Saving a River:
A joint management approach to the Mekong River Basin

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ONLINE APPENDICES A and B

Appendix A: The Model

Water balances and economic values

All indices representing space and time are defined in table A.1. We distinguish two seasons denoted by τ: the wet season (w) and the dry season (d); and two main regions denoted by $i = 1, 2$, where region 1 lies upstream of region 2. Region 2 is divided into two subregions denoted r: the mainstream (m) river and its tributaries (t). Within each (sub)region, we allow for an endogenous number of dams that are denoted by $h = 1, 2, \ldots$, which will be ordered by descending hydropower generating productivity below. The economic costs and benefits arising from the annual inundation of Tonle Sap and the estuary will be directly related to the combined river flow leaving the two subregions of downstream during the wet season. The associated water flows are determined ex-post and will be kept outside the specification of the model.

Table A.1. *A list of all variables and parameters in the model*

Indices	
i	1 = China, 2 = LMB
r	m = mainstream, t = tributaries
h	Index for dams used for each pair i, r
τ	w = wet season, d = dry season

All variables and relevant parameters of our model are defined in table A.2. Water is measured in km^3. In each subregion i, r at season τ, industry and households withdraw $x_{1,w,\tau}$ of water, hydropower generation uses $q_{1,r,h,\tau}$ of water at dam h that is reusable further downstream, and the dam operator stores $y_{i,r}$ of water in the wet season for the dry season. Due to evaporation losses, only $\delta_{i,r} y_{i,r}$, $\delta_{i,r} \in (0,1)$,[1] can be used in the dry season. In region i, irrigated agriculture withdraws $i_{i,d}$ of water in the dry season, the wet season outflow from dams $o_{i,w}$ fosters regional fish reproduction, and $o_{2,w}$ flushes salinity in the estuary. The MRB has already existing dam capacity for these economic activities and a lot of plans for expanding capacity. In subregion i, r, existing (aggregate) dam capacity is denoted $D^0_{i,r}$ and (aggregate) dam capacity expansion $D_{i,r}$, where both are measured in km^3. Finally, total basin-wide water available is determined by total basin-wide precipitation or water (in)flows that is attributed to subregion i, r and season τ by the parameter $\phi_{i,r,\tau}$.

A good understanding of dam capacity is crucial for understanding the model. First, the interpretation of dam capacity in both Haddad (2011) and our model is that if hydropower generation is two units in the wet season and one unit in the dry season, then dam capacity has to be two units, which is the maximum of one and two. Furthermore, recall we have a static annual model with two seasons that mimics an annual cycle in the year 2030. Then, we assume that planning and starting constructing dams will be completed before 2030. Dam expansion should be based on the trade off between benefits and building (and other) costs.

[1] Haddad (2011) assumes a single dam and that there are no evaporation losses, i.e. all $\delta_{i,r} = 1$.

Table A.2. *A list of all variables and parameters in the model*

Variables (in km^3)	Interpretation
$x_{i,r,\tau}$	Water withdrawal by industry and households in subregion i, r at season τ
$q_{i,r,h,\tau}$	In-stream water use for hydropower generation at dam h in subregion i, r at season τ
$y_{i,r}$	Aggregate reserved water in the wet season for use in the dry season in region i
$D_{i,r}$	Aggregate expansion of dam capacity in subregion i, r
$o_{i,r,\tau}$	Aggregate outflow from dams in subregion i, r at season τ
$o_{i,\tau}$	Aggregate outflow from dams in region i at season τ
$i_{i,d}$	Water withdrawal by irrigated agriculture in region i at the dry season d
Parameters (in km^3)	
$\phi_{i,r,\tau}$	Water availability from precipitation in subregion i, r at season τ
$D^0_{i,r}$	Aggregate existing dam capacity in subregion i, r
$\bar{q}_{i,r,h,\tau}$	Maximum capacity for hydropower at dam h in subregion i, r at season τ
Fractions	
$\delta_{i,r} \in (0, 1)$	Fraction of stored water available for use at the dry season d in subregion i, r
$\gamma_{i,d} \in (0, 1)$	Maximum fraction of river flow in season d usable for irrigation in region i

