Topics in Trans-boundary River Sharing Problems and Economic Theory

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Chapter 5

Damming Trans-boundary River Basins: A welfare analysis

5.1 Introduction

Most rivers exhibit seasonal flow. Water flow is high in certain months of the year due to high rainfall precipitation and/or snow melting. In other months, less rainfall and snow melting might result in low water flow or even drought. For instance, the water flow in the wet season (from June to November) in the Mekong River is seven times higher than the flow in the dry season (from December to the next May), as mentioned in Ringler et al. (2004). Similar phenomena can be observed in other river basins, e.g., Zambezi River (Beck (2010)). Dams are constructed to deal with the variability of water flow within a year and play a role to store water from the wet to dry season, to generate hydropower generation and for flood control. For instance, the Grand Millennium Dam under construction in Ethiopia, on the Nile River, is built mainly for hydropower generation and water storage (Gebreluel (2014) and Jeuland and Whittington (2014)); the Three Gorges Dam in China, on the Yangtze River, is mainly used for hydropower generation (Fearnside (1988)).

Decision makers often consider where and how large to build the dam in order to extract maximal benefits from water resources. Several economic studies try to answer this question. Haddad (2011) models dam capacity as a continuous choice variable and assumes linear cost of dam capacity, taking the environmental, social and ecological costs into account. Houba et al. (2013, 2014a) consider the cost of dam construction as a convex function of dam capacity.

Dams alter river flows, resulting in significant impacts on livelihoods, fishery and the environment, etc. For instance, there is a number of studies concerning the impact of dams on fishery in the Mekong River Basin since dams hinder the many migratory fish species in the Mekong River (Baron et al. (2007) and ICEM (2010)); thousands of residents in the area of the Three Gorges Dam have been relocated in China due to the rise of the river level upstream of the dam (Fearnside (1988)); the Itaipu Dam on the Parana River in the La Plata floods 10,000 ha of land and destroys significant aquatic habitat including the Guaira Falls (Tucci and Clarke (1998) and Gilman et al. (2008)); the Grand Millennium Dam on the Nile river in Ethiopia may significantly change the river flow pattern and endanger the livelihoods in Egypt (Gebreluel (2014) and Jeuland and Whittington (2014)). Note that the impact of a dam might not only be local but also be trans-boundary. For instance, the dam construction in upstream Laos might harm fishery in downstream Cambodia in the Mekong River (ICEM (2010)).

Trans-boundary basins account for 60% of global river flows. About 40% of the world population live in trans-boundary river basins and 145 countries share basins (Fox (2009)). Of the world's 261 trans-boundary basins, 176 are bilateral and 85 are shared by more than two riparian countries (Wolf et al. (1999)). Conflicts over the water allocation in trans-boundary river basins are well documented (Just and Netanyahu (1998)). For instance, an upstream country can divert water at its source or pollute water carelessly, decreasing both water quantity and quality available to downstream countries. In the same river basin, different countries may have different interests in water use, e.g., in the Mekong River, Laos heavily depends on the hydropower on dams to reduce its poverty, while Cambodia relies on the fishery to feed its people (Just and Netanyahu (1998)).

This brings the interests of economists to resolve conflicts in trans-boundary river basins. Giannias and Lekakis (1996), Kilgour and Dinar (2001), Ambec and Sprumont (2002) and Houba et al. (2014b) investigate how to allocate water resources in terms of efficiency, i.e., achieving the maximal amount of benefits in the whole river basin. The next relevant question is how to distribute the maximal amount of benefits among countries in the same river basin. Ambec and Sprumont (2002) incorporate two legal principles from International Water Law: Absolute Territorial Sovereignty (ATS) and Unlimited Territorial Integrity (UTI). According to ATS, they argue that each group of agents should not get less than the welfare it could achieve by using the water it controls. Using UTI, they argue that no group of agents could achieve a welfare higher than what it could achieve in absence of the remaining agents. They show that the downstream incremental solution, according to which an agent's welfare is just his marginal contribution to the coalition composed of his predecessors along the river, is the only solution satisfying the above two requirements. Ambec and Ehlers (2008) generalize the analysis to the satiated water use benefit function. Houba et al. (2014b) propose asymmetric Nash solutions to distribute the benefits among countries in the river basin. And the disagreement points in these Nash solutions are based on different scenarios with respect to the above mentioned two legal principles. In the domain of cooperative game theory, van den Brink et al. (2012) consider river situations with satiable agents and multiple springs and propose the class of weighted hierarchical solutions. Other researchers link the water agreements with other relevant issues. Pham Do et al. (2012) and Pham Do and Dinar (2014) consider how to sustain water allocation agreements by linking other relevant issues, for instance, in the Mekong river basin, China might have an incentive to cooperate with other countries in the basin, taking into account trade agreements among these countries.

This chapter contributes to the literature of trans-boundary water allocation problems by taking into account seasonality and the possibility of damming the trans-boundary river. Many developing countries have ambitious hydropower plans for their development, neglecting externalities of such plans. For instance, Laos relies heavily on the income from hydropower of the Mekong River to get rid of its poverty. We assume that due to differences in geographical factors, the cost of dam construction exhibits heterogeneity among countries. For instance, it might be easier to build dams in mountainous areas and much more difficult to construct a dam in flat fields. We also add the possible influence of political power by distributing the joint budget for the dam construction among countries. For instance, for a given budget of dam construction in the Mekong river basin, Thailand might get a larger share than Laos, while in reality Laos has more potential for hydropower development.

Another contribution of this chapter is that we also investigate the stability of an already formed coalition in the International Water Sharing Agreements by examining the possibility of unilateral deviations. This question is vital to preventing existing coalition members from defecting the current coalition in the International Water Sharing Agreements. We employ the concept of internal stability and consider the "outside option" of each country. In this respect, each country should get at least its "outside option" in the current coalition. When one country leaves the current coalition, a new coalition structure in the whole river basin is present and the deviating country can anticipate its benefit in the new coalition structure. This serves as the "outside option" for the current coalition.

In this chapter, we analyze the following three scenarios:

The first scenario is the disagreement point where each agent pursues his own interest. We invoke the principle of Absolute Territorial Sovereignty (hereafter, ATS) from International Water Law (Ambec and Sprumont (2002), McCaffrey (2001) and Houba et al. (2014b)), to calculate the disagreement point for each agent involved in the trans-boundary river basins. As mentioned in Chapter 1, the ATS principle states that a country has absolute sovereignty over the area of any river basin on its territory: it may freely decide how much water to use of the water flowing within its borders but cannot claim the continued and uninterrupted flow from upper basin countries. This scenario specifies the case of no cooperation among agents. In the absence of International Agreements or weak governance of International Agreements regarding water allocations, this scenario provides each agent his fall back option.

The second scenario is the joint cooperation. The 1997 United Nations Report states that, "there is a clear need for cooperation in the management of international and trans-boundary watercourses to maximize mutual benefits for all riparian countries." Joint cooperation in the trans-boundary river basins achieves the first-best outcome in terms of efficiency. Under the efficient water allocation, how to distribute maximal benefits among agents to sustain the cooperation is the next issue. We apply the (asymmetric) Nash bargaining solution as analyzed in Chapter 3 (see also, Binmore et al. (1986), Houba (2008) and Houba et al. (2014b)). The bargaining weights among agents are exogenously determined by the GDP, population sizes, political factors, military powers etc. In short, the final benefits for each agent in the joint cooperation arrangement is equal to his disagreement point calculated by the ATS principle plus a fraction of the net surplus (i.e., the maximal benefits minus the sum of all agents' disagreement points) from cooperation.

