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Transbounday Water Conflicts over Hydropower and Irrigation: Can Multilateral Development Banks Help?

by

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University of Nottingham

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Abstract

Water conflicts may arise on transboundary rivers with upstream hydropower use and downstream irrigation use. This occurs because upstream water release does not coincide with seasonal irrigation needs of the downstream riparian. This paper examines the role that multilateral development banks (MDBs) may play in reducing conflict - a role that arises because MDBs have a comparative advantage over other development agencies in promoting transboundary water management. We consider and rank the qualitative impact of a range of infrastructure projects, potentially initiated and co-financed by MDBs. Basinwide social efficiency and regional stability can, under certain conditions, by improved through Pareto-improving investments, including enhancement of upstream hydropower efficiency and expansion of downstream reservoir capacity. The findings are used to analyse infrastructure projects currently under consideration in the Syr Darya Basin in Central Asia.

Keywords

Common property resources, conflict, externalities, foreign aid, hydropower, irrigation, natural resources, regional public goods, transboundary rivers, water.

JEL Classification:

D62, F35, Q25.

Outline

1. INTRODUCTION

Transboundary water management is a regional public good of increasing concern to the international community. There are 261 international river basins in the world covering almost half of the total land surface of the globe (Wolf *et al*, 1999). Over 40 percent of the world's population lives within transboundary basins, making the successful management of this resource central to poverty reduction, sustainable development and long-term political stability (ODI, 2002).

Transboundary rivers can elicit conflict as well as cooperation.[1] Although no water conflict has yet led to a formal declaration of war between riparian states, such conflicts can undermine regional peace and stability. In this paper we focus on a particular type of conflict which arises when the timing of upstream water releases does not coincide with the needs of the downstream riparian. From the perspective of the downstream riparian, the result is that in any given season either 'too little' or 'too much' water is released relative to its optimum. The conflict on the Syr Darya river shared by the Kyrgyz Republic, Uzbekistan and Kazakstan, is an important and interesting case study which we examine in more detail later in this paper. Other relevant case studies also deserve mention. The other great Central Asian river, the Amu Darya, has characteristics that could create a situation similar to that on the Syr Darya if upstream Tajikistan proceeds with plans to expand its hydropower capacity. On the river Nile there is also potential for conflict if upstream Ethiopia decides to develop its substantial hydropower potential thus disrupting the growing season in Egypt. Namibian plans for the Popa Falls hydropower plant on the Okavango river

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[1] Twenty-eight percent of all recorded international water related events between 1948 and 1999 were conflictive while two-thirds were cooperative (Wolf et al, 2003).

potentially affect wildlife-oriented tourism in Botswana's national parks in the downstream Okavango delta. These examples share a potential conflict between hydropower in an upstream country and other economic interests in a downstream country. In future it is likely that more such conflicts will emerge since only 10 percent of the world's hydropower potential is currently being exploited (Khagram, 2004).

Development agencies can play an important role in fostering regional (basinwide) cooperation in the developing world, for instance by improving technical and political communication between riparians, acting as honest brokers and providing third-party process support and financing, such as setting up basinwide trust funds (ODI, 2001). Multilateral development banks (MDBs) in particular, i.e. the World Bank and the regional development banks, have a comparative advantage in promoting transboundary river management, especially in the area of infrastructure investments. This is partly because of their extensive lending facilities and partly because the co-riparians are typically also their client countries thus enhancing the scope for basinwide solutions. Furthermore, in the case of the World Bank there is substantial in-house experience in river management in light of its involvement as a financier of large dam construction over the past 30 years. Although regional interventions by MDBs, at times, are impeded by their operational mode of country assistance programs (Cook and Sachs, 1999), there has been a gradual shift in recent years towards a more proactive and conscious support of river basin organisations involving several riparian states. *The Nile Basin Initiative*, supported by the World Bank, is by far the most prominent example of this trend although it does represent the exception rather than the rule. The most progressive regional development bank in the area, the Asian Development Bank, recently included a mandate of promoting regional cooperation in its official Water Policy, but still has relatively few activities on the ground (ADB, 2004). There is thus potential for further involvement by multinational development banks in transboundary water management.

Almost all of the economic literature addressing the energy versus irrigation trade-off is concerned with inter-state or domestic rivers, especially in the United States. Particularly pertinent are the studies of the Snake-Columbia river by McCarl and Ross (1985), Houston and Whittlesey (1986), McCarl and Parandvash (1988), and Hamilton *et al* (1989). The Colorado river has been analysed by Gisser *et al* (1979) and the irrigation districts in Central California by Chatterjee *et al* (1998). The study by Owen-Thomsen *et al* (1982) of Egypt's High Aswan Dam therefore represents an exception to the focus on US-based rivers. These studies use mathematical programming to model agricultural production and to analyse the impacts on the agricultural sector of a water transfer to hydropower production because the latter typically has the highest marginal productivity. They generally conclude that such diversions have the potential to generate welfare gains especially in years of low water flow. Authors such as Hamilton *et al* (1989) consider market mechanisms to improve the resource allocation. Others, such as Chatterjee *et al* (1998), have emphasised the establishment of clearer property rights. Both of these policy remedies, however, are less suitable in an international context. International trade in water is rare, partly because the conflicting principles of international law complicate the property rights issue

To our knowledge, there has been only three economic studies of international hydropower-irrigation conflicts. Aytemiz (2001) examines the conflict between Turkey and Syria on the Euphrates. In addition to focusing on the optimal allocation of surface water, this study also addresses the question of whether there is sufficient water for both riparians' needs, and comes to a negative conclusion. The two other papers both use Syr Darya as a case study. World Bank (2004a) finds that basinwide benefits are maximised when the upstream hydropower plant operates to facilitate downstream irrigation. To support a cooperative outcome, downstream riparians should compensate the upstream riparian for its water storage services by issuing side payments. Abbink, Moller and O'Hara (2005) generalise the economic model developed by the World Bank and use it to conduct a behavioural experiment. They demonstrate that cooperation in the laboratory is hard to achieve and explains this as a lack of trust inherit to the existing system of barter payments.

There is also a more general economic literature on transboundary rivers. A non-exhaustive list includes contributions by Barrett (1994), Dinar and Wolf (1994), Moller (2004), Rogers (1997), Kilgour and Dinar (2001) and Ambec and Sprumont (2002). These authors are typically preoccupied with how and under what circumstances riparians can cooperate on their own, but do not directly address the question of whether third-party intervention may be useful. An important reason for this omission is the common underlying assumption of riparian sovereignty, the consequence of which is to ignore the relevance of supra-national bodies in fostering cooperation. While this may be a realistic assumption in some circumstances, this is not always the case. Many international river basins are located in developing nations (twenty percent are located in Africa, for instance). The ability of poor, indebted and aid-recipient countries to fully control their policies, is sometimes compromised in practice. The proposition that external agencies could play a role in promoting riparian cooperation can therefore not be dismissed *a* *priori.*

In this paper we consider a range of policy interventions undertaken by a multinational development bank in the context of a transboundary hydropower-irrigation water conflict. The paper considers two policy issues: First, interventions by an MDB can be motivated by at least two objectives: a) maximising basinwide social welfare and b) promoting regional stability. As noted above, existing economic literature has emphasised (a) and paid little attention to (b). This prioritisation can be readily justified in a domestic context where the problem is primarily one of suboptimal resource allocation. In an international context, on the other hand, it is often political priorities which is the major concern and economic objectives are secondary. The distinction is important because interventions may result in a trade-off. For instance, an intervention which increases upstream welfare more than it reduces downstream welfare enhances basinwide welfare but jeopardises regional stability unless side payments are made. Is it possible to identify Pareto-improving policy interventions that simultaneously promote regional stability and enhance social efficiency? Secondly, an interesting policy option emerges for an MDB that intends to assist a downstream client: Could the client be more effectively assisted through *indirect* intervention in an upstream state, as opposed to *direct* interventions within the client's own territory? To illustrate this point in a broader context, annual floods in Bangladesh have been exacerbated in recent years as a consequence of deforestation and overgrazing in upstream India, Nepal and Tibet. Is Bangladesh best protected against floods through upstream measures, e.g. deforestation control, or through in-country interventions, such as flood control defences?[2]

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[2] Related policy options arise for a host of other international challenges driven by cross-border spillover effects. Apart from the related area of transboundary pollution, this includes many other 'global public goods' (see Kaul et al 1999).

The present paper contributes to existing literature in two ways. First, it adds to the sparse literature on international hydropower-irrigation conflicts by providing an analytical framework within which various case studies of transboundary rivers can be examined. Secondly, it contributes to the literature on transboundary rivers by explicitly considering a potential role for third-party intervention. The paper identifies and ranks a range of policy interventions in terms of their ability to reduce regional tension and enhance basinwide social welfare. It also establishes the conditions under which a downstream riparian is best assisted through intervention in an upstream state. In comparison to the existing hydro-irrigation literature, we present an analytical model that is simple enough to capture the essence of the problem. On the other hand, our model is not sufficiently elaborate to allow for accurate empirical estimations of individual river basins (see Chatterjee *et al*, 1998 for an example). It should also be emphasised from the outset that the interventions analysed here are costly infrastructure projects, such as construction of hydropower plants and dams which take several years, sometimes decades, to complete. The theoretical analysis emphasises the qualitative impact of these projects, but is necessarily silent about other important aspects such as the investment cost or the social, environmental or political impact. A final decision to pursue any such projects must obviously also be informed by these factors. The remainder of the paper is structured as follows: Section 2 presents the model and its noncooperative equilibrium. Section 3 computes the socially efficient allocation. Section 4 contains the policy analysis based on comparative statics. Section 5 ranks and compares policies. Section 6 uses the theoretical findings to illustrate the relevance of the model in the context of the Syr Darya conflict. Section 7 concludes.

