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Sharing the load? Floods, droughts, and managing international rivers

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ABSTRACT. Rivers can be both givers of life and takers of life. Investments that provide protection against flooding are often beneficial during normal or low flows. Investments such as storage reservoirs are long lived, separating construction and management operations. With international rivers, the absence of enforcement mechanisms may preclude infrastructure collaboration. Where physical infrastructure is in an upstream nation, downstream impacts may be ignored after the structure has been completed. Using a game theoretic model, it is shown that downstream cooperation may only be rational when flooding is the primary downstream impact. A stylized arid developing region and humid developed region are compared. Potential gains from collaboration are greatest in arid regions, but may be difficult to achieve. There may be little scope for capturing the gains from basin level management if economic integration does not extend beyond water issues.

1. Introduction

In Kevin Costner's movie 'Field of Dreams', Costner's character was told that if he built a baseball field, the spirits of famous baseball players would return to play a ball game. The memorable phrase 'If you build it, they will come' has become a common metaphor. Bringing back baseball's greats is something that many could agree is good, but what if what is built is not put to its best use? In this paper we explore how working together to build flood control structures, especially storage capacity, may not always be beneficial to all parties involved. In particular, we show that without a means to enforce how storage is managed, a downstream nation may prefer a reduction in upstream storage capacity rather than an increase. Factors affecting when collaboration is mutually beneficial include the probability of droughts and floods, the cost or benefit of using the storage infrastructure, the damage inflicted by a flood, and the consumptive productivity of water during a drought.

It is fairly well accepted that managing rivers at the basin level maximizes total gains (Teclaff, 1996; Chakravorty and Umetsu, 2003; Rosegrant *et al.*, 2000). This concept has been adopted to widely varying degrees in international law and international agreements (Teclaff, 1996). In Europe and northern North America, joint management has a long history. In the last few decades, treaties concerning river management are becoming more common in developing regions as well (Wolf *et al.*, 2003). Collaboration typically began with agreements over navigation and/or fisheries, and has evolved to include agreements to control pollution and jointly finance and manage storage facilities. The best-known example of such management in Europe is the Rhine. Various treaties and informal international working groups have facilitated management of the Rhine since late in the nineteenth century. These various arrangements culminated in the International Commission for the Protection of the Rhine, formally established in 1963. Coordinated flood protection usually begins with information sharing, facilitating the design of flood information and early warning systems. For example, the Danube Commission (ICPDR, 2003), Mekong River Commission (MRC, 2002), the governments of the Ganges, Brahmaputra and Indus Flood-plains (ICIMOD, 2003), and the Nile countries (ICCON, 2001) have recently taken initiatives to increase information sharing. However, jointly financed and managed physical infrastructure is still rare. In the Rhine basin the Dutch government has co-financed projects in Germany and France to prevent flooding or pollution. Riparian states along the Colorado cooperate in building dams, managing reservoirs, and sharing information. However, this may be facilitated by the fact that the US courts arbitrate enforceable water rights. Finally, the Columbia River Treaty between the US and Canada involved large US payments for dam construction in Canada, dams that stabilized water flow in the US (Krutilla, 1968).

Historically however, management of rivers such as the Nile, Colorado, and Ganges is best described as adversarial. The scope for gains from cooperation is recognized, but seldom exploited. Many such cases, both inter- and intra-national, are documented in Dinar and Loehman (1995) and Parker and Tsur (1997), where various approaches to facilitating greater cooperation are also discussed. Rogers (1969) evaluated several infrastructure investment patterns for the Ganges and Brahmaputra rivers shared by India and Bangladesh. Jointly optimal development plans were identified, but it was shown that these were not welfare maximizing for India, the upstream nation, and therefore unlikely to be implemented. Management of the Colorado river has also been conflictual, to the extent that Arizona called out the National Guard in an effort to halt construction of a project it felt would largely benefit California (Sheridan, 1998). In its relationship with Mexico, downstream on the Colorado, the United States insists that Mexico has no right to any water originating within US territory (de Villiers, 2000). US investments to improve the quality of water entering Mexico (Folmer and von Mouche, 2001) are done purely to maintain good international relations. Even with many treaties, the US and Mexico have found substantial cooperation difficult for their various shared water resources (Frisvold and Caswell, 2002). Like the US, Turkey and Ethiopia also claim sovereign rights to all water originating on their territory, over the Tigris and Euphrates and the Nile respectively (Dinar and Alemu, 2000). Where the United States and Turkey are able to finance their own projects, Ethiopia cannot. Cooperative development of the Nile could generate larger benefits for all involved nations (Wiebe, 2001; Wichelns *et al.*, 2003; Whittington *et al.*, 1995), providing an agreed benefit sharing plan can be found. However, progress towards such cooperation has been very slow.