The third scenario is the partial cooperation scenario. In this scenario, some countries involved in the trans-boundary river basin cooperate while each of the other countries acts as a singleton and pursues its own interests. Just and Netanyahu (1998) identify several difficulties to cooperate on the basin-wide level such as, lack of effective enforcement mechanisms and institutions, natural claims for sovereignty, unavoidable conflicting national and international interests, and geographical upstream/downstream considerations. In-

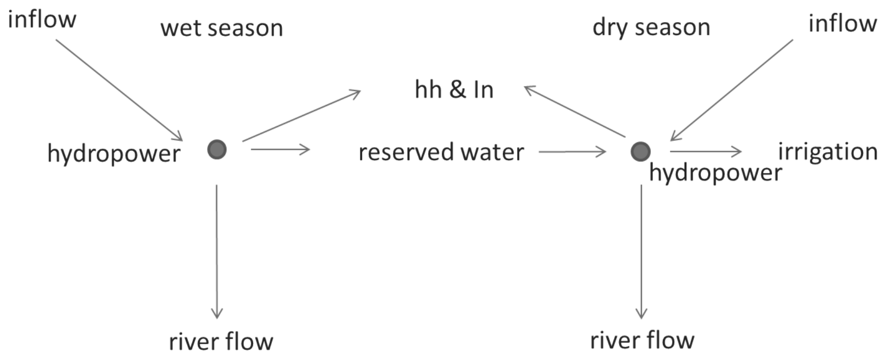

Figure 5.1: Water allocation within a water economy of an agent

deed, basin-wide agreements on water allocation are rarely formed. Instead, agreements involving some agents are often observed. For example, four Lower Mekong countries (i.e., Laos, Thailand, Cambodia and Vietnam) signed the 1995 Mekong Agreement to manage the water allocation in the Lower Mekong Region and upstream China is not in the agreement.[1] In the Nile River, five upstream countries (Rwanda, Tanzania, Uganda, Kenya and Burundi) signed the new Nile River Co-operative Framework Agreement to coordinate the water allocation and other countries in the Nile River basin are not in the agreement. We investigate the stability of partial coalition and how to distribute the benefits in the formed coalition in order to prevent unilateral deviation of one agent from the coalition.

The remainder of this chapter is organized as follows. In Section 5.2, we define the trans-boundary river basin model. In Section 5.3, the disagreement and the joint cooperation scenarios are analyzed. The model with partial cooperation scenario is presented in Section 5.4. We apply the model to investigate the Mekong River Basin in Section 5.5. Section 5.6 concludes.

5.2 The model

Let $N = \{1, 2, \cdots, n\}$ be the set of agents involved in the river sharing problem.[2] An agent should be interpreted as a water use spot, e.g., a nation, a region or a city. Following Chapter 3, we denote P^i as the set of all agents that can possibly transfer water to agent i, $i \in N$. We consider rivers that arise in multiple springs, but we do not consider situations where rivers diverge.[3] We sketch the scenario of water allocation for territory of agent i in Figure 5.1. Within a year, economic activities related to water can be classified as

[1]Though Myanmar is in the Mekong river basin, it accounts for about only 2 percent flow and 3 percent catchment of the whole basin.

[2]In this chapter, we use agent and player interchangeably.

[3]In case the river diverges at a certain point, we need additional information, e.g., water flow speed and altitude difference at the divergent location, to identify the water flow amount to each branch.

the wet and dry season. Each agent i receives inflow $o_{i,s}$ from his predecessors in season s and the amount of water resources arising in agent i's territory is denoted as $e_{i,s}$. The inflow for agent i in Figure 5.1 should be interpreted as the sum of inflows received from his predecessors plus the water resource arising within agent i. Dams play an important role storing water from the wet to dry season, but not across years. Reservoirs behind the dam are emptied at the end of the dry season. The water stored behind the dam is constrained by the dam capacity D_i and can be used for hydropower generation, household and industry, and irrigation. The water reserved from wet to dry season for agent i is denoted as r_i. Water use can be further classified as in-stream and off-stream use. In-stream use means that water used upstream can be re-used further downstream, e.g., the water use for hydropower generation. In case that water use is consumptive,[4] we say that it is off-stream use, e.g., household, industry and irrigation. We assume that there is no seasonal differences in household and industry water related activities, thus they take the same benefit function across seasons. We assume a benefit function $b_{i,k}(x_{i,k,s})$ for off-stream water use of agent i in season s and sectors $k \in K = \{hh, in, ir\}$ could be household, industry and irrigation, where $x_{i,k,s}$ is the water use amount in agent i in season s of sector k.

Assumption 5.1. *The benefit function* $b_{i,k}(x_{i,k,s}) : \mathbb{R}_+ \to \mathbb{R}_+$, $i \in N$, $s \in S$, $k \in K$, *is continuous, differentiable, strictly concave and has a satiation point* $\hat{x}_{i,k,s}$, *with* $\hat{x}_{i,ir,w} = 0$.

The latter assumption states that there is no irrigation taking place in the wet season.

Suppose that agent i, $i \in N$, is endowed with budget C_i to build dams and the cost function for dam construction is $c_i(D_i)$. The budget could be interpreted as the maximum amount of payment available for dam construction. For each agent i with a certain budget C_i, it should hold that $c_i(D_i) \leq C_i$. We allow c_i to exhibit different functional forms across agents and this captures the phenomenon that for some agents a dam is relatively easy to build, e.g., in mountainous areas, while within other agents a dam is difficult to construct and bears significant costs, such as in flat floodplains.

Assumption 5.2. *The cost function of dam construction* $c_i(D_i) : \mathbb{R}_+ \to \mathbb{R}_+$, $i \in N$, *is continuous, differentiable and increasing, i.e.,* $\frac{\partial c_i}{\partial D_i} > 0$.

Note that Haddad (2011) assumes a linear cost function of dam capacity and Houba et al. (2013, 2014a) assume a convex function of dam capacity. All their assumptions need further justification. By only assuming increasing costs, the cost function of dam capacity in this chapter is more general.

The water use for hydropower generation within the territory of each agent i is denoted by $q_{i,s}$ and the benefit function from water use for hydropower generation is $Q_i(q_{i,s})$.

Assumption 5.3. *The benefit function from hydropower generation is continuous, non-decreasing in the amount of water use for hydropower generation. And there exists a* $\hat{q}_{i,s} > 0$ *such that for* $q_{i,s} \in [0, \hat{q}_{i,s}]$, $\frac{\partial Q_i}{\partial q_{i,s}} > 0$ *and for* $q_{i,s} > \hat{q}_{i,s}$, $\frac{\partial Q_i}{\partial q_{i,s}} = 0$, $i \in N$, $s \in S$.

[4]As stated in Pham Do and Dinar (2014) page 501, "consumptive use commonly refers to water that is unavailable for reuse in the basin from which it was extracted due to evaporation, incorporation into production biomass, transfer to another basin, seepage to saline sink, or contamination."

In the above assumption, we allow for the possibility that $\frac{\partial Q_i}{\partial q_{i,s}} = 0$ by taking the maximum capacity of turbines of hydropower generation into account.

We have a damage function for agent i when dams in agent i's territory or his predecessors are built. Note that we allow damage to agent i incurring by the dams from his predecessors. The damage function can be interpreted as environmental and ecological costs, e.g., damage to fishery in downstream Cambodia due to dam construction in upstream Laos in the Mekong River Basin (Baron et al. (2007) and ICEM (2010)). Let $\tilde{\mathbf{D}}_\mathbf{i} \in \bigtimes_{h \in P^i \cup \{i\}} D_h$ and $F_i(\tilde{\mathbf{D}}_\mathbf{i})$ be the annual damage function for agent i.