2. THE MODEL

Two riparian states share a transboundary river. The upstream riparian (UP) is a hydropower producer and the downstream riparian (DOWN) withdraws water for agricultural irrigation.[3] There are two periods which may be thought of as two seasons within a water year. Second-period electricity demand in UP is assumed higher than first-period demand. In the first period, therefore, UP prefers to store some water in its reservoir in order to increase second-period electricity production. This mode of operation conflicts with the interests of DOWN. It receives insufficient irrigation water in the first period, which is the growing season, and may experience flooding in the second period.

2.1 Upstream hydropower production[4]

Upstream hydropower is generated by a single, state-regulated plant which produces y_t units of electricity in period t, $t = (1, 2)$, by making use of q_t units of water flowing to it. Let $\alpha > 0$ be an efficiency parameter. The hydropower production function

$$y_t = \alpha f(q_t) \tag{1}$$

can exhibit either diminishing or constant returns to scale, thus $\frac{\partial f(q_t)}{\partial q_t} > 0$, $\frac{\partial^2 f(q_t)}{\partial q_t^2} \leq 0$ and $f(0) = 0$.[5] The hydropower plant serves the entire domestic market for electricity which has the inverse demand function in period t,

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[3] Note the distinction between consumption and non-consumption water use. Irrigation is an example of the former and hydropower use an example of the latter.

[4] The hydropower model presented here is an extension of that developed by Ambec and Doucet (2003).

[5] Ambec and Doucet (2003) assume constant returns to scale while the models developed by Edwards (2003) exhibit diminishing returns.

denoted p_t:

$$p_t(y_t) = a_t - by_t \tag{2}$$

where $a_t > 0$ and $b > 0$ are parameters and $a_t > by_t$, $\forall y_t > 0$. Let $0 < \delta < 1$ denote the discount factor between the two periods. The relatively higher second-period electricity demand is reflected in the assumption: $\delta a_2 > a_1$. The natural inflow of water, Q_t, denotes the (perfectly forecast) exogenous volume of water supplied in the reservoir controlled by UP in period t and $\overline{Q} = Q_1 + Q_2$ denotes the annual inflow. It is assumed that water is scarce enough not to be wasted. In other words, over the two periods UP uses all of the water inflows to produce electricity.[6] Water available to UP in period one can be used to produce electricity in the first period or can be stored in UP's reservoir for use in the second period. In the first period, UP relies on water in its reservoir (i.e. no water is available from the previous period). Hence, UP faces the input supply constraint

$$q_1 \leq Q_1 \tag{3}$$

The volume of water stored in UP's reservoir during the first period is used in its entirety to produce electricity in the second period. This volume is bounded by the reservoir capacity denoted $s > 0$. In terms of first-period water release we have:

$$q_1 \geq Q_1 - s \tag{4}$$

We normalise operating costs to zero and write profit in period t as a function of water input, q_t:

$$\pi_t^u(q_t) = p_t y_t = \alpha f(q_t)\left(a_t - b\alpha f\left(q_t\right)\right) \tag{5}$$

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[6] This simplifying assumption reflects the physical limitation that, on average in a long-term equilibrium, hydro plants cannot have net positive or negative accumulation of water.

By serving the domestic market, the plant generates a consumer surplus in period t of:

$$CS_t(q_t) = \frac{1}{2} y_t(a_t - p_t) = \frac{b\alpha^2}{2} \left[f(q_t)\right]^2 \tag{6}$$

Let social welfare of the upstream riparian in period t be the sum of consumer surplus and profit: $SW_t^u(q_t) = CS_t(q_t) + \pi_t^u(q_t)$. Since second-period water release is determined residually, $q_2 = \overline{Q} - q_1$, we can write down UP's optimisation problem in terms of choosing q_1 optimally:

$$\max_{q_1} \left\{ SW_1^u(q_1) + \delta SW_2^u(\overline{Q} - q_1) \mid Q_1 - s \leq q_1 \leq Q_1 \right\} \tag{7}$$

The Lagrangian is written:

$$L(q_1, \overline{\lambda}, \underline{\lambda}) = SW_1^u(q_1) + \delta SW_2^u(\overline{Q} - q_1) + \overline{\lambda}(Q_1 - q_1) + \underline{\lambda}(Q_1 + q_1 - s) \tag{8}$$

where $\overline{\lambda}$ and $\underline{\lambda}$ are the Lagrangian multipliers associated with the input supply constraint and the storage constraint, respectively. The first-order conditions yield:

$$\frac{\partial SW_1^u(q_1^*)}{\partial q_1} + \delta \frac{\partial SW_2^u(\overline{Q} - q_1^*)}{\partial q_1} = \overline{\lambda} - \underline{\lambda} \tag{9}$$

$$\overline{\lambda}(Q_1 - q_1^*) = 0 \tag{10}$$

$$\underline{\lambda}(Q_1 + q_1^* - s) = 0 \tag{11}$$

At the interior solution $(\overline{\lambda} = \underline{\lambda} = 0)$, the first-order condition reduces to:

$$\frac{\partial f(q_1^*)}{\partial q_1} p_1\left(y_1^*\right) + \delta \frac{\partial f(q_2^*)}{\partial q_1} p_2\left(y_2^*\right) = 0 \tag{12}$$

Upstream social welfare, SW^u, is strictly concave in q_1. The second-order condition yields:

$$\frac{\partial^2 f(q_1)}{\partial q_1^2} p_1(y_1) - \left(\frac{\partial f(q_1)}{\partial q_1}\right)^2 + \delta \frac{\partial^2 f(q_2)}{\partial q_1^2} p_2(y_2) - \delta \left(\frac{\partial f(q_2)}{\partial q_1}\right)^2 < 0 \tag{13}$$

The first-order condition (12) captures the upstream planner's choice between first- and second-period water release. To maximise social welfare, UP must equate the marginal social welfare of the two periods. The corner solutions are straightforward: When the input supply constraint binds ($\overline{\lambda} > 0$), the optimal production plan requires more water in period one than is available so $q_1^* = Q_1$. This implies that first-period marginal social welfare is higher than that of the second period: $\frac{\partial SW_1^u(q_1^*)}{\partial q_1} > \delta \frac{\partial SW_2^u(q_2^*)}{\partial q_1}$. When the storage constraint binds ($\underline{\lambda} > 0$), the optimal production plan requires more storage capacity in period one than is available thus $q_1^* = Q_1 - s$ and $\frac{\partial SW_1^u(q_1^*)}{\partial q_1} < \delta \frac{\partial SW_2^u(q_2^*)}{\partial q_1}$. Finally, we note that the assumption of water scarcity implies that the technical efficiency coefficient, α, has a maximum value:[7] $\overline{\alpha} \equiv \arg\max_{\alpha} \{SW_1^u(\alpha, q_1^*) + \delta SW_2^u(\alpha, q_2^*)\} = \frac{a_1 f(q_1^*) + \delta a_2 f(q_2^*)}{b\left(\left[f\left(q_1^*\right)\right]^2 + \delta\left[f\left(q_2^*\right)\right]^2\right)}$. For $\alpha > \overline{\alpha}$ the total water inflow $\overline{Q}$ would be larger than the amount of water required to satisfy electricity demand. We henceforth assume that $\alpha < \overline{\alpha}$.

2.2 Downstream agricultural production

In period one, DOWN grows an irrigation-fed agricultural crop x, such as cotton or rice, which it sells on the world market. Irrigation supply is available from two main sources: upstream water releases, q_1^*, and water available from DOWN's own reservoir, $r > 0$, which is assumed full in the beginning of period one. The agricultural production function, $x(q_1^* + r)$, exhibits diminishing returns to scale, $\frac{\partial x(\cdot)}{\partial q_1} > 0$, $\frac{\partial^2 x(\cdot)}{\partial q_1^2} < 0$ and $x(0) = 0$. The cost function $c(q_1^* + r)$ is convex, $\frac{\partial c_1(\cdot)}{\partial q_1} > 0$ and $\frac{\partial^2 c_1(\cdot)}{\partial q_1^2} \geq 0$, and the output price is exogenous: $p(x) = p = 1$. We write DOWN's first-period profit as:

$$\pi_1^d = x(q_1^* + r) - c_1(q_1^* + r) \tag{14}$$

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[7] The second-order condition confirms that SW^u is strictly concave in α: $-b\left(\left[f\left(q_1\right)\right]^2 + \delta\left[f\left(q_2\right)\right]^2\right) < 0$

In the second period DOWN is not engaged in any economic activities which use water from the river as an input. Water may, nevertheless, have economic consequences if flooding occurs. In our model, as in reality, flooding has positive and negative implications. We model the positive effects as a replenishment of DOWN's reservoir, thus we assume $r < \overline{Q} - q_1^*$.[8] The negative effects of flooding, such as damages to physical infrastructure, are described by the convex cost function $c_2(q_2^* - r - \widetilde{q})$ where $\frac{\partial c_2(\cdot)}{\partial q} > 0$ and $\frac{\partial^2 c_2(\cdot)}{\partial q^2} \geq 0$. In words, only second-period water inflow that exceed the sum of the conveyance capacity of the river, $\widetilde{q}$, and the reservoir capacity r have a negative economic impact. Second period profit is given by:

$$\pi_2^d = -c_2(\overline{Q} - q_1^* - r - \widetilde{q}) \tag{15}$$

DOWN's profit is maximised when first-period and second-period marginal profits are equalised:[9]

$$\frac{\partial x(q_1 + r)}{\partial q_1} - \frac{\partial c_1(q_1 + r)}{\partial q_1} = -\delta \frac{\partial c_2(\overline{Q} - q_1 - r - \widetilde{q})}{\partial q_1} \tag{16}$$

Note that maximisation of DOWN's profit implies non-positive marginal profits ($\frac{\partial \pi_t(\cdot)}{\partial q_t} \leq 0$). If the sum of the conveyance and reservoir capacity ($\widetilde{q} + r$) is relatively small, and flooding occurs, then marginal profits are negative. In this case DOWN would prefer to reduce second-period flooding by using more than optimal irrigation input in the first period. If flooding can be avoided ($\widetilde{q} + r$ is relatively substantial) then DOWN would prefer to irrigate until first-period marginal profit equals zero.