One important characteristic of cooperative river management is that it involves the construction of expensive infrastructure, such as dams and reservoirs, and the management of that infrastructure. The physical component of the project is often wholly contained within one nation, placing the control of its use in the hands of one party. A critical aspect determining whether nations will cooperate on these construction projects is therefore an assessment of whether the nation within which the project is built will manage it to maximize joint gains. Absent a sufficiently integrated economy between the riparian neighbors, joint action will only occur if it is sub-game perfect. Agreements or outcomes are sub-game perfect when no nation wants to take a different action at some later point in the game. In this context, sub-game perfection is satisfied when cooperation on dam construction does not make the downstream nation worse off than not cooperating, assuming that the upstream nation will consider only its own interests after the dam is built. Given the generally irreversible nature of large-scale infrastructure investments like dams, and the locational advantage of the upstream nation, collaborative action is often unlikely to be sub-game perfect.

In what follows we argue that the probability of drought is a key factor in determining whether nations will cooperate in managing a shared river. Where water shortages are frequent, infrastructure owning nations will face a strong incentive to use that infrastructure for their own gains. We would therefore expect other affected nations to be extremely reluctant to help finance this infrastructure, even though it may prevent damage to their territory in the event of a flood. Cooperation is unlikely. However, when droughts are rare and floods more common, then the selfish use of flood control infrastructure by the controlling nation generally confers benefits on the downstream nations. Galassi (2002) explored a similar situation, comparing the likelihood of cooperation in areas where water is scarce and where it is plentiful. Optimal group size, where groups 'cooperate', increased with increasing water abundance. In Galassi's work, a dry world and a wet world were compared, with monitoring costs playing an important role in determining the likelihood of cooperation. In this study we allow different water states in a single world, and use sub-game perfection to determine whether any cooperation will occur. Many rivers are characterized by a season when water flows are high enough to cause flooding damage and another when flows are unable to satisfy consumption. Further, with climate change likely to increase variability of water flow, it is important to know the likelihood of cooperation when both shortages and surpluses can occur within a river basin.

Game theoretic analysis of riparian nation interactions over water date back at least to Rogers (1969), who showed that cooperation was not a Nash equilibrium for the game between India and Bangladesh. Dinar and Wolf (1994) compared a range of alternatives for regional water trade between Egypt and Israel/Palestine, arguing that the set of acceptable arrangements had to consider the political as well as the economic relationships involved. Frisvold and Caswell (1997) model negotiations

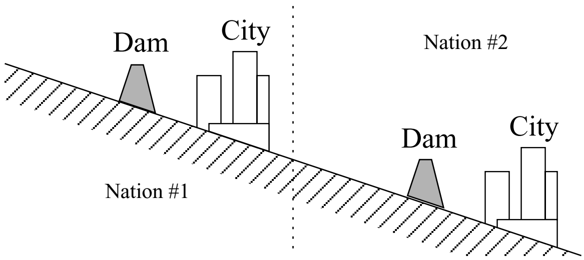

Figure 1. *Riparian neighbors*

between riparian neighbours with a bargaining game. They show that changing entitlements to quantity and quality can alter outcomes, even if entitlements are not fully utilized at the time of negotiation, and that third party assistance may leave one nation worse off. Ambec and Sprumont (2002) look at the possible equilibria when there are riparian rights over a river. The single non-blockable equilibrium has transfers between nations at their marginal valuation, based on their order along the river. Dufournaud and Harrington (1990) introduce a 'propensity to disrupt' in multi-period water sharing projects. Nations can choose to leave a coalition or enter at a later date. To sustain cooperation, payments must be made so that no nation can gain by disrupting. In this paper, we consider a similar situation, with no credible commitment mechanism to bind future actions. Without scope for payments to sustain joint action, it will only occur with a set of strategies that satisfy sub-game perfection.

2. A model

We consider a situation where two nations are riparian neighbors, as shown in figure 1. In each nation there is a city, or other flood sensitive capital structures, downstream of a site suitable to the construction of a dam. Rainfall is assumed to follow a monsoon pattern, with a short season during which there is excess water, and a dry season when water is scarce. A dam provides both flood protection during the monsoon and water storage during the dry season. Each nation has sovereignty over its own territory, thereby controlling how its dam is managed. The headwaters of the river, and the region where most of the precipitation occurs, is in the upstream nation, nation #1. Water stored behind the upstream dam protects both cities from flooding. However, water consumed in the upstream nation is not available to the downstream nation. The size of the upstream dam can therefore benefit or harm nation 2, depending on the realized water flow.

The game between these two nations is shown in figure 2. Two stages are identified, with nature's move separating them. Nations 1 and 2 first choose the size of the dam that they build, with nation 2 able to make its decision after observing nation 1's choice. Once the capacity has been built, nature chooses the water flow. After nature's move, the upstream nation chooses the volume of water it will store. Given the upstream nation's storage, the downstream nation chooses its storage. The storage

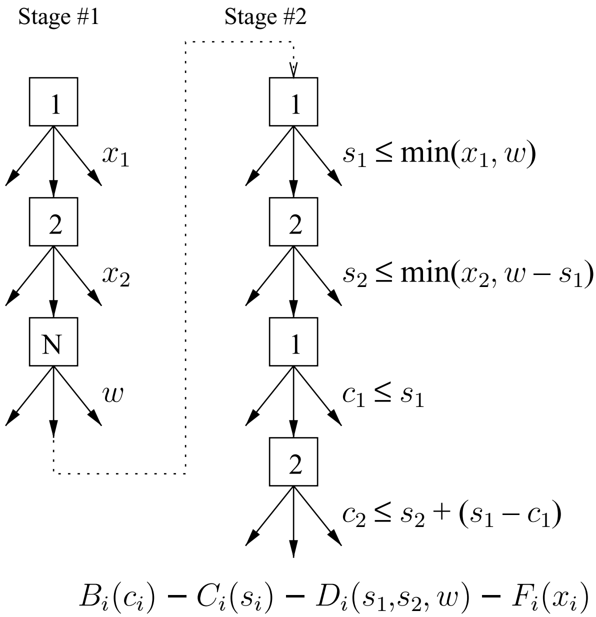

Figure 2. *Game tree*
Notes: Players are upstream (1), downstream (2), and nature (N). Variables are storage capacity (x_i), water flow (w), storage (s_i), and consumption (c_i). The payoff function is consumption benefits ($B_i(c_i)$) less storage costs ($C_i(s_i)$), flood damage ($D_i(s_1, s_2, w)$), and capacity construction costs ($F_i(x_i)$).

choices determine the flood damage. From the storage, each nation then chooses its consumption. Nation 1 cannot consume what it has not stored. Nation 2's consumption cannot exceed the sum of nation 2's storage and the excess water remaining after nation 1's consumption. Consumption is distinct from storage in that water stored but not consumed is available for later consumption by downstream neighbors. Since dams are long lived structures, and their life is determined more by infill of the reservoir than by deterioration of the structure, construction of a dam is assumed to be a one time, irreversible decision. Repetition of the game is therefore not an issue, and is not included in the model. We also assume that nations are risk neutral expected payoff maximizers, so that the payoffs realized over the multiple periods between the construction of the dam and the infill of the reservoir can be represented by a single expected present value.

The payoff for each nation resulting from the choices of consumption, storage, and capacity (c_i, s_i, and x_i) is

$$\begin{aligned} R_i &= B_i(c_i) - C_i(s_i) - D_i(s_1, s_2, w, k_i) - F_i(x_i) \\ &= r_i(c_i, s_1, s_2, w, k_i) - F_i(x_i), \end{aligned}$$

where $r_i(c_i, s_1, s_2, w, k_i)$ is the stage two earnings for nation i. The variable k_i is the channel capacity, the flow the river can accommodate without flood damage occurring. Variable w is the realized flow of water, and s_1 and s_2 are the storage levels in each nation. The payoff function is divided into four components, consumption benefits $B_i(c_i)$, storage costs $C_i(s_i)$, flood damage $D_i(s_1, s_2, w, k_i)$, and storage capacity construction costs $F_i(x_i)$. The constraints have been described above and are displayed in figure 2. The benefit function is assumed to be concave, with a maximum for some finite level of c_i, representative of an agricultural crop that can be drowned. By construction, storage is assumed to be costly. However, if stored water can be used to generate electricity or to provide benefits related to the reservoir, then $C_i(s_i)$ would be negative. Flood damage is also assumed to be costly. Damage to nation i depends on all storage in and above nation i, and on the capacity of the river channel k_i, with marginal damage increasing in the amount of flow exceeding combined channel capacity and storage. Finally, storage capacity construction cost is taken to be increasing in capacity, at an increasing rate.

With uncertain water flows, each nation's problem becomes the maximization of the expected payoff

$$E_w(R_i) = E_w[r_i(c_i, s_1, s_2, w, k_i)] - F_i(x_i)$$

with $E_w()$ being the expectations operator over the range of possible water levels. With arguments suppressed for clarity, the Nash equilibria in storage capacity occurs where

$$\frac{\partial E_w(R_i)}{\partial x_i} = 0 \Rightarrow \frac{\partial E_w(r_i)}{\partial x_i} = \frac{\partial F_i}{\partial x_i}$$

for each nation, with a Nash equilibrium occurring in each second stage realization of w. Since the game is finite, we can assume that the second stage equilibrium is Nash. In general, this outcome will not maximize aggregate payoffs. