ambitious expansion scenarios. If flows were to decrease to such levels on a long-term basis, the economic productivity of the basin could thus be severely hampered. On the other hand, 'wet' conditions only lead to modest improvements in energy generation, since dam and turbine capacities are quickly reached, and irrigated land potential in the basin is fairly limited. These results illustrate the importance of accounting for climate variability and potential change in cost-benefit analysis of infrastructure projects, even in watersheds that are relatively water abundant.

Furthermore, in dry years, water transfers out of the Nam Ngum to Northeast Thailand would create tradeoffs between water allocated to dry season irrigation and that remaining for ecosystems. Indeed, large transfers were found to be infeasible in some months. Large water transfers (300 m^3/s) would also lead to reduced economic benefits and basin outflows under average and wet conditions, particularly when coupled with irrigation expansion. Overall, a 150 m^3/s water transfer to Thailand could reduce basin outflows by 32% in dry conditions, and a larger 300 m^3/s transfer would decrease these outflows by 40% under average conditions.

Overall, our results have two important policy implications for the hydropower and agriculture sectors in Lao PDR. With the recent controversy resulting from poorly managed water releases at NN1 during the typhoon of 2011 that resulted in significant crop damages in the Vientiane Plain, the minimal trade-off between hydropower generation and flood storage suggests that the Lao government could change operating rules for NN1 to ensure adequate storage capacity during the rainy season to buffer such events. For domestic agricultural policy, our results indicate that efforts by the Lao government to turn the Vientiane Plain into a significantly expanded rice production area are economically feasible, if high agricultural returns – in terms of yields and prices – remain possible. If returns decrease, however, the benefits of such an expansion policy would need to be considered carefully, since the capital costs of canal expansion and land clearing might outweigh the benefits obtained.

The implications of development in the Nam Ngum on the wider Mekong are also important to consider. On the one hand, full hydropower development and irrigation expansion would only reduce flows into the Mekong by roughly 10% on an annual basis under 'dry' conditions, and would be much lower (4-6%) under wet and normal conditions. Coupled with large water transfers to Northeast Thailand, however, these effects could become more significant. In addition, the timing of flows into the Mekong would change markedly due to the effects of storage, with lower pulses during the wet season, and higher dry season flows (Lacombe et al, 2012) potentially negatively impacting flood-pulse dependent ecosystems downstream. Careful analysis is needed to better understand the implications of such changes for the wider Mekong region.

There are a number of important limitations to our analysis. First, a critical assumption of the optimization model used here is that operation of control infrastructures in the basin could be coordinated across dams and over time. The reality of management of dams in the Nam Ngum is that they are less coordinated, however, as individual dams appear to be mostly operated by independent companies. However, Electricité du Laos (EDL) is a monopolistic buyer of hydroelectric energy, and improving system operation would likely be in its best interest. Even so, energy production is clearly not the sole objective in the basin, so the benefits simulated here probably represent an upper bound on the economic production that would be possible given the modeled suite of infrastructures. Second, model outcomes are highly dependent on economic and hydrological parameters. As shown, the natural variability in the system has a dramatic effect on power production potential. Similarly, factors such as agricultural returns influence the extent of efficient irrigation expansion. Third, the assumption of profit maximizing behavior may not reflect land management decisions in a region with a high level of subsistence farming. We hope to address this limitation in future work by incorporating recently assembled information on landowner preferences to more adequately address the potential impacts of agricultural development on livelihood of subsistence farmers. Fourth, the model does not value changes in flow that affect areas outside the Nam Ngum (i.e. downstream in the Mekong), nor does it explicitly value the change in ecological services that would result from changing the natural hydrology of the Nam Ngum. With regards to clarification of these points, additional research is needed.

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References

ADB (1996). Report and Recommendation of the President to the Board of Directors on a Proposed Loan to the Lao People's Democratic Republic for the Nam Leuk Hydropower Project Asian Development Bank.

ADB (1996). Summary Environmental Impact Assessment for the Nam Leuk Hydropower Project in Lao PDR. Excerpts from Project Performance Audit Report on the Nam Leuk Hydropower Project in the Lao PDR, ADB Operations Evaluation Department, 2004. Compiled by International Rivers Network.

ADB (2007). Lao People's Democratic Republic: Preparing the Cumulative Impact Assessment for the Nam Ngum 3 Hydropower Project.

Agence Francaise de Developpement and Asian Development Bank (2009). Nam Ngum River Basin Integrated Water Resources Management Plan. Nam Ngum River Basin Development Sector Project. W. R. a. E. Administration, Water Resources and Environment Admininstration (WREA).

Bach, H., J. Bird, et al. (2012). Transboundary River Basin Management: Addressing Water, Energy and Food Security. Vientiane, Lao PDR, Mekong River Commission.

Bangkok Post (2011). Xayaburi dam work begins on sly: Thai construction giant, Laos ignore Mekong concerns. www.bangkokpost.com/news/local/232239/xayaburi-dam-work-begins-on-sly (accessed 23 December 2011).

Bardacke, T. (1998). 'Battery of Asia' may run flat: Thailand's economic crisis is raising questions over the energy exporting hopes of neighbouring Laos. Financial Times.

Department of Irrigation (DOI) and Japan International Cooperation Agency (JICA) (2009). Proposal on Improvement for IMT Legal Framework: Output 1 of Irrigation Development Advisor, JICA.

DWR (2008). Prepared under the Nam Ngum River Basin Development Sector Project. Nam Ngum River Basin Profile. Vientiane, Department of Water Resources, Water Resources and Environment Administration.

Electricite du Laos (EDL) (2010). Annual Report. Statistics-Planning Office. Business-Finance Department.

EPD. (2012, 17 July 2012). "Powering Progress Website." Retrieved 20 July, 2012, from www.poweringprogress.com.

FAO. (2010). "The state of food and agriculture in Asia and the Pacific region." Retrieved Oct. 2012.

Friend, R. M., D. J. H. Blake, et al. (2009). "Negotiating trade-offs in water resources development in the Mekong Basin: implications for fisheries and fishery-based livelihoods." Water Policy **11**(Supplement. 1): 13-30.

Geotech (2012). Hydropower and agriculture land development for irrigation system in Nam Ngum Reservoir of Vientiane Plane areas. Project Proposal on pre-feasibility study. Vientiane, Lao PDR.

Grumbine, R. E. and J. Xu (2011). "Mekong Hydropower Development." Science **332**(6026): 178-179.

Harou, J. J., M. Pulido-Velazquez, et al. (2009). "Hydro-economic models: Concepts, design, applications, and future prospects." Journal of Hydrology **375**(3–4): 627-643.

ICEM (2010). MRC Strategic Environmental Assessment (SEA) of hydropower on the Mekong mainstream. Hanoi, VIetnam, ICEM Australia**:** 198.

IEA (2012). Energy balances of Non-OECD countries. Paris, International Energy Agency. 554 pages.

International Rivers (2009). Existing and Planned Hydropower Projects. internationalrivers.org.

Jeuland, M. (2010). "Economic implications of climate change for infrastructure planning in transboundary water systems: An example from the Blue Nile." Water Resour. Res. **46**(11): W11556.

Keskinen, M., M. Kummu, et al. (2012). "Mekong at the crossroads: Next steps for impact assessment of large dams." Ambio **41**: 319-324.

King, P., J. Bird, et al. (2007). The current status of environmental criteria for hydropower development in the Mekong River: A literature compilation. A Consultants Report to the ADB, MRCS, and WWF. . Vientiane, ADB Consultants Report.

Kingston, D., J. Thompson, et al. (2011). "Uncertainty in climate change projections of discharge for the Mekong River Basin." Hydrology and Earth System Sciences **15**(5): 1459-1471.

Kummu, M. and J. Sarkkula (2008). "Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse." AMBIO: A Journal of the Human Environment **37**(3): 158-192.

Kummu, M. and J. Sarkkula (2008). "Impact of the Mekong river flow alteration on the Tonle Sap Lake: Integrated modeling approach." International Journal of Water Resources **22**: 497-519.

Lacombe, G., S. Douangsavanh, et al. (2012). "Rising food and energy demands: effects on water resources along the Nam Ngum River of the Mekong Basin." Unpublished Manuscript.

Lacombe, G., S. Douangsavanh, et al. (2012). Rising food and energy demands: effects on water resources availability along the Nam Ngum River of the Mekong Basin. Vientiane, Lao PDR.

Lacombe, G., S. Douangsavanh, et al. (2012). Is there enough water in the Vientiane Plain? A water balance assessment of the lower Nam Ngum Basin. Vientiane, Laos, International Water Management Institute**:** 25.