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[8] Although this is a two-period model, there is an implicit assumption that period two is followed by a third period (which has the characteristics of the first period), a fourth period (similar to the second period) and so on. Thus the reason why the downstream reservoir is assumed full in the first period is that it was fully replenished in period zero.

[9] The assumptions about the production and cost functions imply that π^d is strictly concave in q_1.

2.3 Noncooperative equilibrium

Due to the geographic position of the two riparians the noncooperative equilibrium is determined entirely by the actions of the upstream riparian (at least in the short term).[10] Because of assumed water scarcity in the first period, DOWN does not maximise its profit, thus its first-period marginal profit is positive $\frac{\partial \pi_1^d(q_1^*+r)}{\partial q_1} > 0$.

The noncooperative solution may take any of 3 forms: The interior solution or either of the two corner solutions. Figure 1 (at the end of the paper) illustrates the noncooperative equilibrium at the interior solution. The width of the diagram is determined by the total water inflow over the two periods, $\overline{Q}$. First-period water release, q_1, is measured from left to right and second-period water release, q_2, in the opposite direction. Panel (a) depicts the upstream hydropower producer. Each period is represented by a convex marginal social welfare (MSW) curve. At an interior solution, the noncooperative input vector (q_1^*, q_2^*) is determined at the intersection of the two MSW-curves located between the two vertical lines representing, respectively, the storage constraint $(Q_1 - s)$ and the supply constraint (Q_1). Panel (b) illustrates the downstream riparian. First-period crop production is represented by a convex marginal profit curve. DOWN receives q_1^* water units from UP and by using all the water from its reservoir r it operates at B. First-period profit is maximised at D where marginal profit equals zero. In the second period UP releases q_2^* of which r units are used to replenish DOWN's reservoir. The excess water causes flooding in the territory of the downstream riparian, represented by point C on its concave marginal profit

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[10] We ignore here the possibility that DOWN issues a side payment to UP in exchange for a release vector more favourable to DOWN. This possibility is discussed further in the Syr Darya case study (section 6), but not treated explicitly in the theoretical analysis.

curve. In comparison, downstream profit for both periods is maximised at E where the marginal profit curves intersect. If the conveyance capacity $\widetilde{q}$ is sufficiently large and marginal profit curves do not intersect then DOWN's optimum would be at D. Figures 2 and 3 illustrate the two corner solutions. When the storage constraint binds (figure 2) UP must produce more first-period electricity (and release more water) than it would wish if the storage constraint was not binding and the equilibrium is determined by the location of the $(Q_1 - s)$-curve. On the other hand, if the supply constraint binds the equilibria are determined by the location of the Q_1-curve (figure 3).

3. BASINWIDE SOCIAL EFFICIENCY

The presence of a production externality implies that the noncooperative equilibrium is typically not socially efficient. In this paper, the socially efficient allocation is defined as the feasible water allocation (q_1^o, q_2^o) which maximises basinwide social welfare, denoted $SW = SW_1^u + \delta SW_2^u + SW_1^d + \delta SW_2^d$. Note that $SW_1^d + \delta SW_2^d = \pi_1^d + \delta \pi_2^d$, i.e. there is no consumer surplus from agricultural production because DOWN's crop is exported to markets outside the basin. The socially efficient allocation is the solution to the problem:

$$\max_{q_1}\{SW_1^u(q_1) + \delta SW_2^u(q_1) + SW_1^d(q_1) + \delta SW_2^d(q_1) \mid \overline{Q}_1 - \overline{s} \leq q_1 \leq \overline{Q}_1\} \tag{17}$$

The first-order conditions yield:

$$\frac{\partial f(q_1^o)}{\partial q_1} p_1\left(y_1^o\right) + \delta \frac{\partial f(q_2^o)}{\partial q_1} p_2\left(y_2^o\right) + \frac{\partial x\left(q_1^o\right)}{\partial q_1} - \frac{\partial c_1\left(q_1^o\right)}{\partial q_1} + \delta \frac{\partial c_2\left(q_2^o\right)}{\partial q_1} = \overline{\mu} - \underline{\mu} \tag{18}$$

$$\overline{\mu}(Q_1 - q_1^o) = 0 \tag{19}$$

$$\underline{\mu}(Q_1 + q_1^o - s) = 0 \tag{20}$$

where $\overline{\mu}$ and $\underline{\mu}$ are the Lagrangian multipliers associated with the input supply constraint and the storage constraint, respectively. A basinwide social planner aims to equalise the marginal social welfare of both riparians. In comparison to the noncooperative equilibrium, the externality is internalised because downstream agricultural profits and flooding damage are considered when choosing q_1. First-period water release is higher in the socially efficient allocation if the sum of downstream marginal social welfare and upstream marginal social welfare is positive in the noncooperative allocation, $q_1^o > q_1^* \Leftrightarrow \frac{\partial SW^d(q_1^*)}{\partial q_1} + \frac{\partial SW^u(q_1^*)}{\partial q_1} > 0$, and vice versa. Thus, basinwide welfare gains can be attained if water is diverted towards its most productive use. The noncooperative allocation is generally different from the socially efficient allocation, except if there is a binding constraint for the upstream planner as well as for the basinwide planner. Formally, we have:

Proposition 1 *The noncooperative allocation is not socially efficient, except if one of the following three conditions are true:*
(a) $\overline{\mu} = \underline{\mu} = \overline{\lambda} = \underline{\lambda} = 0$ *and* $\frac{\partial x(q_1^o)}{\partial q_1} - \frac{\partial c_1(q_1^o)}{\partial q_1} = \delta \frac{\partial c_2(q_2^o)}{\partial q_1}$.
(b) $\overline{\mu} > 0$ *and* $\overline{\lambda} > 0 \Rightarrow q_1^o = q_1^* = Q_1$
(c) $\underline{\mu} > 0$ *and* $\underline{\lambda} > 0 \Rightarrow q_1^o = q_1^* = Q_1 - s$

Proof. This follows from a comparison of the first-order conditions for the upstream planner (9)-(11) with those of the basinwide planner (18)-(20). ■

4. POLICY ANALYSIS

As outlined in the introduction our aim is to identify policy interventions which promote regional stability and enhance social efficiency. The root cause of riparian conflict and social inefficiency is the unidirectional, negative externality caused by upstream regulation of the natural river flow. Policies that reduce this externality (or its impact) will therefore be successful in attaining both objectives. Although we are primarily interested in interventions co-financed by multinational development banks, the comparative static results derived in this section are independent of agency and could, in principle, also be undertaken by the riparians themselves or other external agents.

4.1. Increase hydropower efficiency

Consider a policy intervention aimed at increasing the parameter α, i.e. the technical efficiency of hydropower production. A higher α implies that each unit of water released upstream produces more units of electricity than previously. This could, for instance, be achieved through the construction of additional hydropower plants along the river cascade so that each water unit passes through several turbines. The upstream impact is straightforward:

Proposition 2 *An increase in the technical efficiency of hydropower production, α, enhances upstream social welfare.*

Proof. This follows from the fact that $SW^u(q_1^*, \alpha)$ is strictly concave in α and the assumption that $\alpha < \overline{\alpha}$. ■

Upstream welfare increases because water is a scarce input. The downstream impact is less straightforward and depends critically upon UP's choice of input vector when it operates with enhanced efficiency. A shift from second- to first-period water release would reduce the negative externality and enhance downstream welfare. We find that UP's input choice depends on several factors, notably: 1) The production technology; 2) Whether it operates at an interior solution or a corner solution;

Proposition 3 *At the interior solution, an increase in upstream hydropower efficiency, α, reduces the negative externality and enhances basinwide social welfare if and only if the following condition is satisfied :*

$$\frac{\delta \frac{\partial f(q_2^*)}{\partial q_1}}{\frac{\partial f(q_1^*)}{\partial q_1}} > -\frac{f(q_1^*)}{f(q_2^*)} \tag{21}$$

Proof. The externality is reduced if first-period water release, q_1, increases (and q_2 decreases). We totally differentiate the first-order condition (12) and re-arrange for $\frac{dq_1^*}{d\alpha}$ to get:
$\frac{dq_1^*}{d\alpha} = \frac{b}{\Psi}\left(\frac{\partial f(q_1^*)}{\partial q_1} f(q_1^*) + \delta \frac{\partial f(q_2^*)}{\partial q_1} f(q_2^*)\right)$, where
$\Psi = p_1\left(y_1^*\right) \frac{\partial^2 f(q_1^*)}{\partial q_1^2} - b\alpha \left[\frac{\partial f(q_1^*)}{\partial q_1}\right]^2 + \delta p_2\left(y_2^*\right) \frac{\partial^2 f(q_2^*)}{\partial q_1^2} - b\alpha\delta \left[\frac{\partial f(q_2^*)}{\partial q_1}\right]^2 < 0 \Rightarrow$
$\frac{dq_1^*}{d\alpha} > 0 \Leftrightarrow \left(\frac{\partial f(q_1^*)}{\partial q_1} f(q_1^*) + \delta \frac{\partial f(q_2^*)}{\partial q_1} f(q_2^*)\right) < 0$, which after re-arranging yields (21). ■

Condition (21) reflects certain requirements on the production function $f(q_t)$. This is best illustrated with an example:

Example 4 *Let $f(q_t) = \kappa q_t^{\beta}$, $\kappa > 0$. Condition (21) reduces to:*

$$\delta (q_2^*)^{2\beta - 1} > (q_1^*)^{2\beta - 1} \tag{22}$$

Assume constant returns to scale ($\beta = 1$) and insert the equilibrium value $q_1^* = \frac{\delta Q}{(1+\delta)} + \frac{(a_1 - \delta a_2)}{b\alpha(1+\delta)}$ to get $\delta a_2 > a_1$ which is true by assumption. More generally, expression (22) is true for $\beta > \frac{1}{2}$ and $\delta = 1$. Intuitively, expression (21) is satisfied provided that the production function is 'sufficiently steep'.