Following Haddad (2011), each (sub)region has the option to build dam capacity. In our model, however, we make three modifications. First, we distinguish between existing dam capacity, whose building costs are sunk, and expanding dam capacity. Second, dam capacity is not only used for hydropower generation and storing water from the wet season for usage in the dry season, but also serves as the necessary infrastructure to provide end users such as industry and households with water. Third, as motivated in the main text, a cascade of mainstream dams has to be modelled differently than dams in tributaries, because water for hydropower generation can be reused at each downstream cascade dam. For a cascade of mainstream dams in region i, m at season τ, a water use of $q_{i,m,1,\tau}$ at the first dam, $q_{i,m,2,\tau}$ at the second dam etc. only requires $\max_h \{q_{i,m,h,\tau}\}$ of water to operate all dams. For dams of tributaries in region i, t at season τ, the amount $\sum_h q_{i,t,h,\tau}$ of water is needed to operate all dams. Note that a cascade of mainstream dams is more efficient in terms of water use because $\sum_h q_{i,t,h,\tau} > \max_h \{q_{i,m,h,\tau}\}$. There is no difference in the capacity that each type of dams requires and, therefore, the associated dam capacity is at least $\sum_h q_{i,r,h,\tau}$ independent of $r = m, t$. The existing dams of region 1 are a cascade of mainstream dams, and all existing dams of region 2 are dams in tributaries of the LMB.

Table A.3. *The constraints for upstream (in km*^{3}*)*

Water balances mainstream dams upstream (in $i, r = 1, m$)	Interpretation
$x_{1,m,w} + y_{1,m} + \max_h \{q_{1,m,h,w}\} \leq \phi_{1,m,w}$	Feasible aggregate water use from dams at season w
$x_{1,m,d} + \max_h \{q_{1,m,h,d}\} \leq \phi_{1,m,d} + \delta_{1,m} y_{1,m}$	Feasible aggregate water use from dams at season d
$x_{1,m,w} + y_{1,m} + \sum_h q_{1,m,h,w} \leq D^0_{1,m} + D_{1,m}$	Dam capacity on water use in at season w
$x_{1,m,d} + \sum_h q_{1,m,h,d} \leq D^0_{1,m} + D_{1,m}$	Dam capacity on water use at season d
$q_{1,m,h,\tau} \leq \bar{q}_{1,m,h,\tau}$	Capacity hydropower generation dam h at season τ
$o_{1,m,w} = \phi_{1,m,w} - x_{1,m,w} - y_{1,m}$	Aggregate outflow from mainstream dams at season w
$o_{1,m,d} = \phi_{1,m,d} + \delta_1 y_{1,m} - x_{1,m,d}$	Aggregate outflow from mainstream dams in at season d
Other balances (in $i = 1$)	
$o_{1,\tau} = \sum_r o_{1,r,\tau}$	Aggregate outflow from dams in region 1 at season τ
$i_{1,d} \leq \gamma_{1,d} o_{1,d}$	Feasible irrigation in region 1 at season d

Having introduced all our notation, we are ready to introduce our model. We start with discussing upstream China first and refer to table A.3 for a specification of all equations. Water availability determines water usage in region 1 and each season $\tau = w, d$. Feasibility of seasonal water use from dams is captured by the first pair of equations of table A.3. In the wet season w at region 1, inflow $\phi_{1,m,w}$ can be spent on water use by industry and households $x_{1,m,w}$, storage $y_{1,m}$ for the dry season, hydropower generation $\max_h \{q_{i,m,h,\tau}\}$ that is reusable further downstream, and pass through the dam to downstream.[2] Because pass through can be seen as a slack variable, a weak inequality holds. Similar at season