Assumption 5.4. *Refraining from building of dams on agent i's territory and his predecessors does not cause damages to agent i, i.e.,* $F_i(0, \cdots, 0) = 0$. *The marginal damage of building dams on agent h territory,* $h \in P^i \cup \{i\}$ *is nonnegative for agent i, i.e.,*

$$\frac{\partial F_i}{\partial D_h} \geq 0.$$

Given the inflow $o_{i,s}$ received from his predecessors in the wet and dry seasons, we have the following maximization problem for agent i,

$$\max_{x_{i,k,s}, q_{i,s}, D_i} \sum_{k \in K} \sum_{s \in S} b_{i,k}(x_{i,k,s}) + \sum_{s \in S} Q_i(q_{i,s}) - c_i(D_i) - F_i\left(\tilde{\mathbf{D}}_\mathbf{i}\right) \tag{5.1}$$

$$\text{s.t.} \quad \sum_{k \in K} x_{i,k,w} + q_{i,w} + r_i \leq e_{i,w} + o_{i,w}, \tag{5.2}$$

$$\sum_{k \in K} x_{i,k,d} + q_{i,d} \leq e_{i,d} + o_{i,d} + r_i, \tag{5.3}$$

$$\sum_{k \in K} x_{i,k,w} + q_{i,w} + r_i \leq D_i, \tag{5.4}$$

$$c_i(D_i) \leq C_i, \tag{5.5}$$

where

$$o_{i,w} = \sum_{h \in P^i} \left(e_{h,w} - r_h - \sum_{k \in K} x_{h,k,w} \right) \tag{5.6}$$

is the water resources agent i receives from his predecessors in the wet season and

$$o_{i,d} = \sum_{h \in P^i} \left(e_{h,d} + r_h - \sum_{k \in K} x_{h,k,d} \right) \tag{5.7}$$

is the water resources agent i receives from his predecessors in the dry season. The objective function (5.1) summarizes the water use benefits derived from corresponding sectors (household, industry, irrigation and hydropower), the costs for dam construction and negative externalities from dam construction from agent i and his predecessors. Water resource constraint for agent i in the wet season is given by (5.2) and the constraint in the dry season is given by (5.3). Note that r_i is stored in the wet season and can be used in the dry season. The water storage behind the dam should not exceed the capacity as stated in (5.4) and it can be used for consumptive use in any sector k, hydropower generation and water reservations. We only add the water storage constraint in the wet season since we assume that in most cases the storage capacity behind the dam is more demanding in the wet season than the dry season.

5.3 The disagreement and joint cooperation scenarios

In this section, we discuss how to apply the Absolute Territorial Sovereignty principle to calculate the disagreement scenario, how to calculate the maximal benefits and distribute the benefits among all agents in the joint cooperation scenario by applying the asymmetric Nash bargaining solution. Similar analysis can be found in Chapter 3.

In trans-boundary river basins, the property rights for water are not properly defined. Two principles are invoked in most situations, i.e., Absolute Territorial Sovereignty (ATS) and Unlimited Territorial Integrity (UTI) (Ambec and Sprumont (2002) and McCaffrey (2001)). The ATS principle, also known as the Harmon doctrine (McCaffrey (1996)), states that a country has absolute sovereignty over the area of any river basin on its own territory: it may freely decide how much water to use of the water flowing within its borders but cannot claim the continued and uninterrupted flow from upper basin countries. Based on this principle, we calculate each agent's disagreement point and denote the corresponding result as $\mathbf{d} = (d_1, d_2, \cdots, d_n) \in \mathbb{R}_+^N$.
Similar to Houba et al. (2014b), we use the following algorithm to calculate the disagreement point $\mathbf{d}$.

1. We start with any agent that does not have any predecessors, i.e., $P^i = \emptyset$. For agent i with $P^i = \emptyset$, $o_{i,s} = 0, s = w, d$. Then we solve the maximization problem (5.1)-(5.5) for agent i and d_i is the value of (5.1) in the solution.
2. For agent i, in case that his predecessors' disagreement points are calculated, $o_{i,s}$ follows from equations (5.6) and (5.7). Then we solve the maximization problem (5.1)-(5.5) for agent i.

Note that for each agent i, we will be able to calculate the disagreement point as illustrated in Step 2 in the above algorithm conditional on that his predecessors' optimal disagreement points are settled down and are common knowledge. We denote the solution of (5.1)-(5.5) for $i \in N$ as $\{x^*_{i,k,s}, q^*_{i,s}, D^*_i\}$. Subsequently, we can obtain the disagreement vector d^* by plugging the above solution into (5.1). It is quite straightforward to prove the existence of $\{x^*_{i,k,s}, q^*_{i,s}, D^*_i\}, i \in N$, by applying Weierstrass extreme value theorem.

In the above algorithm, we have solved the disagreement scenario by applying the ATS principle. Next, we are going to consider the joint cooperation scenario. In the river sharing problem, given each agent's disagreement point, applying (asymmetric) Nash bargaining solutions to solve the joint cooperation scenario is appropriate (Nash (1950), Binmore et al. (1986) and Houba et al. (2014b)). Nash bargaining solutions achieve the maximal amount of benefits in the whole river basin and distribute the benefits among all agents based on the disagreement point and the bargaining weights. The bargaining weights of the agents, given by $\alpha = (\alpha_1, \alpha_2, \cdots, \alpha_n) \in \mathbb{R}_+^N$, with $\sum_{i=1}^n \alpha_i = 1$, are assumed to be exogenously determined by GDP, population sizes, political factors, military strength and other factors. There are two elements to be considered for the final outcome in the asymmetric Nash solutions: the disagreement vector $\mathbf{d}$ and the maximal benefits from cooperation. Let v be the value of the objective function in a solution of the following maximization problem,

$$\max_{x_{i,k,s},q_{i,s},D_i} \sum_{i\in N}\left(\sum_{k\in K}\sum_{s\in S} b_{i,k}(x_{i,k,s}) + \sum_{s\in S} Q_i(q_{i,s}) - c_i(D_i) - F_i\left(\tilde{\mathbf{D}}_{\mathbf{i}}\right)\right) \tag{5.8}$$

$$\begin{aligned}
\text{s.t.} \quad & \sum_{k\in K} x_{i,k,w} + q_{i,w} + r_i \le e_{i,w} + o_{i,w}, i = 1, \cdots, n, \\
& \sum_{k\in K} x_{i,k,d} + q_{i,d} \le e_{i,d} + o_{i,d} + r_i, i = 1, \cdots, n, \\
& \sum_{i=1}^{n} c_i(D_i) \le \sum_{i=1}^{n} C_i, \\
& \sum_{k\in K} x_{i,k,w} + q_{i,w} + r_i \le D_i, i = 1, \cdots, n, \\
& o_{i,w} = \sum_{h\in P^i}\left(e_{h,w} - r_h - \sum_{k\in K} x_{h,k,w}\right), i = 1, \cdots, n, \\
& o_{i,d} = \sum_{h\in P^i}\left(e_{h,d} + r_h - \sum_{k\in K} x_{h,k,d}\right), i = 1, \cdots, n.
\end{aligned}$$

Note in the joint cooperation scenario, we allow monetary transfers among agents to support the dam construction as specified in $\sum_{i=1}^{n} c_i(D_i) \le \sum_{i=1}^{n} C_i$. Let $\{\hat{x}_{i,k,s}, \hat{q}_{i,s}, \hat{D}_i\}$, $i \in N$, be a solution of the maximization problem (5.8). It can be easily verified that $\sum_i d_i \le v$ since the solution of the maximization (5.1)-(5.5) for all agents is an admissible choice for maximization problem (5.8).

In the joint cooperation scenario in which all agents involved cooperate, let u_i be the final outcome for agent $i, i \in N$. Application of Houba et al. (2014b) yields the following result.

Proposition 5.1. *In the joint cooperation scenario, each agent gets its disagreement payoff plus a share of the surplus, i.e.,*

$$u_i = d_i + \alpha_i(v - \sum_i d_i), i \in N.$$

The final outcome for agent i under joint cooperation is obtained by applying the asymmetric Nash bargaining solution with total payoffs v, disagreement payoff d_i and his bargaining weight α_i. Each agent i gets his disagreement payoff d_i plus his fractional share (which is equal to his bargaining power α_i) of the surplus $(v - \sum_i d_i)$.