If condition (21) is satisfied then we can fully characterise the effect of enhanced hydropower efficiency at the interior solution: First-period hydropower production increases partly because more water is released and partly because of enhanced efficiency. In period two, higher efficiency more than off-sets the reduction in water release so production increases. Upstream welfare increases in both periods because of water scarcity. The shift towards first-period water release has positive implications downstream. In period one, agricultural production and profit increase due to a higher irrigation input. In period two, the cost of flooding is reduced (provided that it occurs). Figure 4 illustrates this scenario where we have assumed CRS. An increase in α pivots both MSW-curves downward and changes the noncooperative equilibrium from A to F.

If, on the other hand, condition (21) is not satisfied then upstream welfare increases, while downstream welfare decreases due to lower irrigation input in period one and increased flooding in period two. Graphically, this corresponds to a situation where the ex-post equilibrium F is located to the left of the ex-ante equilibrium A. Under these circumstances, the intervention exacerbates the conflict of interest. The impact on basinwide welfare depends on whether upstream gains outweigh downstream losses. If basinwide welfare improves then there is a trade-off between the two policy objectives of regional stability and social efficiency.

If the hydropower plant is operating at a corner solution (and continues to do so ex-post) then basinwide welfare increases without reducing the externality. This is true, irrespective of whether condition (21) is satisfied. Upstream welfare increases, cf. proposition 2, but downstream welfare remains unchanged. This is because an increase in hydropower efficiency has no impact on the water release pattern across the two periods. Figure 5 illustrates this situation in the case where the supply constraint binds. The downward shift in the $MSW-$curves has no effect upon the equilibrium which is determined by the resource constraint rather than the intersection of the $MSW-$curves.

Finally, if the hydropower plant is facing a binding constraint, then there is the possibility that increase in α implies a move to the interior solution ex-post. With a binding supply constraint this must imply a fall in q_1, i.e. the intersection of the MSW-curves move to a point to the left of the Q_1-curve. Conversely, a binding storage constraint ex-ante must imply an increase in q_1 and an intersection to the right of the $(Q_1 - s)$-curve. Table 1 summarises the results:

Table 1. Comparative static results ($\alpha \uparrow$)

Case	$\frac{\partial SW^u}{\partial \alpha}$	$\frac{\partial SW^d}{\partial \alpha}$	$\frac{\partial SW}{\partial \alpha}$
1. a) IN and (21) or; b) from ST to IN	> 0	> 0	> 0
2. a) IN not (21) or; b) from SU to IN	> 0	< 0	$\lesseqgtr 0$
3. Corner solutions (ex-ante and ex-post)	> 0	$= 0$	> 0

Note: IN = interior solution, ST = storage constraint binds, SU=supply constraint binds.

4.2 Expand downstream reservoir capacity

DOWN benefits from its own reservoir, r, in two ways: In period one, it increases irrigation input by augmenting to upstream releases, q_1^*. In period two, it enhances the absorptive capacity thus reducing the potentially negative impact of flooding.

Proposition 5 *An expansion in downstream reservoir capacity* r *reduces the negative externality and enhances basinwide social welfare.*

Proof. The comparative static yields: $\frac{\partial \pi_1^d}{\partial r} = \frac{\partial x(\cdot)}{\partial r} - \frac{\partial c_1(\cdot)}{\partial r} > 0$ and $\frac{\partial \pi_2^d}{\partial r} = -\frac{\partial c_2(\cdot)}{\partial r} \geq 0$, thus $\frac{\partial SWF^d}{\partial r} = \frac{\partial \pi_1^d}{\partial r} + \frac{\partial \pi_2^d}{\partial r} > 0$. ■

An expansion in r increases first-period agricultural output. The impact on downstream welfare is positive because water is assumed scarce in the first period. In the second period, the cost of flooding (if it occurs) is reduced. This intervention is illustrated in figure 6.

4.3 Expand upstream reservoir capacity

UP benefits from its own reservoir, s, because it expands the production possibility set. Higher upstream dam capacity changes the production plan if, and only if, the storage constraint is binding.

Proposition 6 *If the storage capacity constraint is binding, an expansion of the upstream reservoir, s, would exacerbate the negative externality.*

Proof. If the storage constraint is binding then $q_1^* = Q_1 - s$, $q_2^* = Q_2 + s$. We get the following comparative static results: $\frac{\partial q_1^*}{\partial s} = -\frac{\partial q_2^*}{\partial s} = -1 \Rightarrow$ $\frac{\partial SW_1^u(q_1^*)}{\partial q_1} < \delta \frac{\partial SW_2^u(q_2^*)}{\partial q_1} \Rightarrow \frac{\partial SW^u}{\partial s} = \frac{\partial SW_1^u(q_1^*)}{\partial q_1}\frac{\partial q_1^*}{\partial s} + \frac{\partial SW_2^u(q_2^*)}{\partial q_1}\frac{\partial q_2^*}{\partial s} > 0$. $\frac{\partial SW_1^d}{\partial s} = \frac{\partial \pi_1^d}{\partial q_1^*}\frac{\partial q_1^*}{\partial s} < 0$ and $\frac{\partial SW_2^d}{\partial s} = \frac{\partial \pi_2^d}{\partial q_2^*}\frac{\partial q_2^*}{\partial s} < 0 \Rightarrow \frac{\partial SW^d}{\partial s} < 0$. ■

An increase in upstream reservoir capacity s enables the upstream riparian to produce more electricity in the second period where the marginal social welfare is relatively higher. Thus, it releases less water in the first period and more in the second period. Unfortunately, the change in the operating mode of the hydropower plant has negative ramifications downstream because it enhances the negative externality effects of ‘too little’ water in period one and ‘too much’ in period two. Graphically, this intervention would imply a leftward shift of the $(Q_1 - s)-$curve in figure 2. As mentioned previously, a trade-off between the twin policy objectives of regional stability and basinwide welfare will occur if upstream gains outweigh downstream losses.

5. EVALUATION OF POLICY INTERVENTIONS

5.1 Policy ranking

On the basis of the comparative statics derived above we have ascertained the qualitative implications of three different policy interventions. These policies are ranked below in terms of their ability to reduce the negative externality. The rank of a particular intervention depends critically on the characteristics of the upstream riparian. More specifically, whether the hydropower plant is operating at an interior or a corner solution, and, whether condition (21) is satisfied or not.

Table 2. Ranking of policy interventions

Policy intervention	∂SW^u	∂SW^d	Externality	Welfare
1. UP HP efficiency (IN and (21))	> 0	> 0	Reduced	Higher
2. DOWN reservoir ($IN/ST/SU$)	$= 0$	> 0	Reduced	Higher
3. UP HP efficiency (ST/SU)	> 0	$= 0$	Same	Higher
4. UP reservoir (IN/SU)	$= 0$	$= 0$	Same	Same
5. UP reservoir (ST)	> 0	< 0	Increased	Uncertain
6. UP HP efficiency (IN not (21))	> 0	< 0	Increased	Uncertain

Note: IN = interior solution, ST = storage constraint binds, SU=supply constraint binds. Policy interventions 1 and 6 includes the possibilities of moving from a corner solution to an interior solution, cf. table 1.

An expansion in upstream hydropower efficiency is the qualitatively most attractive policy, but only at the interior solution and provided that the hydropower production function is ‘sufficiently steep’, i.e. condition (21) is satisfied. If this is not the case, then the second-best policy is to expand downstream reservoir capacity. Expansion of upstream storage capacity is at best ineffective, at worst, exacerbates the externality problem. An intervention in an upstream state by a multinational development bank would therefore wisely include a policy conditionality that prevents a unilateral expansion of upstream reservoir capacity without consultation with co-riparians. We also note that if (21) is not satisfied and the hydropower plant is operating at an interior solution then expanded hydropower efficiency emerges as the least attractive policy option. Thus, while this intervention guarantees a positive upstream impact, its downstream implications are uncertain unless accurate and reliable data can be obtained about the hydropower production function and the electricity demand function. If this is not possible, a risk-averse policy maker would prefer the 'safer option' of expanded downstream capacity. Policy conditionality, if effective, may help reduce risk if the multinational development bank can credibly persuade the upstream hydropower plant to increase first-period water release, possibly in exchange for part-financing the intervention.

While these observations give policy makers an overview of the merits and demerits of alternative interventions they are not a shortcut to a detailed cost-benefit assessment. The above ranking necessarily ignores several important aspects, including economic (e.g. cost of investment), social impact (e.g. local population displaced by dam construction) and environmental impact (e.g. soil erosion caused by flow alterations). Such aspects must obviously be considered before a final policy decision is made.

5.2 Direct or indirect intervention?

Our research was also motivated by the question of whether the downstream riparian is best assisted by an MDB through upstream or downstream intervention. In our context, this reduces to a question of whether DOWN should be assisted *indirectly* by increasing upstream hydropower efficiency, or *directly,* through an expansion in downstream reservoir capacity. This comparison is relevant only at the interior solution, since upstream intervention would otherwise be ineffective or counterproductive. Both investments have the same desirable property of reallocating irrigation water from period two to period one. Letting c_α and c_r denote the investment cost of improving hydropower efficiency and constructing a new reservoir, respectively, the cost-effectiveness of the two investments can be compared. We have the following result:

Proposition 7 *Indirect intervention (hydropower investment at the interior solution) is more cost-effective than direct intervention (downstream reservoir expansion) in terms of reducing the negative externality if and only if:*

$$\frac{b}{c_\alpha \Psi}\left(\frac{\partial f(q_1^*)}{\partial q_1} f(q_1^*) + \delta \frac{\partial f(q_2^*)}{\partial q_1} f(q_2^*)\right) > \frac{1}{c_r} \tag{23}$$

Proof. This result follows directly from the expression: $\frac{\frac{\partial(q_1^*+r)}{\partial \alpha}}{c_\alpha} > \frac{\frac{\partial(q_1^*+r)}{\partial r}}{c_r}$. Where $\frac{dq_1^*}{d\alpha}$ has been derived from total differentiation of (12) and $\Psi < 0$ is the variable defined in the proof of proposition 3. ■

The intuition behind this result is most easily derived by considering the case of constant returns to scale and setting $c_\alpha = c_r$. Condition (23) becomes $\delta a_2 - a_1 > 1$, i.e. indirect intervention is likely to be more attractive than indirect intervention when the difference between first- and second-period electricity demand is sufficiently large.