Lauri, H., H. de Moel, et al. (2012). "Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge." Hydrology and Earth System Sciences Discussions **9**: 6569-6614.

MAF (2009). Crop Statistics Yearbook 2008. Department of Planning, Government of Laos. Vientiane, Lao PDR.

MAF (2010). Crop Statistics in dry season: Year 2008-2009. Department of Planning, Government of Laos. Vientiane, Lao PDR.

MAF (2010). Crop Statistics in rainy season: Year 2009. Department of Planning, Government of Laos. Vientiane, Lao PDR.

MAF (2010). Government investment plan to supply water in Vientiane Prefecture Province for years 2011 to 2015. Provincial Agriculture and Forestry Office, Department of Irrigation, Vientiane Province, Lao PDR.

Matthews, N. (2012). "Water Grabbing in the Mekong Basin–An Analysis of the Winners and Losers of Thailand's Hydropower Development in Lao PDR." Water Alternatives **5**(2): 392-411.

Mekong River Commission (2010). Assessment of basin-wide development scenarios - Main report. Vientiane, Mekong River Commission.

Molle, F., T. Foran, et al. (2009). Contested waterscapes in the Mekong region: Hydropower, livelihoods and governance, Earthscan London.

MRC (2005). Overview of the Hydrology of the Mekong Basin. Vientiane, Lao PDR.

OECD/FAO (2012). OECD-FAO Agricultural Outlook 2012. OECD Publishing.

Pearse-Smith, S. W. D. (2012). "The impact of continued Mekong Basin hydropower development on local livelihoods." Consilience: The Journal of Sustainable Development **7**(1): 73-86.

Räsänen, T. A., J. Koponen, et al. (2012). "Downstream Hydrological Impacts of Hydropower Development in the Upper Mekong Basin." Water Resources Management: 1-19.

Ringler, C. (2001). Optimal water allocation in the Mekong River basin. ZEF - Discussion Papers on Development Policy. Bonn.

Ringler, C. (2001). Optimal water allocation in the Mekong River basin.

Ringler, C. and X. Cai (2006). "Valuing Fisheries and Wetlands Using Integrated Economic-Hydrologic Modeling---Mekong River Basin." Journal of Water Resources Planning and Management **132**(6): 480-487.

Ringler, C., N. V. Huy, et al. (2006). "Water allocation policy modeling for the Dong Nai river basin: An integrated perspective." JAWRA Journal of the American Water Resources Association **42**(6): 1465-1482.

Rogers, P. P. and M. B. Fiering (1986). "Use of systems analysis in water management." Water Resources Research **22**(9): 146S-158S.

SCI (2004). Nam Ngum Water Management Project for Vientiane Plain of Lao PDR and Northeast Thai Region. Bangkok, Sanyu Consultants Inc (SCI). in associateion with Sanyu Consultants (Thailand) Ltd.

SD & XP Consultants Group and Nippon Koei (2009). Final Report: Environmental and Social Management Plan (ESMP) of Nam Ngum 1 (NN1) Hydropower Station Expansion. Vientiane, Lao PDR, Electricité du Laos (EDL), Lao PDR.

Setboonsarng, S., L. Pingsun, et al. (2008). Rice Contract Farming in Lao PDR: Moving from Subsistence to Commercial Agriculture. ADBI Discussion Paper 90. Tokyo, Asian Development Bank Institute.

UNEP and AIT (2001). State of the Environment Report: Lao People's Democratic Republic. www.rrcap.unep.org, United Nations Environment Program. Asian Institute of Technology.

UNFAO (2009). CROPWAT Version 8.0. J. Swennenhuis. www.fao.org, Water Resources Development and Management Service, United Nations FAO,.

Vastila, K., M. Kummu, et al. (2010). "Modelling climate change impacts on the flood pulse in the lower Mekong floodplains." J. Water Clim. Change **1**: 67-86.

Vattenfall Power Consultant AB (2008). Lao People's Democratic Republic: Preparing the Cumulative Impact Assessment for the Nam Ngum 3 Hydropower Project. Technical Assistance Consultant's Report. Ramboll Natura AB and Earth Systems Lao.

WREA (2008). Nam Ngum River Basin Profile. Nam Ngum River Basin Development Sector Project, ADB and AFD.

WREA, ADB, et al. (2009). Component 2 - Reservoir Management and River Basin Modeling Project Completion Repor and the Technical Reports. Hydrosult Inc., STS Consultants, EDF-CIH Electricité de France and I. B. d. I. Conselis.

Wu, X., M. Jeuland, et al. (2012). "Interdependency of Water Resource Development in the Ganges: Perception and Realities2." Water Policy (Forthcoming).

Ziv, G., E. Baran, et al. (2012). "Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin." Proceedings of the National Academy of Sciences **109**(15): 5609-5614.

Appendix: Additional Modeling Details

Local Inflows

The sub-catchments corresponding to model nodes were obtained using spatial flow modeling and a drainage map developed in ArcGIS 10. Beginning at the node furthest upstream in the catchment—representing the surface diversion for the Xiangkhoang Plateau—node sub-catchment areas were determined using a 50 meter resolution Digitial Elevation Model (DEM), a GIS polyline file of the main streams in the basin, and the Arc Hydro package of spatial hydrology tools in ArcGIS 10. Creating the drainage map required a four step process: 1) "burning" of the stream file into the DEM through simple subtraction to ensure accurate representation of real stream conditions in the basin; 2) filling "sinks" in the DEM to account for small non-draining irregularities in the relatively low resolution elevation map data; 3) using the "Flow Direction" tool to mathematically determine how cells drain downstream; and 4) using the Flow Accumulation tool to determine the drainage area at each point on the river, based on the direction of the flow determined in the previous step. The map created through this process contains data on the number of 50m by 50m cells that drain into any point along the tributaries and mainstem of the Nam Ngum river system.

Moving from upstream to downstream, the mapped sub-catchment area of each node was then converted into hectares, with downstream areas determined via subtraction of upstream areas from total catchment area. For example, while the drainage area for Nam Ngum 4 was simply its upstream catchment area, the next downstream node, the confluence of the Nam Ting and Nam Ngum rivers, was determined by subtracting the Nam Ngum 4 catchment area from the total drainage area at the confluence point (measured on the Nam Ngum) to get the unique catchment sub-catchment area for this specific node. All subsequent downstream node sub-catchments were determined similarly.

Once all sub-catchment areas had been so determined, the local inflows for each node sub-catchment were calculated by multiplying the total flows at the closest downstream gauge by the ratio of that sub-catchment's area to that of the entire catchment draining into the point coinciding with that gauging station. For example, local inflows for the Nam Ngum 2 dam were calculated as follows:

$$\text{NN2}_{\text{inflows}} = \text{Ban Naluang}_{\text{inflows}} * (\text{Ha NN2}_{\text{subcatch}} / \text{Ha Ban Naluang}_{\text{subcatch}}) \qquad \text{(A1)}$$

For intermediate points between gauging stations, the incremental change in flows between stations was similarly ascribed to the sub-catchments lying between those stations. This was then replicated for each node for each of the three climate scenarios: wet, dry, and average, resulting in three separate years of inflows for each node.

There were also two important exceptions in the derivation of flows related to diversions in and out of the Nam Ngum Basin, specifically the diversions into the Nam Ngum 1 dam reservoir from the Nam Song River in the basin, and from the Nam Leuk Dam outside the basin. In modeling these diversions, actual historical flows obtained from the Government of Lao were directly included as flows into and out of the corresponding nodes, since we do not know the precise operating rules governing the amounts of these diversions.

This methodology also has some key limitations. Because each cell in the DEM contains 2,500m^2 surface area, it misses much of the finer resolution surface geology, resulting in smaller streams and rivers draining incorrectly, confluence points mapping to incorrect locations, as well as other problems related to spatial scale. The flow accumulation model, and thus the sub-catchment areas that are calculated, are not exact representations of the river system. Ideally, LIDAR, or other finer resolution imaging (unobtainable for this study) could be used to determine the exact flow paths and accumulations for the smaller streams, resulting in a more accurate hydrological model for the basin. The lower-scale resolution spatial modeling was deemed sufficient for the purposes of basin-scale optimization.

Current and Potential Irrigated Area

Three data sources were used to determine current and future irrigated areas: 1) satellite imagery from the dry season; 2) pumping station capacity and irrigated area per pumping station (data from the MAF); and 3) local surveys of actual and planned irrigated areas by district, weighted according to their portion in the basin (Department of Irrigation (DOI) and Japan International Cooperation Agency (JICA) 2009). The images used were freely-available, high resolution (0.46 to 0.60m) satellite images taken during the dry season months of March 2002, April 2003, December 2007, January 2008, and December 2010, and displayed in Google Earth. The high resolution and contrast between dry and cultivated land in the images allowed for relatively straightforward delineation of currently developed irrigation areas located near existing canals and pumping stations in the Vientiane Plain using ArcGIS software. Unfortunately, similar images depicting dry season production are not available for the upstream areas of the basin where additional irrigated production occurs, so ground level DOI/JICA data by district and government data from planning documents were used for estimating production areas in the Xiengkhouang Plateau. Future expansion potential was then estimated as described in Section 4.4 above.

Hydropower data

The parameters for hydropower dams are presented in Table A1. These parameters were obtained from various sources: basin development reports, project profiles, dam developers, the electricity authority of Lao PDR, Electricité du Laos (EDL), and the Department of Energy Promotion and Development (EPD) of the Ministry of Energy and Mines (MEM).

Table A1. Model inputs for hydropower dams

Name	Dead Storage (Mm^3)	Total Storage (Mm^3)	Turbine Height (M)	Minimum Operating Height (M)	Maximum Operating Height (M)	Spillway Capacity (Mm^3)
NN1	2330	7030	75	196	212.3	70.3
NN2	2269	4886	181	345	378.75	48.86
NN3	337	1316	220	660	720	13.2
NN4A	111	443	65	1025	1045	4788
NN5	65.2	314	99	1060	1100	31.4
Nam Lik 1-2	270	1095	103	270	305	11.13
Nam Bak 2B	65	238	85	1010	1050	1.86
Nam Bak 1	147	473	83	600	640	4.73

Notes: Compiled from EPD, 2012; Lacombe et al., 2012; ADB, 1996; Vattenfall Power Consultants AB, 2008; and SD & XP Consultants Group and Nippon Koei, 2009.

Additional results

Additional results for hydropower and agricultural water use by scenario and hydrological conditions are summarized in Tables A2 and A3 below.

Table A2. Annual hydropower production by scenario

	Dry Year	Average Year	Wet Year
Current (3 dam) Scenario	2,547	6,891	7,454
HP Expansion Only	6,104	9,857	10,632
HP + ID1 Expansion	6,103	9,856	10,631
HP + ID2 Expansion	6,087	9,849	10,623
HP + ID3 Expansion	6,074	9,840	10,614
HP + ID2 Expansion + 150 m3/s Transfer	5,975	9,848	10,623
HP + ID3 Expansion + 150 m3/s Transfer	5,973	9,839	10,614
HP + ID2 Expansion + 300 m3/s Transfer	NA	9,510	10,580
HP + ID3 Expansion + 300 m3/s Transfer	NA	9,500	10,558
HP + ID2 Expansion + 95% Flood Control	NA	9,834	10,611
HP + ID3 Expansion + 95% Flood Control	NA	9,825	10,603
HP + ID2 Expansion + 90% Flood Control	NA	9,805	10,584
HP + ID3 Expansion + 90% Flood Control	NA	9,796	10,575
HP + ID2 Expansion with Low Returns	6,104	9,861	10,632
HP + ID3 Expansion with Low Returns	6,104	9,857	10,632

Table A3 Total agricultural water use by scenario

	Dry Year	Average Year	Wet Year
Current (3 dam) Scenario	262	262	262
HP Expansion Only	262	262	262
HP + ID1 Expansion	431	431	431
HP + ID2 Expansion	823	830	830
HP + ID3 Expansion	1,375	1,390	1,398
HP + ID2 Expansion + 150 m3/s Transfer	308	824	824
HP + ID3 Expansion + 150 m3/s Transfer	548	1,384	1,392
HP + ID2 Expansion + 300 m3/s Transfer	n.a.	538	824
HP + ID3 Expansion + 300 m3/s Transfer	n.a.	548	1,392
HP + ID2 Expansion + 95% Flood Control	n.a.	830	830
HP + ID3 Expansion + 95% Flood Control	n.a.	1,390	1,398
HP + ID2 Expansion + 90% Flood Control	n.a.	830	830
HP + ID3 Expansion + 90% Flood Control	n.a.	1,390	1,398
HP + ID2 Expansion with Low Returns	284	284	284
HP + ID3 Expansion with Low Returns	284	284	284