5.4 Partial cooperation scenario

In trans-boundary river basins, we only allow neighboring agents to cooperate since for the agents that are not contiguous, water transfers are more difficult and the agents in between can take some water bearing no extra cost. Let Π be the collection of all possible partitions of N. We denote an exogenous partition of N into m connected groups of agents as $\pi = \{P_1, P_2, \ldots, P_m\} \in \Pi$ and we call an element in π a group of agents. In particular, each P_j has a unique most downstream agent p_j^d and each $h \in P_j$ is connected to p_j^d within P_j.[5] Note that $|P_1| + |P_2| + \cdots + |P_m| = n, m \leq n$, where $|P_j|$, $j = 1, \ldots, m$, is the number of agents in P_j, $P_j \in \pi$. In case $m = n$, each agent is a singleton and the situation is degenerated into the disagreement scenario discussed in Section 5.3. In case $m = 1$, the grand coalition is formed and the situation is degenerated into the joint cooperation scenario in Section 5.3. Let the maximal payoff for each group of agents in partition π be $d(P_j|\pi)$, $P_j \in \pi$. We implement the following algorithm to calculate $d(P_j|\pi)$, $P_j \in \pi$:

Algorithm 1: ATS principle to calculate $d(P_j|\pi)$

We calculate the payoff of P_j, $P_j \in \pi$ given the disagreement points under π for those group of agents that can possibly transfer water to any agent within P_j is calculated (also including the case that P_j has no predecessor) and are common knowledge. Note that the calculation of the payoff of P_j can be formulated in a similar way as (5.8) given all group of agents' disagreement points that can possibly transfer water to any agent within P_j are calculated.

We give one example to illustrate Algorithm 1. In this example, we simplify the river geography of the Mekong Basin as represented in Figure 5.2. The river geography in the Mekong Basin can be expressed as $N = \{China, Thailand, Laos, Cambodia, Vietnam\}$, $P^{China} = P^{Thailand} = \emptyset$, $P^{Laos} = \{China,\ Thailand\}$, $P^{Cambodia} = \{China,\ Thailand,\ Laos\}$ and $P^{Vietnam} = \{China,\ Thailand,\ Laos,\ Cambodia\}$.

Example 5.1. *Four countries, Laos, Thailand, Cambodia and Vietnam in the Mekong River, signed the Mekong Agreement in 1995 and this leaves the upstream country China alone. The current partition of Mekong River can be written as $\pi = \{P_1, P_2\}$, where $P_1 = \{China\}$ and $P_2 = \{Laos,\ Thailand,\ Cambodia,\ Vietnam\}$. Applying Algorithm 1, we first calculate $d(P_1|\pi)$ because there are no countries that can possibly transfer water to China; then we proceed to P_2 given that the disagreement point for China is common knowledge.*

We need to assign a payoff to each agent $i \in P_j$, $P_j \in \pi$.

Definition 5.1. *An allocation rule γ is a function $v : \Pi \to \mathbb{R}^N$, that for all $\pi \in \Pi$ assigns a payoff $v_i(\pi)$ to any $i \in N$.*

The group efficiency condition for the allocation rule γ is imposed, i.e., we should have $\sum_{i \in P_j} v_i(\pi) = d(P_j|\pi)$ for $P_j \in \pi, \pi \in \Pi$.

The next question is whether the allocation rule γ makes the partition π internally stable. We consider the deviation of one agent leaving his group of agents in partition π. For some j with $|P_j| \geq 2$, let $i \in P_j \subset N$ be the deviating agent that leaves $P_j \in \pi$. After agent i leaves P_j, the new partition will be $\pi^i = \{P_1, P_2, \ldots, P_j \setminus \{i\}, \{i\}, \ldots, P_m\}$. Note that the new partition is finer and has $m + 1$ groups of agents including at least one

[5]In graph theory, this can be expressed as there exists a path between two agents within any connected group of agents.

singleton, namely $\{i\}$. We differentiate the following two cases to calculate $d(P_h|\pi^i), P_h \in \pi^i$ after i deviates from P_j.

1. When $i \in P_j$ leaves coalition $P_j \in \pi$ and i is in a most upstream position within P_j (i.e., i has no predecessors in P_j), it is trivial to see that Algorithm 1 applies to the calculation of $d(P_h|\pi^i)$, $P_h \in \pi^i$. In case i is the most downstream agent in P_j (i.e., i has no successors in P_j) and the remaining agents in P_j are still geographically connected, we can still apply Algorithm 1 to calculate the payoff for the remaining agents in P_j. Note that in case i is positioned most downstream and i's deviation makes the remaining agents in P_j disconnected, e.g., at least two branches in P_j merge at i, we apply Algorithm 1 for subgroups of agents in $P_j \setminus \{i\}$ that are connected. Then the payoff for $P_j \setminus \{i\}$ is the sum of those subgroups' payoffs.

   Example 5.2. *In Example 5.1, in case Thailand or Vietnam deviates coalition P_2, without loss of generality, we assume that Vietnam deviates coalition P_2, then the new partition π' will be $\{\{China\}, \{Laos, Thailand, Cambodia\}, \{Vietnam\}\}$. Note that Vietnam's deviation makes the remaining agents in P_2 still geographically connected. Then we can apply Algorithm 1 to calculate the payoff for each coalition in π'.*

2. In case that deviating agent i is positioned in between the remaining agents in P_j and this makes the remaining agents in coalition $P_j \in \pi$ disconnected, we employ the idea of backward induction from Ambec and Ehlers (2008) to calculate the payoffs $d(P_h|\pi^i), P_h \in \pi^i$. Note that there exist an issue whether the upstream agents of the remaining agents in $P_j \in \pi$ will pass water to downstream agents of the remaining agents in $P_j \in \pi$. In certain cases, the remaining agents in P_j still cooperate by passing water from upstream to downstream even if agent $i \in N$ might take some water and reach its satiation point. In this situation, the cooperation of the remaining agents in $P_j \in \pi$ exerts a positive externality on agent i and makes him to reach his satiation point.

   Example 5.3. *In Example 5.1, suppose that Cambodia deviates from coalition P_2, then the new partition is $\{\{China\}, \{Laos, Thailand, Vietnam\}, \{Cambodia\}\}$. There is an issue whether Laos and Thailand will pass water to Vietnam. If so, then Cambodia reaches its satiation point.*

Definition 5.2. *Under allocation rule γ, partition π is internally stable if $v_i(\pi) \geq d(\{i\}|\pi^i)$ for all $i \in N$.*

Proposition 5.2. *There exists an allocation rule γ to make partition π internally stable if and only if $d(P_j|\pi) \geq \sum_{i \in P_j} d(\{i\}|\pi^i)$, for all $P_j \in \pi$.*

The above proposition is straightforward. Note that it could be well possible that $d(P_j|\pi) < \sum_{i \in P_j} d(\{i\}|\pi^i)$, $P_j \in \pi$, see, e.g., Theorem 2 and Example 1 in Ambec and Ehlers (2008). In this scenario, the payoff of the coalition under π is not able to satisfy each agent's outside option in terms of unilateral deviation from the current coalition.

In Eyckmans and Finus (2004), Weikard (2009) and Weikard et al. (2006), they consider only one coalition with more than one agent under π and all remaining agents

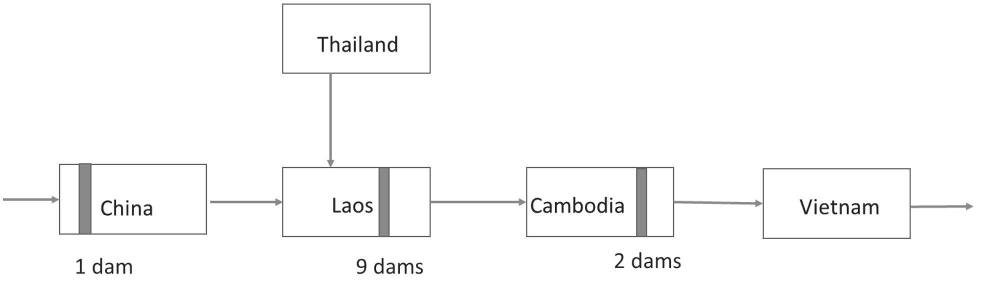

Figure 5.2: Proposed mainstream dams in the Mekong River Basin

are singleton. In case there is only one coalition with more than one agent under π, the definition of internal stability of partition π under allocation rule γ is equivalent to say that the only coalition with more than one agent in π is internally stable under allocation rule γ as studied in the above mentioned literature. In our following application of the Mekong River Basin, there exists only one coalition with more than one agent under the 1995 Mekong Agreement. Therefore, we do not strictly differentiate that the partition of Mekong as mentioned in Example 5.1 is internally stable and that the 1995 Mekong Agreement is internally stable.

5.5 A case study: Mekong River

In this section, we will investigate the disagreement, joint cooperation and partial cooperation scenarios in details for the Mekong River Basin.

5.5.1 Background

The Mekong River runs through China's Yunnan province, Burma, Laos, Thailand, Cambodia and Vietnam, then it flows into the South China Sea. It is not only the source of food and water for more than 70 million people, but the river basin is also home to more than 1,300 species of fish, creating one of the most diverse inland fisheries in the world (Campbell (2009)). In 1995, the four Lower Mekong countries (Laos, Thailand, Cambodia and Vietnam), signed an agreement on the cooperation for the sustainable development of the lower part of the Mekong River Basin. The main spirit of the agreement is for those four countries, being equally desirous, to continue to cooperate in a constructive and mutually beneficial manner for sustainable development, utilization, conservation, and management of the Mekong River Basin. However, the governance of the agreement is relatively weak and unstable due to the fact that huge profits of potential hydropower in Laos are considered without taking into account the negative externalities of dam operation on fishery in Cambodia and salinity in Vietnam. The estimated hydropower potential of the Lower Mekong Basin is 30,000 MW and only 3,235 MW has been met through facilities built largely over the past ten years on the Mekong tributaries (MRC (2010)). Recently, 12 mainstream dams, mainly in Laos, have been proposed, see Figure

5.2.[6] All these proposed dams are run-of-river hydropower plants and do not have a significant amount of active water storage. Laos relies heavily on the financial support from Thailand for dam construction and in return, it supplies Thailand with electricity for a certain number of years. Several international organizations, e.g., the World Bank and the Asian Development Bank, also contribute financially to the dam construction in the Mekong River Basin.

Certain concerns have been raised for the Mekong mainstream hydropower plan, e.g., the fishery in the Lower Mekong Basin will be damaged due to the fact that the fish migration is hindered by those dams (Baron et al. (2007), Ziv et al. (2012) and ICEM (2010)). Cambodia, where the main fish production of the Mekong River in the Tonle Sap Lake is located, is likely to bear the brunt of fisheries decline as a result of dam development. Furthermore, Ziv et al. (2012) conclude that the closer the dam is located to the Tonle Sap Lake, the larger the negative impact of the dam on the Lower Mekong fishery. According to most recent estimates, Cambodian capture and aquaculture fisheries produce around 527,000 tons of fish, worth between 1.2-1.6 billion USD (FAO, 2011) annually. Fishery production (not including processing and other related activities) thus makes up around 10 percent of Cambodia's overall GDP. The fishery sector also provides full-time, part-time and seasonal employment for up to 6 million people, approximately 40 percent of the population, in capture and subsequent value-adding services (Sothorn et al. (2011)).[7] Thus, a reasonable estimate for the fishery income (including direct capture fishery values and indirect employment benefits in the fishery sector) is approximately 4 billion USD.

Let $G_{i_j} \in \{0,1\}$ (dam j in agent i) be a binary variable indicating whether the proposed mainstream dams should be built. In case $G_{i_j} = 1$, then dam j in the territory of agent i should be built, otherwise not. The cost of dam building is estimated based on the installed capacity. For large hydropower plant, the average investment costs range from as low as USD 1,050 per KW to as high as USD 7,650 per KW (IRENA (2012)). The differences of investment costs in dam construction are mainly due to the differences of wages. In this chapter, taken the local labor costs in Laos and Cambodia into account, we take the cost of dam construction as 5,000 USD per KW. Experience from existing plants worldwide have shown that the life cycle of hydropower dams is in the range of one hundred years or more, but in the economic calculations and estimates, a period of 30 years is often used. Therefore, we spread the investment cost over a dam life expectancy of 30 years. The damage to fishery is calculated according to the distance of the dam to Phnom Penh in Cambodia. In case dam i_j is built, we would expect an impact factor of dam i_j to the fishery income f in Cambodia. In more details, we assume that in case all the proposed mainstream dams are built, the fishery income in Cambodia will decline to 0. The impact of individual dams is proportional to its distance to Phnom Penh. The closer the proposed mainstream dam is located to Phnom Penh, the larger the negative

[6]These 12 dams are Nuozhadu, Pak Beng, Luang Prabang, Xayaburi, Pak Lay, Sanakham, Pakchom, Ban Koum, Lat Sua, Don Sahong, Stung Treng and Sambor. Except Nuozhadu in China and Stung Treng and Sambor in Cambodia, all other dams are in Laos or on the Laos-Thailand border.

[7]In Cambodia, the average income is about 950 USD per capita per year. So we approximate that 3 million people are fully employed in the fishery sector. Thus, the total amount of value from employment could be 2.85 billion USD.

impact of this dam on the fishery income in Cambodia. The detailed results are reported in Table 5.1.[8]

The water flow in the Mekong River can be used for other sectors like household, industry and irrigation and the water use in the above mentioned sectors are consumptive. Note that irrigation takes place only in the dry season in the Mekong River Basin. According to the data in FAO AQUASTAT, irrigation water use constitutes 90 percent of the total water withdrawal in the Mekong River Basin. The extreme seasonal variations in flow for the Mekong River are well documented, with the wet season from June to November and the dry season from December to May (next year). The Mekong is known for its large seasonal variability, with the ratio of 7:1 for water availability in the wet and dry seasons (Ringler et al. (2004)). All details of estimating these benefit functions for household, industry, hydropower and irrigation sectors are presented separately as an appendix at the end of this chapter.

We also take existing tributary dams in Laos and Vietnam (with installed capacity more than 100 MW) into account.[9] Note that within a country on the mainstream, the water use for hydropower demonstrates cascade characteristics, i.e., water use for upstream dams in a country can be re-used further for downstream dams. But this is not the case for the hydropower dams on different tributaries.

In this empirical study, a significant amount of results are focused on the externalities of dam constructions in Laos on the fishery income in Cambodia. In the disagreement scenario, Laos government builds dams without taking the externalities on the fishery in Cambodia into account. Therefore, when we calculate the disagreement point for Cambodia, it has to bear the externality issues of fishery decline from dam construction of Laos. Cambodia can only internalize the externality issues on fishery from its own dams constructions. In the scenario of joint cooperation and partial cooperation with respect to (5.8), only in case Laos and Cambodia are included in the same coalition, the externality issue between Laos and Cambodia will be internalized.

In a nutshell, we formulate the empirical maximization problem (5.1)-(5.5) for the Mekong River Basin in the following way:

$$\max_{x_{i,k,s}, q_{i,s}, G_{i_1}, \cdots, G_{i_n}} \sum_{k \in K} \sum_{s \in S} b_{i,k}(x_{i,k,s}) + \sum_{s \in S} Q_i(q_{i,s}) - \sum_{j=1}^{n} cG_{i_j} D_{i_j} - ind_i f \sum_{j=1}^{n} G_{i_j} imf_{i_j} \tag{5.9}$$

$$\text{s.t.} \quad \sum_{k \in K} x_{i,k,w} + q_{i,w} + r_i \leq e_{i,w} + o_{i,w}, \tag{5.10}$$

$$\sum_{k \in K} x_{i,k,d} + q_{i,d} \leq e_{i,d} + o_{i,d} + r_i, \tag{5.11}$$

where $o_{i,w}$ and $o_{i,d}$ are as in (5.6) and (5.7), $G_{i_j}, j = 1, \cdots, n$ denotes mainstream dam j to be built on agent i territory, c is the cost in USD per KW, D_{i_j} is the installed

[8] Note that Nuozhadu is far away from the Tonle Sap Lake, thus we assume that the impact of this dam on the fishery income in Cambodia is 0.

[9] Among these, we take HouayHo, NamLik2, NamNgum1, NamNgum2, NamTheun2 and TheunHinboun in Laos and Pleikrong, Sesan4, SrePok3 and YaliFalls in Vietnam into account. Details of these dams are also included in the appendix of this chapter.

capacity of dam i_j, imf_{i_j} is the impact factor of dam i_j on the fishery in Cambodia, ind_i is an indicator. For the calculation of the disagreement point of Cambodia, ind_i is taken to be 1. For other countries' disagreement calculation, ind_i is taken to be 0. Note that the cumulative impact of dam construction from agent i on the fishery income in Cambodia is the sum of the impact of individual proposed mainstream dams as expressed by $\sum_{j=1}^{n} G_{i_j} imf_{i_j}$. Moreover, we drop constraints (5.4) and (5.5) in this maximization problem compared with the general approach presented in Section 5.2 because of the special characteristics in the Mekong River Basin.[10]

In the following, we are interested in the disagreement and joint cooperation scenarios. In addition, we are interested in the total payoffs of the four countries under the 1995 Mekong Agreement and also the scenario of unilateral deviation within the 1995 Mekong Agreement. In summary, the following seven coalition structures are interesting for us:

1. {China}, {Thailand}, {Laos}, {Cambodia}, {Vietnam}: the disagreement scenario;
2. {China}, {Thailand}, {Laos, Cambodia, Vietnam}: Thailand deviates the 1995 Mekong Agreement;
3. {China}, {Vietnam}, {Thailand, Laos, Cambodia}: Vietnam deviates the 1995 Mekong Agreement;
4. {China}, {Thailand, Laos, Cambodia, Vietnam}: the 1995 Mekong Agreement;
5. {China}, {Laos}, {Thailand, Cambodia, Vietnam}: Laos deviates the 1995 Mekong Agreement;
6. {China}, {Cambodia}, {Thailand, Laos, Vietnam}: Cambodia deviates the 1995 Mekong Agreement;
7. {China, Thailand, Laos, Cambodia, Vietnam}: the joint cooperation scenario.

We calculate the above seven scenarios (note that each scenario refers to a coalition structure) in GAMS.[11] Here we illustrate the main idea of the calculation. Firstly, note that there are substantial differences in calculating the values between the coalitions that are connected and the coalitions that are not geographically connected as discussed in Section 5.4.[12] For the latter scenario (i.e., scenarios 5 and 6), we will apply the algorithm of backward induction proposed by Ambec and Ehlers (2008). For the geographically connected coalitions, we apply Algorithm 1. The key issue is that a coalition (or a country) is able to calculate its payoff conditional on all its predecessors' payoff and water consumptive uses are calculated and are common knowledge. We first calculate scenario 1, i.e., the disagreement scenario. Given that China and Thailand's disagreement points are calculated, we proceed to scenario 2. Given that China's disagreement point is calculated, we proceed to scenario 3, then to scenario 4. Since the coalitions in scenarios 5 and 6 are not connected, we will apply the algorithm of backward induction in Ambec and Ehlers (2008) to calculate the payoff. Finally, we end up the calculation with the grand coalition of scenario 7.

[10]Most dams in the Mekong River Basin are run-of-river hydropower plant and only have a small amount of active water storage and we also assume that all countries will have enough external funding for the dam construction.

[11]GAMS code for calibration is available upon request.

[12]Here by saying that the coalitions are not geographically connected, we mean the case of Example 5.3.

5.5.2 The disagreement scenario

We adapt the ATS principle and calculate the disagreement point for each country in the Mekong River Basin. There are externality issues of the dam construction in Laos on the fishery income in Cambodia. Without taking Cambodia's benefits into account, Laos builds dam for its own benefits. In case all proposed mainstream dams in Laos are built, the fishery income in Cambodia will decrease at a level of 57.2 percent of the current income (Table 5.1). The gross domestic product (GDP) for Laos in 2013 is reported around 11.24 billion USD (World Bank, 2015). With the potential of hydropower benefits in our model, the GDP in Laos will boom at a level of 22.159 billion USD (Table 5.2). According to our calculations, Mekong mainstream dams will boom Laos's GDP by an amount of 10.936 billion USD (Table 5.3). We also notice that the GDP of Cambodia is reported around 15.24 billion USD in 2013 (World Bank, 2015). With the Mekong mainstream dam construction, fishery in Cambodia will be mainly damaged. This leads to a substantial drop in the GDP of Cambodia, which is estimated at around 12.864 billion USD (Table 5.3). Note that according to our estimates, the fishery income in Cambodia will sharply go down to a level of 0.040 billion USD in the disagreement scenario (Table 5.3). Note that in this scenario, all the proposed mainstream dams will be built (Table 5.1).

5.5.3 The joint cooperation scenario

Next, we consider the situation that all countries in the Mekong River Basin cooperate. An important issue is that the externalities of dam construction in Laos on the fishery income in Cambodia will be internalized. Some proposed dams, i.e., Xayaburi, PakLay, Bankoum, LatSua and Don Sahong will not be built in this scenario (Table 5.1). The total economic value of the grand coalition is estimated to be around 71.641 billion USD for the whole river basin (Table 5.2). This leads to a welfare increase of 1.420 billion USD for the whole river basin compared with the disagreement scenario.

5.5.4 The partial cooperation scenario

Finally, we consider the scenario of the strong governance of the 1995 Agreement that all countries in the Lower Mekong River Basin would pursue the goal of a sustainable long-term development and a maximal total economic benefit. Part of the goal involves how to distribute the benefits to sustain cooperation. We employ the idea of "internal stability", i.e., the total benefits of the coalition should be able to satisfy each country's outside option, and the outside option is defined as each country's payoff in case of his unilateral deviation. In case that Thailand or Vietnam deviates from the 1995 Agreement, the remaining three countries in the agreement are still geographically connected. In case Laos or Cambodia deviates, the remaining 1995 agreement is not geographically connected.

According to our estimates, the total economic value for the Lower Mekong Basin is around 56.058 billion USD (Table 5.2). The outside option of each country in the 1995 Mekong Agreement is also reported in Table 5.2. The sum of the outside option of the four

Lower Mekong Countries (54.745 billion USD) is lower than the total economic benefits of the 1995 Mekong Agreement if all countries cooperate. Therefore, the 1995 Mekong Agreement is internally stable in terms of unilateral deviation.

In Table 5.1, we report the relevant parameters of the proposed mainstream dam and whether these dams should be built in different scenarios. In case that the dam should be built, "1" is assigned in the table, otherwise "0" is assigned. In Table 5.2, we report the economic value for all coalitions in different coalition structures. In Table 5.3, we report the economic value of hydropower from mainstream dams in Laos and the fishery income in Cambodia in different coalition structures. Indeed in the case that Cambodia and Laos are included in the same coalition, the externality issues of dam construction on fishery are internalized and this results in a higher payoff in the fishery sector in Cambodia and relatively lower benefits in the hydropower sector in Laos.

5.6 Concluding remarks

In this chapter, we extend the current literature on water resource allocations in trans-boundary river basins by adding the possibility of building dams and conduct a thorough analysis of costs and benefits of dam construction. Three scenarios are analyzed, i.e., the disagreement scenario in which each agent pursues his own interests, joint cooperation scenario across the river basins to extract maximal benefits, and partial cooperation scenario between neighboring river basin agents. One key issue is the trans-boundary externalities, i.e., the dam construction in upstream countries might have negative externalities on downstream countries. We examine our approach further in details in the Mekong River Basin. Indeed, the negative externality issues of dam construction in Laos on the fishery income in Cambodia are internalized if Laos and Cambodia are included in the same coalition. This might refrain Laos from building some dams. We also conclude that the 1995 Mekong Agreement among Lower Mekong countries is internally stable in terms of unilateral deviation.

