Supplementary Material: Description of Hydro-Economic Optimization Model of the Nam Ngum Watershed

This supplemental appendix describes the mathematical structure of the hydro-economic optimization model used to assess the potential economic costs of uncoordinated infrastructure management in the Nam Ngum Basin, Lao PDR, as applied in the manuscript: "The costs of uncoordinated infrastructure management in multi-reservoir river basins." The model is a nonlinear mathematical program that maximizes net returns to regional economic activities that rely on water as a primary factor of production (principally, irrigated agriculture and hydropower generation). Additional information on data sources can be found in Bartlett et al. (2012).

1.1. 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 A-1). 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, 2009), the Ministry of Energy and Mines (MEM), and NGOs working in the hydropower sector. The schematic only includes the most important surface diversions in the basin, and does not include connections to groundwater systems.

1.2 Model Objective

As with many other previous hydro-economic models, water is allocated over space and time to optimize net economic returns. The time-step for the model is monthly. Due to a lack of data availability on the value of municipal water supplies and ecosystem services provided by Nam Ngum flows, the model focuses purely on returns to energy and agricultural production. The objective function of the model maximizes the net returns to hydropower ($HydroBenefits_i$) and agricultural profits ($AgBenefits_i$) across all months (t) and river "nodes" (i) within the system (expressed by Equation A-1), over the course of a modeled year. Nodes refer to any modeled point or area along the watershed and includes both confluence points between tributaries, and locations where water is regulated, consumed, stored, or diverted.

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

The model constraints are described below.

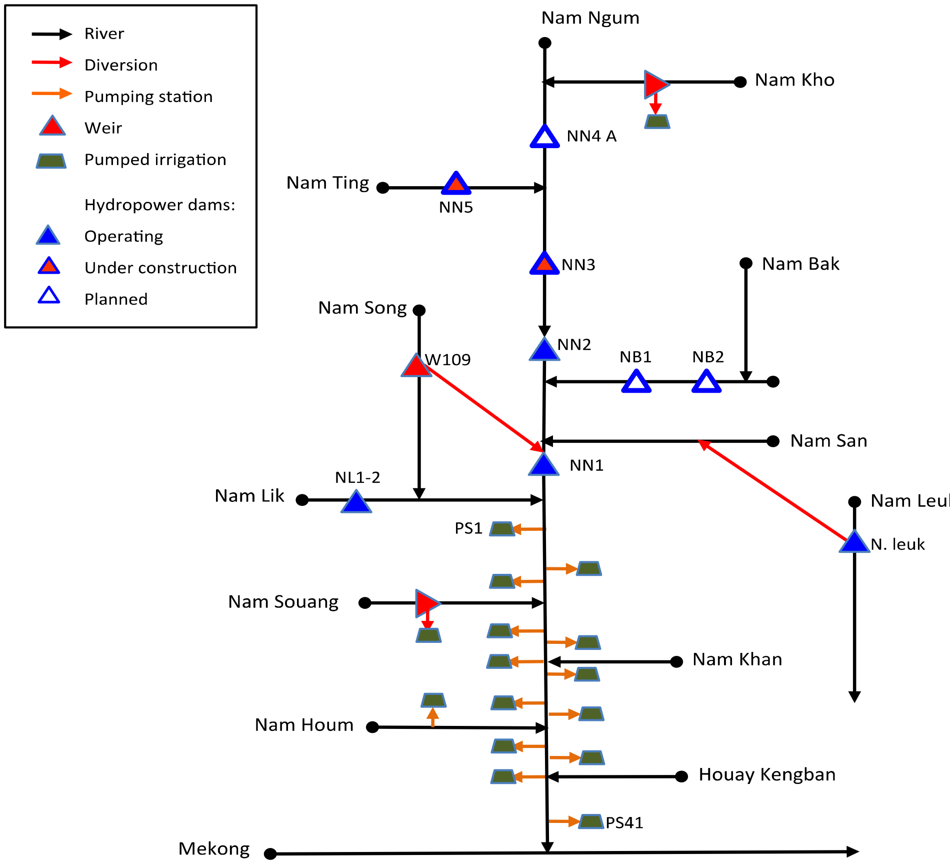

Figure A-1. The Nam Ngum River basin node-link hydrological schematic

1.3. Flow continuity constraints

The continuity constraints ensure proper accounting of the water quantities flowing through the system, from upstream reaches towards the downstream. Equation A-2 depicts the continuity flow conditions for intermediate nodes without storage, whereas Equation A-3 dictates the continuity of flows at hydropower dams.

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

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

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 A-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. (2013)). 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.

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.

1.3.1. Calculation of 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 main stem 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:

$$NN2_{inflows} = Ban\ Naluang_{inflows} * (Ha\ NN2_{subcatch} / Ha\ Ban\ Naluang_{subcatch}) \quad \text{(A4)}$$

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 hydrological 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.

1.3.2. Nam Ngum Basin Hydrographs

Figure A-2 displays annual hydrographs for the dry, average, and wet scenarios discussed in Jeuland et al., 2014. These hydrographs represent monthly Nam Ngum basin outflows at the Mekong River confluence point, and are based on scenario projections from the economic optimization model. For each case, we assume that 6% of storage capacity is reserved for flood control, and high returns for agricultural production.

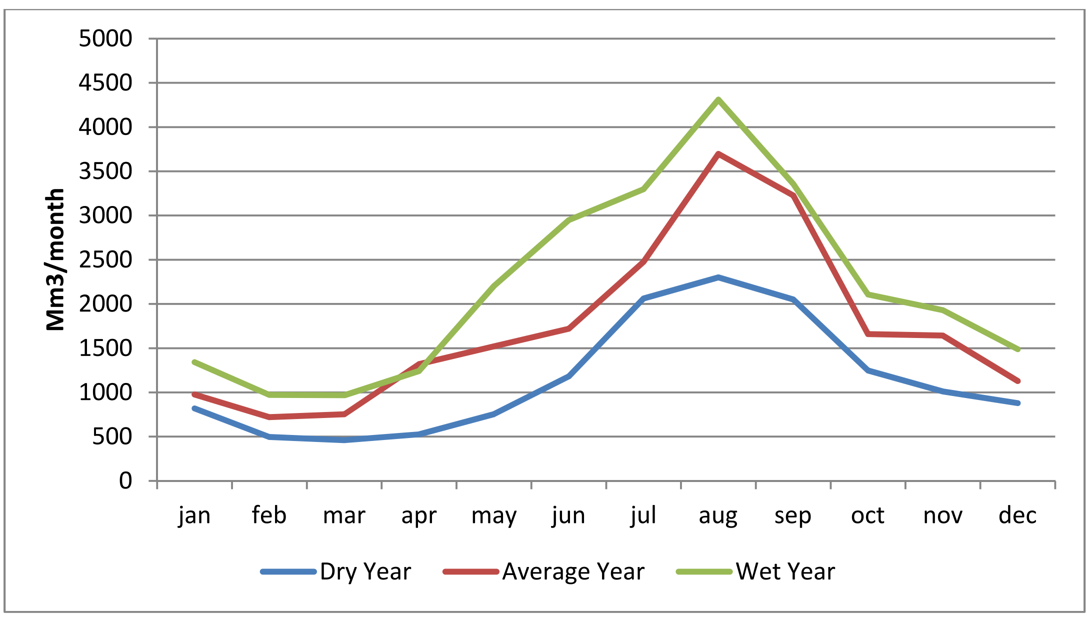

Figure A-2: Model-projected hydrographs for representative dry, average, and wet hydrologic conditions (Mm^3 per month)

1.4. 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 A-4 illustrates the net outflow relationship for hydropower facilities:

$$W_{i\to i+1,t} = TurbineOutflow_{i\to i+1,t} + SpillwayOutflow_{i\to i+1,t} \quad \forall\, i\, \in D \qquad \text{(A-5)}$$

Equations A-6 and A-7 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):

$$Hydro_{it} = TurbineOutflow_{i\to i+1,t} \cdot NetHead_{it} \cdot \emptyset_{it} \cdot 9.81 \qquad \text{(A-6)}$$

$$NetHead_{it} = StorageHeight_{it} - TurbineIntake_{it} \qquad \text{(A-7)}$$

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 A-8:

$$StorageHeight_{it} = \alpha_i + \beta_i \cdot WS_{it} \qquad \text{(A-8)}$$

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). Model parameters for current and proposed dams were obtained from various sources as summarized in Bartlett et al. (2012). These dam-specific parameters are summarized in Table A1 and are consistent with those used in Lacombe et al. (2012). Price data ($0.06/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 1996a; ADB 1996b; International Rivers 2009; SD & XP Consultants Group and Nippon Koei 2009). These costs were normalized to be in constant year terms (2010).

In addition, minimum and maximum bounds are imposed on the proportion of hydropower produced, by dam, in any given month:

$$\theta^{min} \cdot Hydro_{it} \leq {Hydro_{it}}\Big/{\textstyle\sum_{t=1}^{12} Hydro_{it}} \leq \theta^{max} \cdot Hydro_{it} \qquad \text{(A-9)}$$

Equation A-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.

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	6858	164	196	212	70
NN2	2269	5104	200	340	375	48.86
NN3	337	1317	540	660	720	13
NN4A	111	443	885	1020	1040	4788
NN5	65.2	314	99	1060	1100	31
Nam Lik 1-2	270	1289	216	270	305	11
Nam Bak 2B	65	2387	960	1010	1050	2
Nam Bak 1	147	473	462	600	640	5

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.

Revenue generated at each dam is the product of hydropower generation (in megawatt hours) and the electricity price (P^e = \$60 per megawatt-hour). Equation A-10 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).

$$HydroBenefits_i = (\sum_{t=1}^{12} Hydro_{it} \cdot P^e) - CapCostsHydro_i \quad \text{(A-10)}$$

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

1.5. Flood control constraints

To allow for flood control upstream of the Vientiane plain, we require that total storage for all eight dams be maintained at some threshold below maximum capacity (*StorageCapacity* is equal to the sum of storage capacity over all individual dams) during wet season months (May-October) to protect against extreme flooding events. For the coordinated watershed management scenarios, this constraint requires that the sum of reservoir storage in all dams not to exceed the limit placed by the flood control parameter, which represents the portion of storage capacity set aside for flood control purposes. Note that for the coordinated case, flood control obligation is shared by all dams, and the model endogenously determines how much storage capacity to leave unfilled for each dam in order to satisfy the overall flood control constraint provide by Equation A-11a.

$$\sum_{i=1}^{I} WS_{i,t} \leq (1-\gamma) * StorageCapacity \quad for\ t = Wet\ Season \tag{A-11a}$$

For the uncoordinated scenarios, flood control constraints are only imposed on the NN1 storage reservoir, which is the dam furthest downstream in the system where flood control would need to be provided in the absence of coordination. Note that in this case, NN1 is required to meet basin-wide flood control goals in isolation, meaning that NN1 is theoretically dealt a much larger share of the total flood control obligation when compared to the coordinated case. Equation A-11b depicts the flood control constraint for this uncoordinated system:

$$WS_{NN1,t} \leq (1-\gamma) * StorageCapacity \quad for\ t = Wet\ Seas \tag{A-11b}$$

1.6. 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* ($LExp_i^{max}$):

$$\sum_{j=1}^{J} L_{ij} \leq L_i^{max} + LExp_i^{max} \tag{A-12}$$

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). Details of these data sources can be found in Bartlett et al. (2012).

We model crop production in areas irrigated with Nam Ngum water using three composite crop groups: rice, cereals (including maize), and fruits/vegetables. 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.

Area weighted prices and yields (exogenous model parameters which were specified at the district level) for each composite crop group were formed by dividing commodity-specific yields and prices by the total area for the crop group, as shown in equations A-13 and A-14. 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 (Y_{ijt}) and price P_{ijt}^{Ag}.

$$Y_{ij} = \sum_{k=1}^{K} \frac{Yield_k}{Area_k} \quad \forall\, k \in J \tag{A-13}$$

$$P_{ij}^{Ag} = \sum_{k=1}^{K} \frac{P_k}{Area_k} \quad \forall\, k \in J \tag{A-14}$$

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, low, and average 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. This choice is justified given recent trends in high global commodity prices that have been observed in recent years.

Similar to the yield and price parameters, an area-weighted procedure was used to generate crop water requirements for each composite crop type. Crop water requirements (per unit area) were estimated for individual crops using CROPWAT 8.0 (UNFAO 2009), and cropping calendars for Lao obtained from the Ministry of Agriculture and Forestry (MAF) (MAF 2010a; MAF 2010b), following the procedure described in Bartlett et al. (2012)

Equation A-15 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):

$$W_{it}^{Ag} = \frac{\sum_{j=1}^{J} \phi_{ijt} \cdot L_{ij}}{\mu} \qquad \text{(A-15)}$$

Equation 16 then denotes total profits (or economic benefit) generated from irrigated production at each node (where $LExp_i$ is the amount of irrigated area expansion beyond the baseline land endowment L_i^{max}):

$$AgBenefits_i = \sum_{j=1}^{J} \begin{Bmatrix} (L_{ij} + Lexp_i) \cdot \left[P_{ij}^{Ag} \cdot Y_{ij} - C_{ij}\right] - \\ Lexp_i \cdot [\kappa \mp \eta] \end{Bmatrix} \qquad \text{(A-16)}$$

In this equation, C_{ij} represents cultivation cost (see Bartlett et al. (2012) for a description of the survey data that were used), 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).

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 electric water pumps preparing dirt canals, 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.

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 (2010c) 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:

$$MinCropArea_{ij} \leq \frac{L_{ij}}{\sum_{j=1}^{J}\left(L_{ij}^{max} - L_{ij}\right)} \leq MaxCropArea_{ij} \quad \text{(A-17)}$$

1.7. Instream flow protection and terminal constraints

Finally, we impose two 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 at a level of 94 m^3/sec., or approximately 247 million m^3 per month:

$$W_{i \rightarrow \text{Mekong},t} \geq MinInstreamFlow_t \quad \forall\, t \quad \text{(A-18)}$$

Next, 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, except for the "Dry" year scenarios, in which the lower bound is reduced to 90%. 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):

$$0.95 \cdot InitialStorage_i \leq WS_{it} \leq 1.05 \cdot InitialStorage_i \quad \text{(A-19)}$$

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