6. CASE STUDY: SYR DARYA[11]

As highlighted in the introduction, the overall aim of this paper is to provide an analytical framework within which various case studies can be examined. To illustrate the relevance of this framework we consider here the case of the Syr Darya river in Central Asia. The current conflict centres on the operation mode of the Toktogul reservoir located in the upstream Kyrgyz Republic. The reservoir has an active storage capacity of 19 billion cubic meters (BCM) and was designed during the Soviet period to facilitate irrigated agriculture in midstream Uzbekistan and downstream Kazakhstan. The so-called 'irrigation mode' called for 75% of annual releases in a normal year to take place in summer months and for restricting winter releases to no more than 25%. Surplus electricity generated in summer was fed into the Central Asian Power System for use by Uzbekistan and Kazakhstan. Since the Kyrgyz region lacked any significant resources of fossil fuels, central planners in Moscow arranged transfers from Uzbek and Kazakh regions to enable the Kyrgyz region to meet its winter demand for electricity. Once the Soviet Union was dissolved and the countries became independent, these arrangements came under great strain. The Kyrgyz Republic could no longer afford to import fossil fuels, which were now demanded in hard currency at world market prices, and started to operate Toktogul in a 'power mode'. During 1990-2000, summer releases declined to 45% and winter releases increased to 55%. As a consequence, Uzbekistan and Kazakhstan faced irrigation water shortages in summer and flooding in winter. In attempts to solve the problem of competing (and now international) claims on the water, Uzbekistan and Kazakhstan issued side payments to induce the Kyrgyz Republic

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[11] The background information provided in this section draws upon ICG (2002), Moller et al (2005) and World Bank (2004a and 2004b).

to increase summer releases. This was formalised in the 1998 Framework Agreement, under which the downstream riparians purchase Kyrgyz surplus summer electricity (at above market prices) and supply fossil fuels needed for Kyrgyz winter needs. In actual practice the annual barter agreements concluded under this arrangement have proven unsatisfactory due to bad timing, lack of trust and lack of control mechanisms.

The multinational development banks (the World Bank in particular, and, to a lesser extent, the Asian Development Bank) have been actively involved in attempts to resolve the conflict in recent years, as have bilateral donors, notably the US Agency for International Development, USAID. Thus far, interventions have tended to focus on facilitating political and technical dialogue between riparians with the ultimate purpose of brokering a regional agreement which maximises Syr Darya net benefits. The prospects of reaching a regional agreement have diminished considerably in recent years, however, as illustrated by the fact that the co-riparians failed to conclude barter agreements in 2003 and 2004. Increasingly disillusioned by these developments, the World Bank (2004b) recently revised its approach away from 'encouraging multi-country consensus and contractual agreements' towards 'national interventions' with the objective of 'promoting intra-state cooperation'. This change of strategy clearly increases the relevance of the type of interventions analysed in this paper. Below we discuss a range of infrastructure projects currently under preparation (or construction) in the region and comment on their potential impact on the river conflict using insights from the analytical framework developed in the previous sections.

The Kyrgyz government, in an attempt to ensure energy self-sufficiency, is actively pursing the construction of two new hydropower plants (Kambarata

I and II) with a combined capacity of 2,260 MW on the Naryn cascade above the Toktogul reservoir. The qualitative implications of this project, which could be completed by 2020, are broadly similar to those of increasing α in the model although it also offers the potential of electricity exports beyond the Central Asian region. The estimated cost of construction of USD 2.3 billion, or approximately one and a half times the Kyrgyz GDP, implies that a co-financing scheme is essential. The World Bank would be an ideal facilitator and contributor to such a scheme, but it argues that the economic cost of 0.0717 USD/kwh is too high. Interestingly, downstream Kazakhstan, which is considerably richer than its co-riparians, has offered to invest in the Kambarata projects. Given the high cost of investment, this offer is likely to have been driven primarily by an intention to project a positive international image in the region (see LeMarquand, 1977). In return for this investment, the Kyrgyz authorities would have to allow Kazakh representatives to sit on the board of the Toktogul hydroelectric plant controlling downstream releases (EIU, 2004).[12] Kyrgyz officials have so far rejected the proposal, possibly because they do not wish to surrender their sovereign right to control the water and because Toktogul represents the only source of regional influence of the Kyrgyz Republic. On the basis of the results developed in this paper, however, it could be argued that it makes good sense for Kazakhstan to demand 'political influence' in exchange for co-financing. While the Kyrgyz Republic stands to benefit from this investment, Kazakhstan (and Uzbekistan) would benefit only if the Kyrgyz Republic releases more water during summer and less during winter. As the theoretical analysis has demonstrated, an upstream riparian may only under certain conditions voluntarily choose to alter the release pattern in this manner. Additional conditionality

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[12] Such an arrangement is not uncommon. To illustrate, Egyptian officials are also represented at the Owen Falls Dam in Uganda (Waterbury, 2002).

must therefore be imposed by the co-financier to make this outcome more likely.

An alternative project which aims to increase winter power generation in the Kyrgyz Republic involves the completion of a 400 MW thermal power plant, Bishkek II, by 2007. At a cost of USD 200 million or 0.0255 USD/kwh, this project has better prospects of attracting external financial support, notably from the World Bank. A major drawback, however, is the increased Kyrgyz dependency on Uzbek natural gas. The Kyrgyz government is therefore hesitating to pursue this investment essentially because the international relations between the two countries are strained, as a result of disputes over water and international borders. An increase in second-period electricity supply cannot be analysed explicitly in the model without further modifications. However, its implications for the negative externality are similar to that of a reduction in second-period hydropower demand, represented by the variable a_2.[13] Graphically speaking, an decrease in a_2 implies a downward shift in the $SW_2-curve$. At the interior solution we get $-\frac{dq_1^*}{da_2} = \frac{b}{\Psi}\delta\frac{\partial f(q_2^*)}{\partial q_1} > 0$, i.e. the negative externality would be reduced. If the hydropower plant is operating at a corner solution then a decrease in a_2 has no impact on q_1^*, unless if the supply constraint becomes non-binding in which case q_1^* increases. Since the Toktogul reservoir generally operates at an interior solution, although the storage constraint is occasionally binding, the construction of Bishkek II has good prospects of promoting regional stability.

With respect to reservoir construction, a number of interesting and important developments have taken place in recent years. Most importantly, Uzbekistan has intensified efforts to increase its downstream water-regulating

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[13] This comparative static, however, does not adequately reflect the impact on upstream, and hence, basinwide social welfare.

reservoir capacity which could provide additional storage of about 2.5 billion BCM of water downstream. As demonstrated in the model, this could absorb the equivalent additional release from Toktogul in winter and subsequently release the same quantity of water again in summer for downstream irrigation. Downstream Kazakhstan is expected to benefit primarily from reduced flooding in winter as Uzbekistan would be expected to abstract most of the increment in summer irrigation availability. These projects are self-financed, although the Uzbek government did apply for financial assistance from US-AID and the US Department of Agriculture (USDA). This application was later withdrawn, however, because the Uzbek government did not agree to conduct an environmental impact assessment.[14] Finally, the Kazakh government is also contemplating the construction of a reservoir (Koksarai) west of Shymkent. This reservoir would cost USD 200 million and have an active storage capacity of 3 BCM. The proposed increment to the combined active storage capacity of Uzbekistan and Kazakhstan may, according to some observers, be sufficient to eliminate the seasonal conflict.[15] Whether this would indeed be the case depends partly on the behavioral response of the co-riparians.

A complete ranking of the four infrastructure projects discussed above, akin to that presented in section 5.1, would be beyond the scope of this paper. Nevertheless, in conclusion, we do make a few partially comparative remarks. Based on the information available, the construction of the Bishkek II thermal power plant does emerge as one of the most attractive investments due its relatively low costs and good prospects for reducing the externality. Given their high relative cost, the Kambarata projects appear less attractive

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[14] Personal communication, Mr Ken McNamara, USAID, Almaty 14/12-04.

[15] Personal communication, Mr Leonid Dmitriev, Kazgiprovodhoz, Almaty 15/12-04.

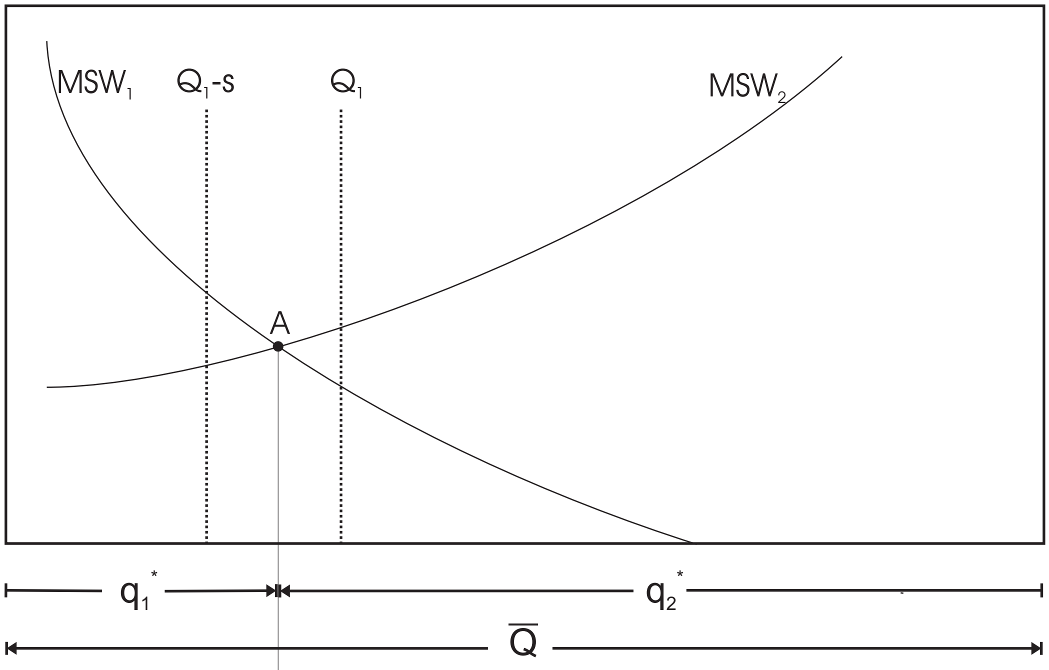
than the theoretical analysis would suggest, even if the Kyrgyz government should agree to surrender political control over Toktogul.

7. CONCLUSION

In this paper we analysed the potential conflict of interest embodied in upstream hydropower use and downstream irrigation use on a transboundary river. More specifically, we addressed the question of whether there is a role for multinational development banks in reducing regional tension and improving basinwide social welfare. We identified two Pareto-improving policy interventions, both of which have the beneficial effect of reducing the (impact of the) unidirectional, negative externality caused by upstream regulation of the natural river flow. Investment in upstream hydropower efficiency is one such intervention, but it requires that the MDB (or any other co-financier) can credibly enforce policy conditionality. This is necessary, because the upstream riparian may face incentives which could undermine the positive impact on the downstream riparian. The MDB should reach an agreement with the upstream riparian over the amount by which first-period releases must increase. In addition, in exchange for co-financing, the upstream riparian must also agree not to expand its reservoir capacity since this increases the negative externality. The second type of intervention, expansion of the downstream reservoir capacity, involves less risk. This reduces the need for conditionality, but brings benefits only to the downstream riparian. The paper also argued that the presence of a unidirectional externality presents policy options which could potentially be attractive. More specifically, we established the conditions under which an MDB could more effectively assist a downstream client through upstream intervention. Similar options are available on other transboundary rivers and should be explored further.

Figure 1. Noncooperative equilibrium (interior solution)

a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

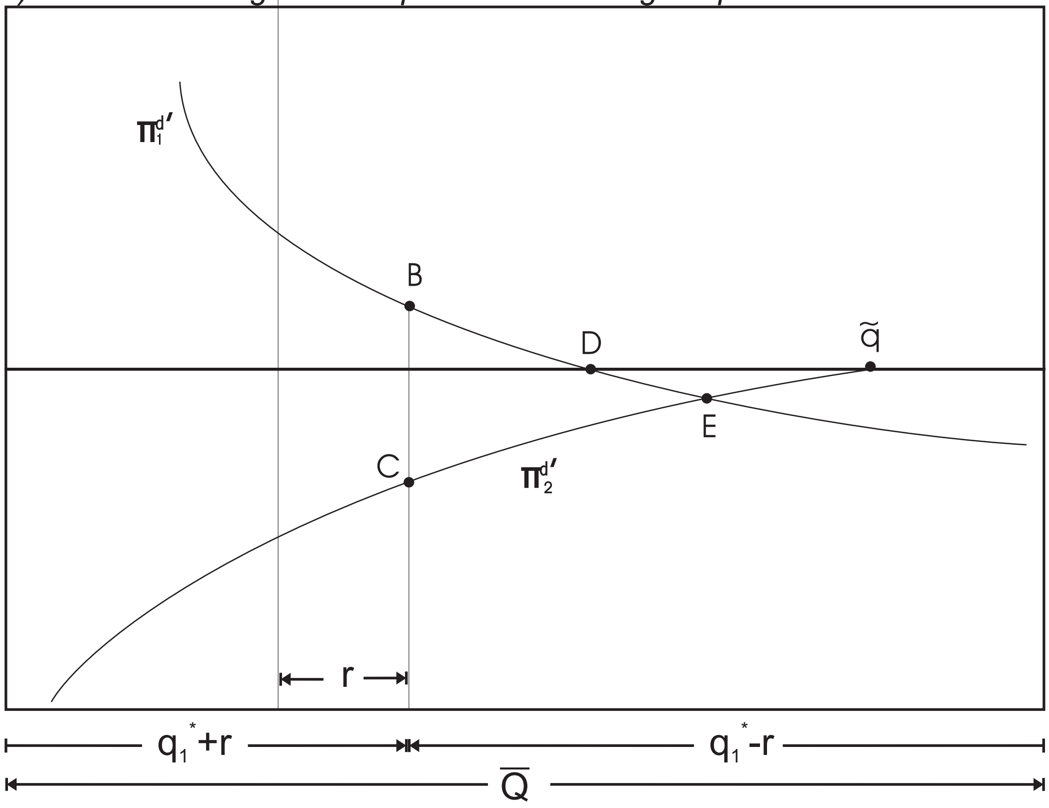
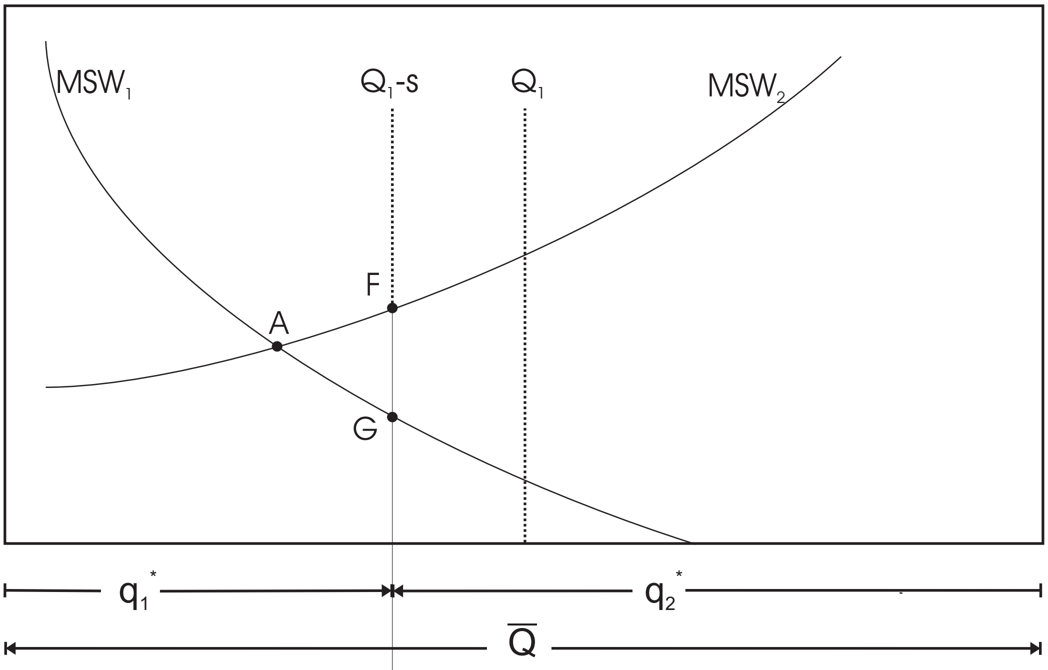


Figure 2. Noncooperative equilibrium (storage constraint binding)

a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

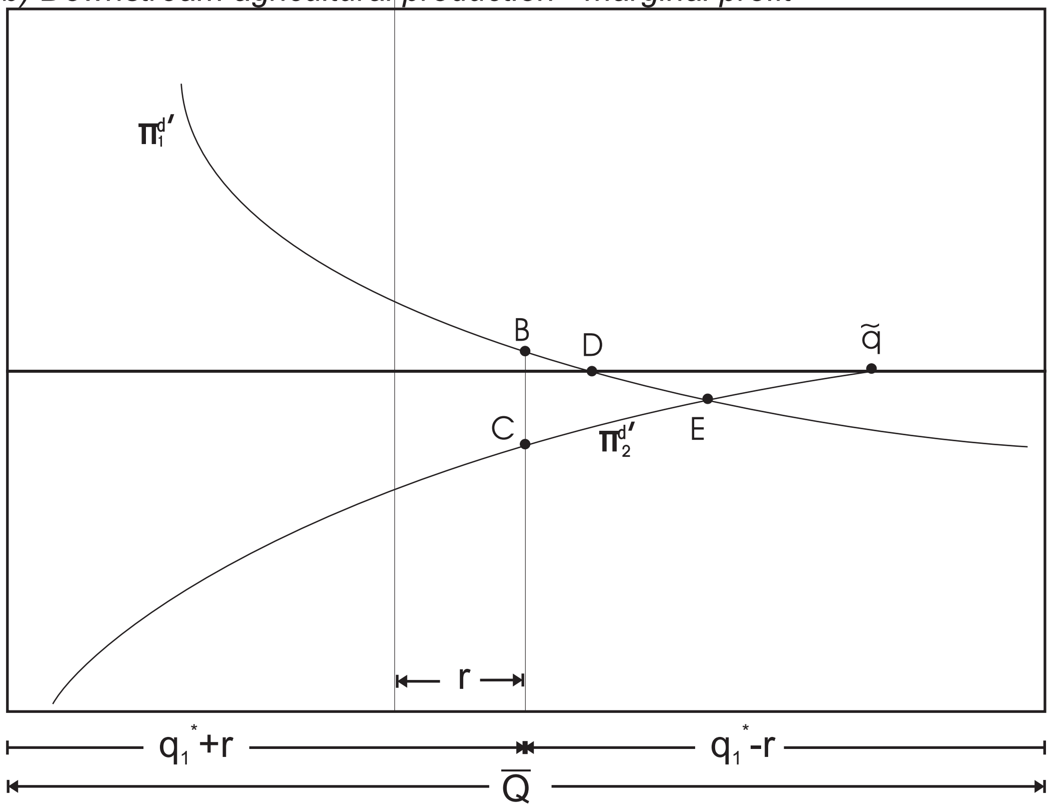
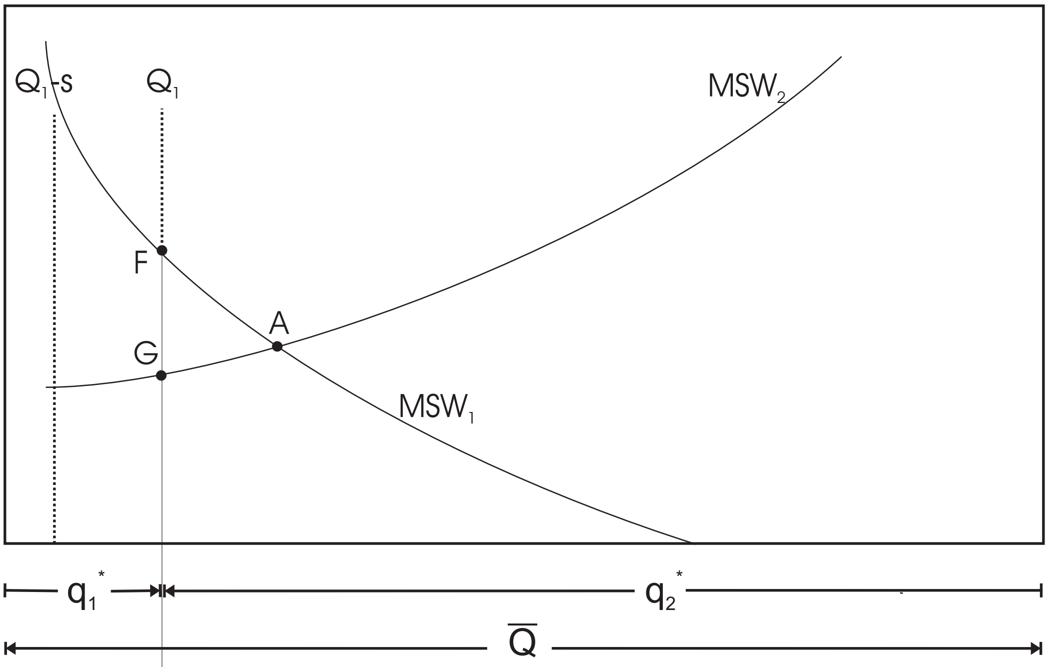