Further empirical research could extend the analysis to include more relevant externality issues, e.g., the environmental and/or ecological costs. For instance, due to the dam construction, local environment might be impacted and human beings have to be relocated. It is necessary that more relevant data become available to assess relevant benefits and costs more accurately. We believe that our approach is general enough and could also provide some guidance for a rather complete assessment of damming construction in other river basins.

Table 5.1: Relevant parameter of the proposed Mekong mainstream dams and whether these dams should be built in different coalition structures

Name of the proposed dam	Nuozhadu	Pak Beng	Luang Prabang	Xayaburi	Pak Lay	Sanakham	Pakchom	Ban Koum	Lat Sua	Don Sahong	Stung Treng	Sambor
Dams in which country	China	Laos	Laos	Laos	Laos	Laos	Laos	Laos	Laos	Laos	Cambodia	Cambodia
Installed capacity of the proposed dam (MW)	5,850	1,230	1,410	1,285	1,320	700	1,079	1,872	686	240	980	2,600
Distance to Phnom Penh, Cambodia (km)	N/A	2389.6	2247.8	2035.1	1928.7	1857.8	1690.5	850.9	680.7	510.5	404.2	312
Impact on the fishery income in Cambodia (%)	0	0.031	0.033	0.037	0.039	0.041	0.045	0.088	0.111	0.147	0.186	0.241
{China}, {Thailand}, {Laos}, {Cambodia}, {Vietnam}	1	1	1	1	1	1	1	1	1	1	1	1
{China}, {Thailand}, {Laos, Cambodia, Vietnam}	1	1	1	0	0	1	1	0	0	0	1	1
{China}, {Vietnam}, {Thailand, Laos, Cambodia}	1	1	1	0	0	1	1	0	0	0	1	1
{China}, {Thailand, Laos, Cambodia, Vietnam}	1	1	1	0	0	1	1	0	0	0	1	1
{China}, {Laos}, {Thailand, Cambodia, Vietnam}	1	1	1	1	1	1	1	1	1	1	1	1
{China}, {Cambodia}, {Thailand, Laos, Vietnam}	1	1	1	1	1	1	1	1	1	1	1	1
{China, Thailand, Laos, Cambodia, Vietnam}	1	1	1	0	0	1	1	0	0	0	1	1

Data of the installed capacity come from ICEM (2009).

Table 5.2: Payoffs for each coalition in different coalition structures in billion USD

<table>
<tr><th>The coalition structures</th><th>China</th><th>Thailand</th><th>Laos</th><th>Cambodia</th><th>Vietnam</th></tr>
<tr><td>{China}, {Thailand}, {Laos}, {Cambodia}, {Vietnam}</td><td>15.528</td><td>8.373</td><td>22.159</td><td>12.864</td><td>11.297</td></tr>
<tr><td>{China}, {Thailand}, {Laos, Cambodia, Vietnam}</td><td>15.528</td><td>8.373</td><td colspan="3">47.630</td></tr>
<tr><td>{China}, {Vietnam}, {Thailand, Laos, Cambodia}</td><td>15.528</td><td colspan="3">44.732</td><td>11.322</td></tr>
<tr><td>{China}, {Thailand, Laos, Cambodia, Vietnam}</td><td>15.528</td><td colspan="4">56.058</td></tr>
<tr><td>{China}, {Laos}, {Thailand, Cambodia, Vietnam}</td><td>15.528</td><td>A</td><td>22.159</td><td colspan="2">A</td></tr>
<tr><td>{China}, {Cambodia}, {Thailand, Laos, Vietnam}</td><td>15.528</td><td colspan="2">B</td><td>12.891</td><td>B</td></tr>
<tr><td>{China, Thailand, Laos, Cambodia, Vietnam}</td><td colspan="5">71.641</td></tr>
</table>

Note that A denotes the coalition value of Thailand, Cambodia and Vietnam and is equal to 32.588, and B denotes the coalition value of Thailand, Laos and Vietnam and is equal to 41.834.

Table 5.3: Fishery income in Cambodia and hydropower benefits for mainstream Laos in different coalition structures in billion USD

The coalition structures	Hydropower Laos	Fishery Cambodia
{China}, {Thailand}, {Laos}, {Cambodia}, {Vietnam}	10.936	0.040
{China}, {Thailand}, {Laos, Cambodia, Vietnam}	10.550	1.692
{China}, {Vietnam}, {Thailand, Laos, Cambodia}	10.550	1.692
{China}, {Thailand, Laos, Cambodia, Vietnam}	10.550	1.692
{China}, {Laos}, {Thailand, Cambodia, Vietnam}	10.936	0.040
{China}, {Cambodia}, {Thailand, Laos, Vietnam}	10.936	0.040
{China, Thailand, Laos, Cambodia, Vietnam}	10.550	1.692

5.7 Appendix of Chapter 5

In this appendix, we present how we estimate the water resources $e_{i,s}$ per season arising within a country and the benefit functions for the sectors of hydropower, household, industry and irrigation. We also report relevant parameters for existing Mekong tributary dams in Laos and Vietnam with an installed capacity of more than 100 MW at the end of this appendix.

Water resources in the wet and dry seasons

The Mekong discharges 457 km^3 of water annually (MRC (2010)). Seasonality issue is well documented for the Mekong River Basin. We only have the relevant data for the annual average flow of each country. In order to calculate the wet and dry season water inflows in each country within the Mekong River Basin, we should have a reasonable estimate for the ratio of the water resources of the wet to dry season. The wet season happens from June to November and the dry season refers to the period from December to May (next year). Several gauging stations (Chiang Saen, Luang Prabang, Vientiane, Nakhom Phanom, Mukdahan, Pakse and Kratie) along the Mekong River measure the monthly flow rate. The ratio of the water flow in the wet and dry seasons in a certain country is decided by the gauging station in the country. Chiang Saen is used to estimate the ratio for China. Due to the long river border between Thailand and Laos, the ratio for these two countries is the average over the gauging stations Luang Prabang, Vientiane, Nakhon Phanom, Mukdahan and Pakes. The ratio for Cambodia and Vietnam is estimated from Kratie. In Table 5.4, we report the wet and dry season flows for each country.

Table 5.4: The wet and dry season flows for each country in the Mekong River Basin

Items	China	Laos	Thailand	Cambodia	Vietnam
Percentage of total flow	16	35	18	18	11
Annual flow in km^3	73.12	159.95	82.26	82.26	50.27
Ratio (wet/dry)	3.8	5.286	5.286	6.853	6.853
Dry season flow in km^3	15.23	25.445	13.086	10.475	6.401
Wet season flow in km^3	57.887	134.505	69.174	71.785	43.869

Data source: MRC (2005).

Hydropower sector

Generated hydropower is calculated by the following formula,

$$P = g \times \eta \times Q \times H,$$

where P is power in KW, η is the turbo-generator efficiency,[13] g is the gravitational acceleration measured in 9.81 m/s^2, Q is the quantity of water flowing measured in m^3/s and H is the effective head measured in m. We simply take the dam height as the effective

[13] In practice, the efficiency ranges from 75 to 95 percent.