[2]This formulation extends the model for optimal hydropower generation in Haddad (2011) to include the necessary infrastructure for industrial and households' water use.

d, inflow $\phi_{1,m,d}$ and the fraction of stored water $\delta_{1,m} y_{1,m}$ can be spent on water use $x_{1,m,d}$, hydropower generation $q_{1,m,d}$ that remains available further downstream, and pass through the dam to downstream. As in Haddad (2011), dam capacity $D_{1,m}^0 + D_{1,m}$ should exceed the above mentioned water uses in each season, where we should take into account that generating a flow of $\max_h \{q_{1,m,h,\tau}\}$ hydropower generation through a cascade of mainstream dams requires at least $\sum_h q_{1,m,h,\tau}$ of capacity. These considerations imply the second pair of equations. Seasonal hydropower generation at each dam is restricted by the maximum capacity of the dam. This maximum capacity is proportional to the monthly maximum capacity and, therefore, is seasonal because of the unequal of the seasons. This explains the fifth equation, an equation that has to hold for all seasons and all dams. The last two equations state the aggregate seasonal outflow from dams in region 1. In essence, this outflow $o_{1,m,\tau}$ at season $\tau = w, d$ consists of $\max_h \{q_{1,m,h,\tau}\}$ and pass-through of unused water. Since pass through in the wet season is the slack of the first equation, we may define outflow $o_{1,m,\tau}$ as inflows minus water use. For upstream, outflow from all types of dams $o_{1,\tau}$ is equal to outflow $o_{1,m,\tau}$ in region 1. River outflow from dams $o_{1,d}$ can be used either for irrigation $i_{1,d}$ in upstream (assuming an unmodeled irrigation infrastructure that is independent of dam capacity $D_{1,m}$) or runs to downstream. This imposes $i_{1,d} \leq \gamma_{1,d} o_{1,d}$, where the fraction $\gamma_{1,d} \in (0, 1)$ restricts the maximum of river flow that can be taken out of the river.

The mainstream of the LMB $(i, r = 2, m)$ is modelled similarly as upstream, except that there is no water use by industry and households and seasonal inflows consists entirely of river outflow $o_{1,w}$ and $o_{1,d} - i_{1,d}$ from upstream. The resulting equations are given by the top part of table A.4, which do not need further discussion. Also the tributaries of the LMB $(i, r = 2, t)$ are modelled similarly as upstream, except that seasonal inflows are equal to $\phi_{2,t,w}$ and $\phi_{2,t,d}$ from precipitation, and water use for hydropower generation becomes $\sum_h \{q_{2,m,h,\tau}\}$ instead of $\max_h \{q_{2,m,h,\tau}\}$. The equations describing the tributaries are stated in the lower part of table A.4 and we forego further discussion. This completes the description of the water balances.

Table A.4. *The constraints for downstream (in km^3)*

Water balances mainstream dams downstream $(i, r = 2, m)$	Interpretation
$y_{2,m} + \max_h \{q_{2,m,h,w}\} \leq o_{1,w}$	Feasible aggregate water use from dams at season w
$\max_h \{q_{2,m,h,d}\} \leq o_{1,d} + \delta_{2,m} y_{2,m}$	Feasible aggregate water use from dams at season d
$y_{2,m} + \sum_h q_{2,m,h,w} \leq D^0_{2,m} + D_{2,m}$	Dam capacity on water use at season w
$\sum_h q_{2,m,h,d} \leq D^0_{2,m} + D_{2,m}$	Dam capacity on water use at season d
$q_{2,m,h,\tau} \leq \bar{q}_{2,m,h,\tau}$	Capacity hydropower generation dam h at season τ
$o_{2,m,w} = o_{1,w} - y_{2,m}$	Aggregate outflow from mainstream dams at season w
$o_{2,m,d} = o_{1,d} + \delta_2 y_{2,m}$	Aggregate outflow from mainstream dams at season d

Water balances mainstream dams downstream $(i, r = 2, t)$	Interpretation
$x_{2,t,w} + y_{2,t} + \sum_h q_{2,t,h,w} \leq \phi_{2,t,w}$	Feasible aggregate water use from dams at season w
$x_{2,t,d} + \sum_h q_{2,t,h,d} \leq \phi_{2,t,d} + \delta_{2,t} y_{2,t}$	Feasible aggregate water use from dams at season d
$x_{2,t,w} + y_{2,t} + \sum_h q_{2,t,h,w} \leq D^0_{2,t} + D_{2,t}$	Dam capacity on water use at season w
$x_{2,t,d} + \sum_h q_{2,t,h,d} \leq D^0_{2,t} + D_{2,t}$	Dam capacity on water use at season d
$q_{2,t,h,\tau} \leq \bar{q}_{2,t,h,\tau}$	Capacity hydropower generation dam h at season τ
$o_{2,t,w} = \phi_{2,t,w} - x_{2,t,w} - y_{2,t}$	Aggregate outflow from tributary dams at season w
$o_{2,t,d} = \phi_{2,t,d} + \delta_2 y_{2,t} - x_{2,t,d}$	Aggregate outflow from tributary dams at season d

Other Water balances (in $i = 2$)	
$o_{2,\tau} = \sum_r o_{2,r,\tau}$	Aggregate outflow from dams in region 2 at season τ
$i_{2,d} \leq \gamma_{2,d} o_{2,d}$	Feasible irrigation in region 2 at season d

All benefit functions of water use are quadratic and of the functional form $f(x) = x(a - bx)$, which has a satiation level at $x = \frac{1}{2}a/b$. Also, all cost and loss functions are quadratic and of the functional form $f(x) = cx^2$. For construction costs, this modifies the linear cost function for dam capacity in Haddad (2011). The calibrated functions for upstream are represented in table A.5 and those for downstream in table A.6. The estimation of the benefit functions for hydropower generation is involved and a discussion is deferred to Appendix B. This appendix also contains details about the calibration of the cost functions. Given these benefit and cost functions, the other benefit functions and parameters were calibrated directly from the first-order conditions determining the disagreement point (discussed below), where we assume weak governance for downstream. The satiation level of irrigation was chosen to coincide with the plans for the future, presuming that these plans seen in isolation reflect a realistic cost-benefit trade off.

The salinity issues are concentrated in the estuary, downstream of any planned dam construction. The wet season river flow partly flows into Tonle Sap in Cambodia, where it fosters the world largest inland fish resource, and the remaining part flows to the estuary flushing salinity from agricultural land. In the dry season, the constant river flow from Tonle Sap to the estuary minimizes salt water intrusion (Campbell, 2009). In our model, the intake by Tonle Sap (and wetlands) in the wet season is modeled ex-post as $87.000 \cdot o_{2,w}/\bar{o}_{2,w}$, where $\bar{o}_{2,w}$ is current river outflow and 87.000 km^3 is our estimate of Tonle Sap capacity to store water. This linear relation allows us to relate the losses due to reduced flushing of salinity in the estuary directly in terms of the wet season flow $o_{2,w}$. We assume that twenty per cent less $o_{2,w}$ would destroy irrigated agriculture in the estuary (Campbell, 2009). The calibrated loss function is stated in table A.6.

Finally, we denote the net benefit functions for region $i = 1, 2$ as $w_i(\cdot)$, where we suppress the long list of its arguments. The net benefit function of upstream, is informally given by

$$w_1(\cdot) = \sum \text{benefit functions table A.5} - \sum \text{cost and loss functions table A.5}, \qquad (1)$$

and that of downstream by

$$w_2(\cdot) = \sum \text{benefit functions table A.6} - \sum \text{cost and loss functions table A.6}. \qquad (2)$$

This completes the description of costs and benefits of water use.

Table A.5. *The benefit and cost functions of upstream (in billion US$)*

Benefit functions upstream	Interpretation
Mainstream dams $(i, r = 1, m)$	
$x_{1,m,w}\,(0.638 - 0.428x_{1,m,w})$	Industry and households in season w
$x_{1,m,w}\,(0.638 - 0.598x_{1,m,w})$	Industry and households in season d
$q_{1,m,h,w}\,[(900 - 144.72\,(h-1)) - 3.81q_{1,m,h,w}] \cdot 10^{-5}$	Hydropower generation at dam h in season w
$q_{1,m,h,d}\,[(900 - 144.87\,(h-1)) - 5.34q_{1,m,h,d}] \cdot 10^{-5}$	Hydropower generation at dam h in season d
Other sectors	
$i_{1,d}\,(0.372 - 0.029i_{1,d})$	Irrigated agriculture in season d
$o_{1,w}\,(800 - 6.65o_{1,w}) \cdot 10^{-5}$	Fishery on annual basis
Cost and loss functions upstream	
$7.475D_{1,m}^{2} \cdot 10^{-6}$	Building costs of mainstream dam capacity
$4.875D_{1,m}^{2} \cdot 10^{-6}$	Losses to fishery of building dams

Table A.6. *The benefit and cost functions for downstream (in billion US\$)*

Benefit functions downstream	Interpretation
Mainstream dams $(i, r = 2, m)$	
$q_{2,m,h,w}\left[(2000 - 173.76\,(h-1)) - 2.54q_{2,m,h,w}\right] \cdot 10^{-6}$	Hydropower generation at dam h in season w
$q_{2,m,h,d}\left[(2000 - 173.96\,(h-1)) - 3.56q_{2,m,h,d}\right] \cdot 10^{-6}$	Hydropower generation at dam h in season d
Tributary dams $(i, r = 2, m)$	
$x_{2,t,w}\,(1.205 - 0.318x_{2,t,w})$	Industry and households in season w
$x_{2,t,w}\,(1.206 - 0.446x_{2,t,w})$	Industry and households in season d
$q_{2,t,h,w}\left[(400 - 28.225\,(h-1)) - 3.33q_{2,t,h,w}\right] \cdot 10^{-5}$	Hydropower generation at dam h in season w
$q_{2,t,h,d}\left[(400 - 28.272\,(h-1)) - 4.67q_{2,t,h,d}\right] \cdot 10^{-5}$	Hydropower generation at dam h in season d
Other sectors	
$i_{2,d}\,(0.276 - 0.001i_{2,d})$	Irrigated agriculture in season d
$o_{2,w}\,(1600 - 2.26o_{2,w}) \cdot 10^{-5}$	Fishery on annual basis
Cost and loss functions downstream	
$9.455D_{2,m}^2 \cdot 10^{-7}$	Building costs of mainstream dam capacity
$2.497D_{2,t}^2 \cdot 10^{-6}$	Building costs of tributary dam capacity
$5.769D_{2,m}^2 \cdot 10^{-6}$	Losses to fishery of building mainstream dams
$1.685D_{2,t}^2 \cdot 10^{-5}$	Losses to fishery of building tributary dams
$2.202\,(421.900 - o_{2,w})^2 \cdot 10^{-4}$	Losses agriculture due to salinity

The Nash bargaining solution

The asymmetric Nash bargaining solution (Nash, 1950; Kalai 1977) that we apply in our analysis maximizes an objective function that depends on the regions' net benefits, disagreement points, and bargaining weights.

As discussed in the main text, upstream maximizes its own regional net benefit and this determines its disagreement utility

$$d_1 \equiv \arg\max w_1\left(\cdot\right), \qquad \text{s.t. all equations of table A.3.} \tag{3}$$

The seasonal outflows from upstream to downstream, $o_{1,w}$ and $o_{1,d} - i_{1,d}$, that result from (3) is given for downstream. Weak governance by downstream is modeled as a sequence of two maximization problems. First, given the mentioned inflows, downstream dam operators solve

$$\begin{aligned} \max \quad & \sum\nolimits_{r,h} \text{economic benefit hydropower generation} - \sum\nolimits_{r} \text{construction costs} \\ & + \sum \text{economic benefit industry and households,} \\ & \text{s.t. the equations of table A.3 except those for } o_{2,r,\tau},\ o_{2,\tau} \text{ and } i_{2,d} \end{aligned} \tag{4}$$

The seasonal outflows from both types of downstream dams to Tonle Sap and irrigated agriculture, $o_{2,w}$ and $o_{2,d}$, that result from (4) are given for irrigated agriculture, fishery and determines the losses of reduced flushing of salinity. Second, the downstream irrigated agricultural sector solves

$$\max_{i_{2,d}} i_{2,d} \left(0.276 - 0.001 i_{2,d}\right), \text{ s.t. } i_{2,d} \leq \gamma_{2,d} o_{2,d}. \tag{5}$$

This program can be solved straightforwardly as $i_{1,d} = \min \left\{138.0, \gamma_{2,d} o_{2,d}\right\}$. The disagreement point for downstream under *weak governance* is given by the sum of the net benefits resulting from (4) and (5) minus losses due to externalities. Formally,

$$d_2^{weak} \equiv (4) + (5) + \text{economic benefit fishery} - \text{losses externalities} \tag{6}$$

specifies the disagreement point under weak governance.

As one of the scenarios, we also consider the case in which downstream has strong governance. This is modeled similarly as for upstream. Given inflows from upstream, downstream under strong governance maximizes its own regional net benefit and this determines its disagreement utility

$$d_2^{strong} \equiv \arg\max w_2 \left(\cdot\right), \qquad \text{s.t. all equations of table A.4.} \tag{7}$$

A measure for the welfare loss of weak governance in the LMB is the difference $d_2^{strong} - d_2^{weak}$, which is an issue of interest in our study. We write $d_2 = d_2^{weak}, d_2^{strong}$ to capture the two scenarios for downstream governance.

The regions' disagreement levels play an important role in the Nash bargaining solution. An important part of this solution is a (financial) transfer, denoted $t \in \mathbb{R}$, from downstream to upstream. If positive, it is a compensation of upstream for measures taken that cause positive externalities. If negative, it is a compensation of downstream for negative externalities caused by upstream. Recall that $\alpha \in [\frac{1}{2}, 1)$ is upstream's bargaining weight and $1 - \alpha$ is downstream's weight. Formally, the asymmetric Nash bargaining solution is given by the unique maximizer of the following program:

$$\max \left(w_1(\cdot) + t - d_1\right)^{\alpha} \left(w_2(\cdot) - t - d_2\right)^{1-\alpha}, \tag{8}$$

s.t. all equations of tables A.3 and A.4.

Appendix B: Costs and benefits of hydropower

In this appendix, we discuss the estimation of the benefit functions and construction cost functions for hydropower generation and the loss functions for fishery. The estimation of the benefit functions is involved in order to capture the difference between a cascade of mainstream dams and separate dams on separate tributaries.

Our data on dams consisted of the name of the dam, location, height, capacity MW and occasionally GWh. All data were obtained from the internet.[3] From these data we calculated a data set on water use in km^3 and GWh per dam. Water use for hydropower generation is determined by

$$m^3/s = 1000 \cdot 1000 \cdot MW/(9.8 \cdot 998 \cdot Height),$$

where 9.8 m^2/s is the gravitational force and 998 is the weight in kg of 1000ℓ of water. Multiplication by annual effective operation time 2.280×10^7 (s/year) and dividing by 10^9 yields annual water use in km^3, from which monthly and seasonal water use follows. Data on capacity MW per dam is converted into annual GWh: Multiplication of capacity by annual

[3] Among the websites are Wikipedia Mekong River Basin Hydropower, the Asian Development Bank, the China International Water and Electric Corporation, the HydroChina Zhongnan Engineering Corporation, and www.InternationalRivers.org.

effective operation time determines energy generated in Mjoule, from which GWh follows:

$$MJoule = 2.280 \cdot 10^7 \cdot MW, \qquad GWh = \frac{1}{3.6 \cdot 10^6} MJoule.$$

The obtained estimates required some scaling down to match our sparse data on GWh per region and type of dam (mainstream versus tributary). The reason for the overestimation is that the height of the dam is larger than the average height of the water in the dam and the latter determines the GWh.

Next, for each region and type of dam, we ordered our dam data by descending average productivity GWh per km^3 from which we constructed another data set with cumulative km^3 and cumulative GWh, where both were calculated on a monthly basis. Scatter diagrams reveal an almost perfect quadratic relation $f(x) = x(a - bx)$. Ordinary least square estimation determines our coefficients a and b for each region and type of dam with an R^2 of 0.931 or above. Finally, Thailand pays Laos a price of 0.013 million US$ per GWh for electricity from the Nam Theun 2 dam, which we used as a proxy for the electricity price throughout the entire basin.

Dams are heterogeneous. This is captured as follows. First, we impose an average hydropower generating capacity per dam, say $\bar{x}$. Second, we assume that each first dam per region and type generates hydropower x_1 according to our estimated cumulative benefit function up to its maximum capacity, that is $x_1(a - bx_1)$ for $x_1 \leq \bar{x}$. Then, the second dam starts to generate hydropower x_2 and follows the estimated cumulative curve between one and two times the maximum dam capacity, that is $x_2(a - 2b\bar{x} - bx_2)$ for $\bar{x} \leq x_2 \leq 2\bar{x}$, etc.[4] Then, it is as if hydropower generation from dam h is given by $x_h(a - (h-1)2b\bar{x} - bx_h)$ for $h\bar{x} \leq x_2 \leq (h+1)\bar{x}$. This explains the expressions for hydropower generation in tables A.5 and A.6. Note that this way of modeling orders all dams per region and type by descending (marginal) productivity. In the optimum, the most productive dams will be used

[4]The formula follows from

$$(\bar{x} + x_2)(a - b(\bar{x} + x_2)) = \bar{x}(a - b\bar{x}) + x_2(a - 2b\bar{x} - bx_2).$$

for hydropower generation.

For four mainstream dams in China and five tributary dams in Laos, we have retrieved building costs. Applying the same procedure as above, we obtain scatter diagrams that reveal an almost perfect quadratic relation $f(x) = cx^2$. After the estimation, we rescaled these cost functions such that future plans for hydropower generation maximize the net economic benefit $x(a - bx) - cx^2$. Rescaling is necessary because otherwise dam expansion for hydropower generation would be unprofitable. The estimated cost functions are presented in tables A.5 and A.6.

Dam capacity disrupts fish migration and fish reproduction and the exact effects are unknown but huge. For downstream, we assume that constructing all mainstream dams of the LMB damages fishery by 80% of its current economic benefit and all tributary dams damages fishery by only 10%. For upstream, we assume 20%. We calibrated the cost coefficient of cx^2 per region and type of dam by equating this function to the assumed loss and taking x equal to the cumulative future hydropower generation for the associated region and type of dam from our calculated data set.

References

Campbell, I. (2009), *The Mekong: Biophysical Environment of an International River Basin*, Elsevier publishers.

Haddad, M. (2011), 'Capacity choice and water management in hydroelectricity systems', *Energy Economics* **33**: 168-177.

Kalai, E. (1977), 'Nonsymmetric Nash solutions and replication of 2-person bargaining', *International Journal of Game Theory* **6**: 129–133.

Nash, J. (1950), 'The bargaining problem',*Econometrica* **18**: 155-162.