Figure 3. Noncooperative equilibrium (supply constraint binding)

a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

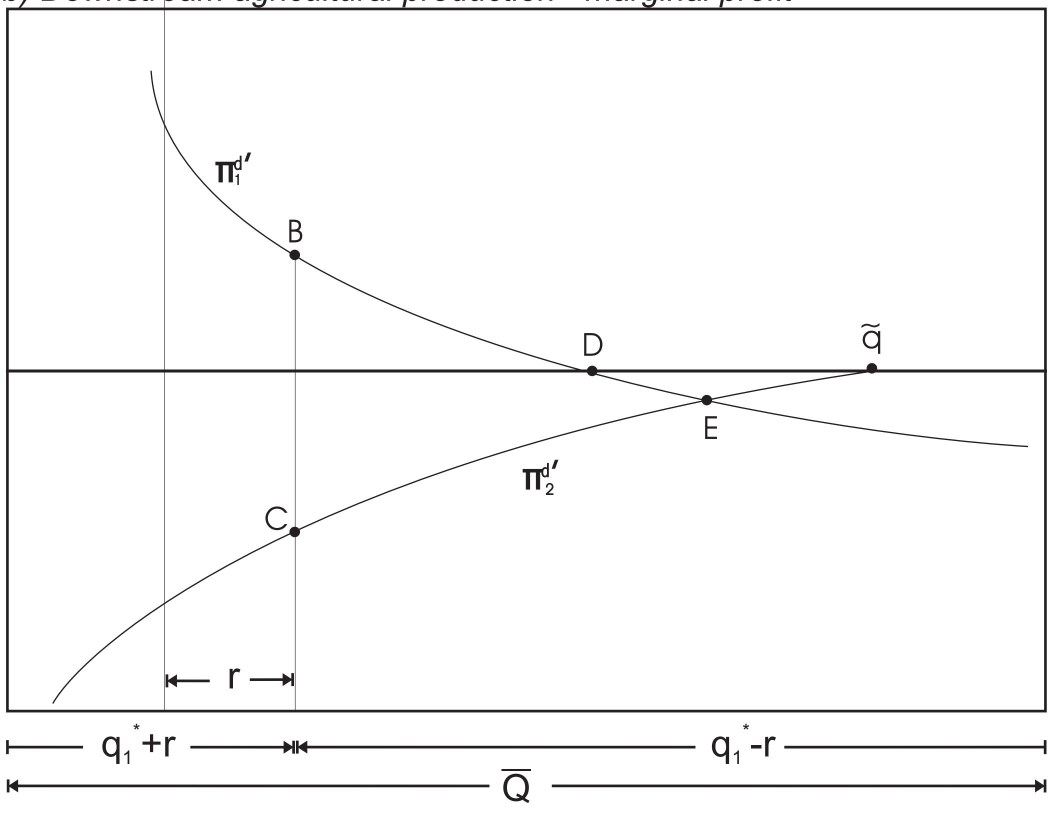
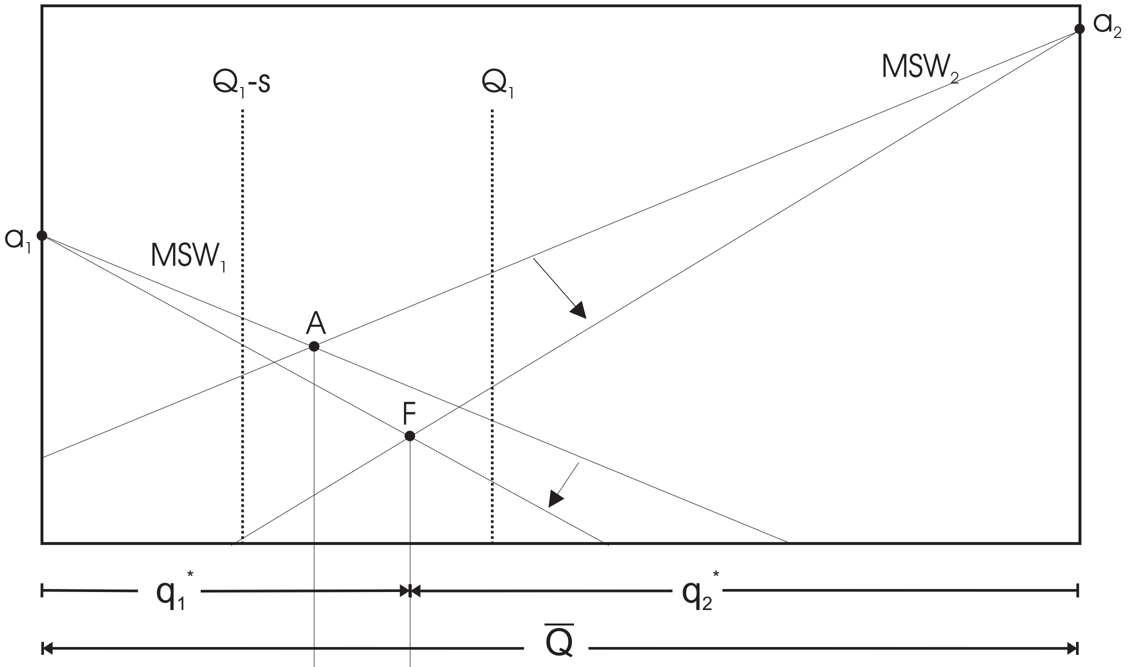


Figure 4. Expanded hydropower efficiency (interior solution and CRS)

a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

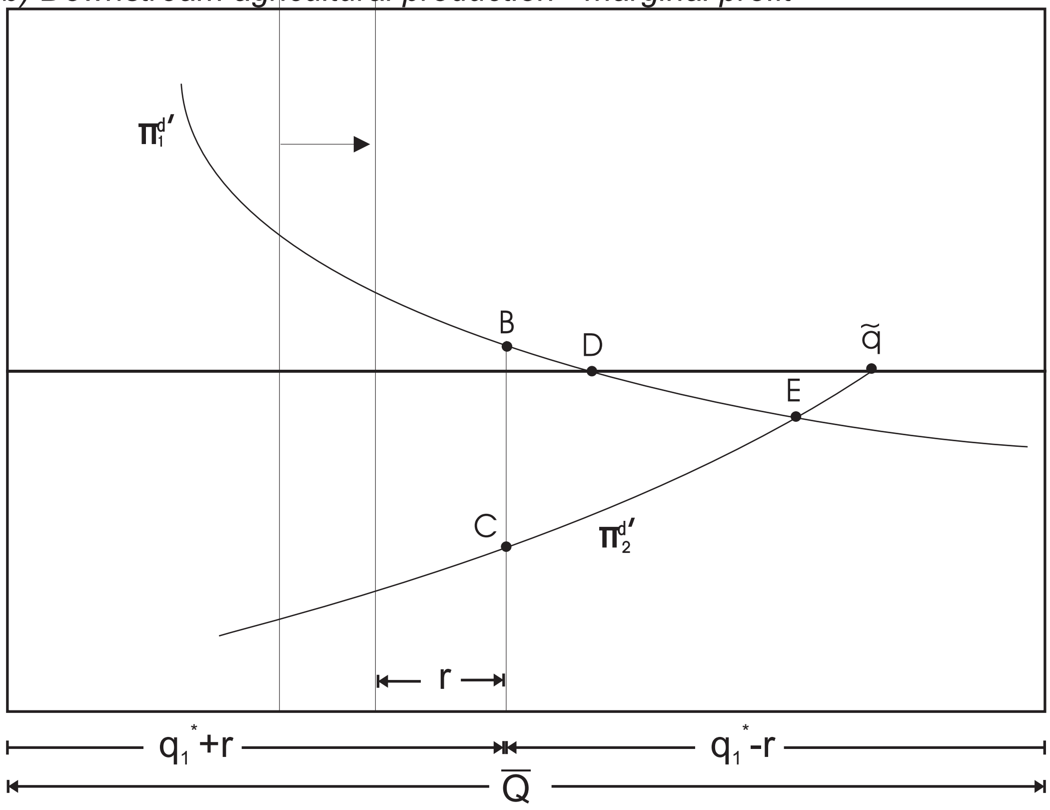
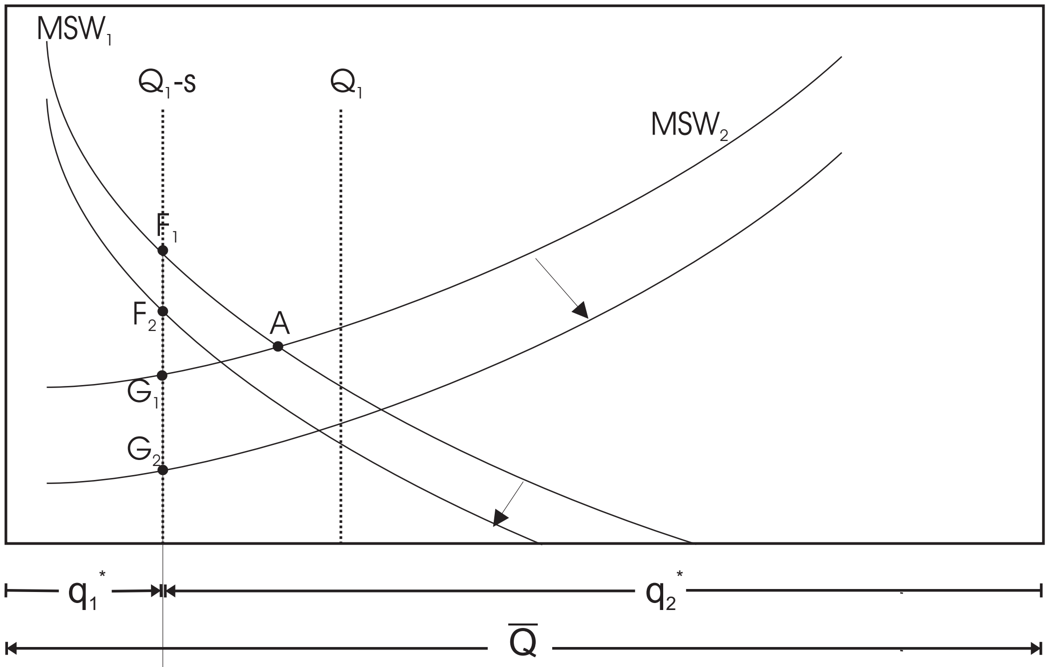