Table 5.5: Proposed Dams on the Mekong Mainstream

Dam	Country	Installed capacity (MW)	Height (m)	Active storage (million m^3)
Nuozhadu	China	5,850	261.5	21.749
Pak Beng	Laos	1,230	76	442
Luang Prabang	Laos	1,410	68	734
Xayaburi	Laos	1,285	32	225
Pak Lay	Laos	1,320	35	384
Sanakham	Laos	700	38	106
Pakchom	Laos	1,079	1,200	12
Ban Koum	Laos	1,872	53	0
Lat Sua	Laos	686	27	0
Don Sahong	Laos	240	10.6	115
Stung Treng	Cambodia	980	22	70
Sambor	Cambodia	2,600	56	465

Data source: ICEM (2010).

head since most of the mainstream dams in the Mekong are run-of-river hydropower plants and the heights for proposed mainstream dams are reported in Table 5.5. In practice, we take

$$P = 8 \times Q \times H.$$

We need to further convert the above formula into KWh and take 180 days per season. We use hb_i to denote the electricity price in USD per KWh, where $i = \{CN, TH, LA, CM, VT\}$.[14]

Household sector

In this section, we will discuss how we estimate the household water inverse demand function. According to FAO AQUASTAT, we have the annual household water use in km^3 for each country. The price of water in the household sector can be obtained from Houba et al. (2013). With respect to the elasticities of the water demand function, we gather the relevant data from Basani et al. (2008), Cheesman et al. (2008) and Nauges and Whittington (2010). For instance, based on household level data from seven provincial towns and one district in Cambodia, Basani et al. (2008) report that the price elasticities of water demand for the connected households lie in a range between -0.5 and -0.4. Cheesman et al. (2008) estimate the water demand elastiticies of households using municipal water exclusively and municipal water and household well water in the capital city of Dak Lak Province in Vietnam. They report that the price elasticities of municipal water are -0.51 and -0.44 for well water. Nauges and Whittington (2010) review the estimated price elasticities of water demand in developing countries and conclude that most estimates of the price elasticities of water demand from private connections are in the range of -0.3 to -0.6. We take the price elasticities of demand as -0.45 and assume a linear water demand function for each country. Based on the observed price P'_{hh}, the observed water use amount per season Q'_{hh} per season and the price elasticity of demand

[14] This is the short notation for countries involved in the Mekong River Basin, i.e., China, Thailand, Laos, Cambodia and Vietnam.

Table 5.6: Coefficients of the benefit function for household water use billion USD per km^3

countries	coefficient of the quadratic term	coefficient of the linear term
Yunnan, China	N/A	N/A
Laos	-4.27	0.81
Thailand	-0.28	1.13
Cambodia	-5.67	0.81
Vietnam	-0.27	0.47

is ε_{hh}, the slope of the household water demand function is,

$$\text{slope} = \varepsilon_{hh} \cdot \frac{Q'_{hh}}{P'_{hh}}.$$

Hence, the household water demand function follows from,

$$Q_{hh} - Q'_{hh} = \varepsilon_{hh} \frac{Q'_{hh}}{P'_{hh}} (P_{hh} - P'_{hh}) \Rightarrow Q_{hh} = \varepsilon_{hh} \frac{Q'_{hh}}{P'_{hh}} P_{hh} + (1 - \varepsilon_{hh}) Q'_{hh},$$

where Q_{hh} is the water use amount in the demand function and P_{hh} is the corresponding water price. Therefore, the inverse demand function is,

$$P_{hh} = \frac{P'_{hh}}{\varepsilon_{hh} Q'_{hh}} Q_{hh} - \frac{1 - \varepsilon_{hh}}{\varepsilon_{hh}} P'_{hh}. \tag{5.12}$$

We take constant marginal cost (P'_{hh}) of water extraction into account. So the benefit of water use amount x_{hh} is,

$$\int_0^{x_{hh}} \left(\frac{P'_{hh}}{\varepsilon_{hh} Q'_{hh}} Q_{hh} - \frac{1 - \varepsilon_{hh}}{\varepsilon_{hh}} P'_{hh} \right) dQ_{hh} - P'_{hh} x_{hh} = \frac{P'_{hh}}{2\varepsilon_{hh} Q'_{hh}} (x_{hh})^2 - \frac{1}{\varepsilon_{hh}} P'_{hh} x_{hh}. \tag{5.13}$$

The results for the Mekong countries are reported in Table 5.6. Note that the household water use benefit function holds both for the wet and dry seasons.

Industry sector

We use industry water use amount from FAO AQUASTAT and industry water price from Houba et al. (2013). With respect to the elasticities, we extract data from Renzetti (1992) and he reports that the average values for the estimated own-price elasticities for industry water use range from -0.1534 to -0.5885. Reynaud (2003) studies 51 French industrial facilities and estimates the average demand elasticities of -0.29 for water purchased from utilities, with a range of -0.10 to -0.79, depending on the type of industry. More relevant results for industry water demand elasticities are reported in Olmstead and Stavins (2007). We take the price elasticities of water demand in industry as -0.29. Then we can construct the industrial inverse water demand function similar as (5.12) and the benefit of water use amount in industry similar as (5.13). And the results for the Mekong countries are reported in Table 5.7. Again, the industry water use benefit function holds both for the wet and dry seasons.

Table 5.7: Coefficients of the benefit function for industry water use billion USD per km^3

countries	coefficient of the quadratic term	coefficient of the linear term
Yunnan, China	N/A	N/A
Laos	-15.21	3.34
Thailand	-1.06	3.78
Cambodia	-78.37	3.34
Vietnam	-0.90	3.56

Table 5.8: Coefficients of the benefit function for irrigation billion USD per km^3

countries	coefficient of the quadratic term	coefficient of the linear term
Yunnan, China	N/A	N/A
Laos	-0.061414	0.413442
Thailand	-0.009313	0.34726
Cambodia	-0.691658	2.442355
Vietnam	-0.010055	0.312703

Irrigation sector

We assume that the irrigation sector has the following quadratic benefit function,

$$z = r(a_{ir} - b_{ir}r),$$

where r is the water use for irrigation, z is the economic benefit from irrigation, and a_{ir} and b_{ir} are parameters to be estimated. The quadratic benefit function has a peak point at $\frac{a_{ir}}{b_{ir}}$. Beyond the peak point, we have decreasing benefits of irrigation because of the possibility of flooding. Water use for irrigation is available for each country in FAO AQUASTAT. The economic benefit of irrigation is estimated from rice output only. Since both data are reported on a country basis, we scale both data by the proportion of Mekong Basin in the whole country. According to FAO AQUASTAT, 85 percent of Laos, 36 percent of Thailand, 86 percent of Cambodia, and 20 percent of Vietnam, are in the Mekong River Basin. Following Houba et al. (2013), we assume that rice output accounts for 88% of irrigation water use. Given r and z, we do a point estimate for a_r and b_r,

$$a_{ir} = \frac{2z}{r}, \quad b_{ir} = \frac{z}{r^2}.$$

The results are reported in Table 5.8.

Existing Mekong tributary dams in Laos and Vietnam

In this section, we report relevant parameters for the existing Mekong tributary dams in Laos and Vietnam with an installed capacity of more than 100 MW, see Table 5.9 and 5.10.

Table 5.9: Existing dams in Laos on its Mekong River tributaries with an installed capacity of more than 100 MW

Dam	River	Installed capacity (MW)	Height (m)	Active storage (million m^3)
Houay Ho	Houay Ho/Xekong	150	79	620
Nam Lik 2	Nam Lik	103	328	24.4
Nam Ngum 1	Nam Ngum	148.7	75	7,000
Nam Ngum 2	Nam Ngum	615	181	2,970
Nam Theun 2	Nam Theun/Xe Bangfai	1,075	48	3,680
Theun-Hinboun	Nam Theun/Nam Gnouang	500	235	291

Data source: King et al. (2007).

Table 5.10: Existing dams in Vietnam on its Mekong River tributaries with an installed capacity of more than 100 MW

Dam	River	Installed capacity (MW)	Height (m)	Active storage (million m^3)
Plei Krong	Se San/Kroon Po Ko	100	65	162
Sesan 4	Sesan	360	60	N/A
Sre Pok 3	Sre Pok	220	52.5	N/A
Yali Falls	Sesan	720	65	1,037

Data source: King et al. (2007).