Figure 5. Expanded hydropower efficiency (supply constraint binding)

a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

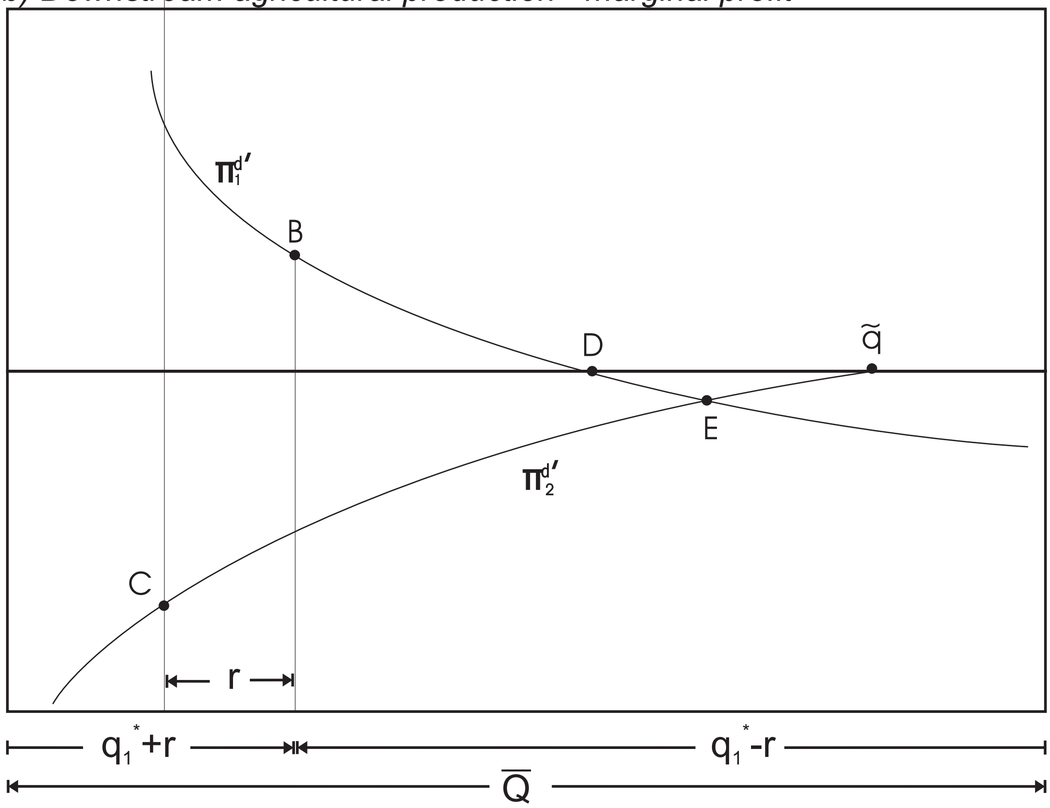
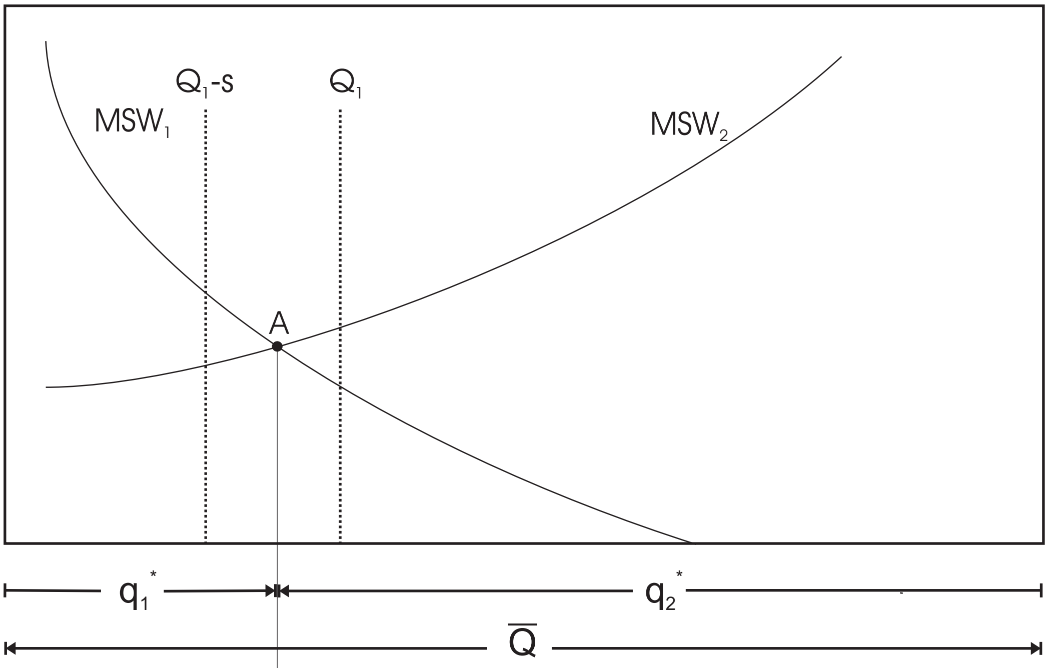
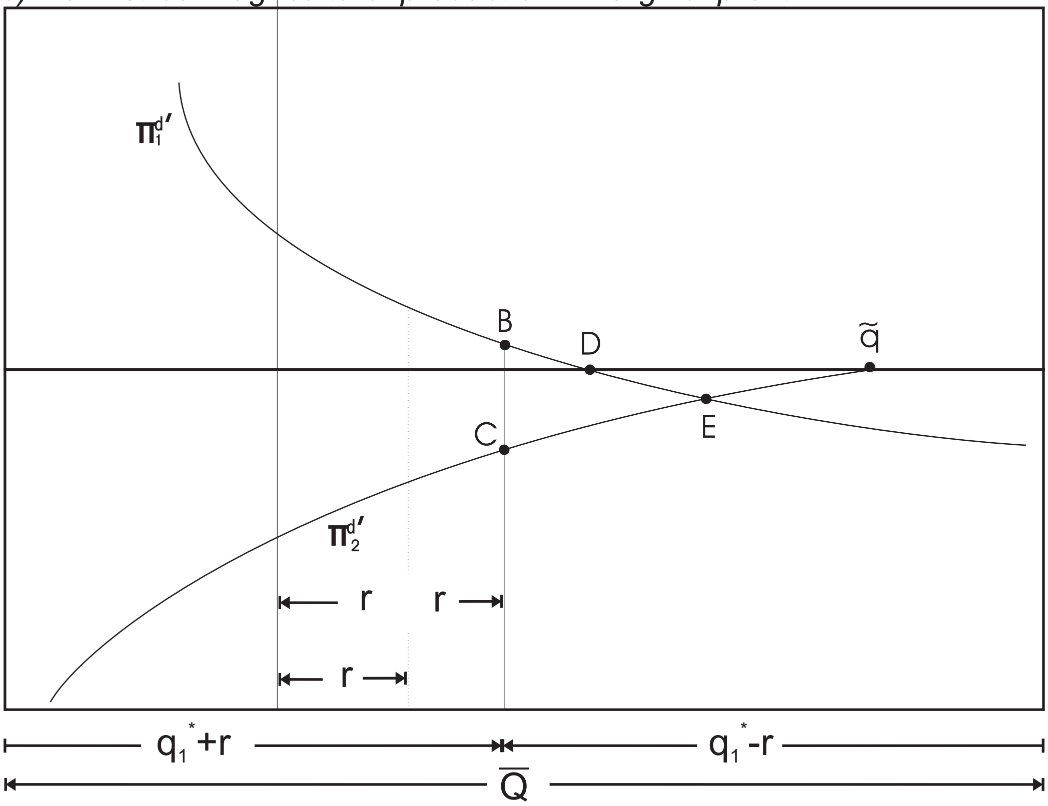


Figure 6. Expanded downstream reservoir capacity

a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit



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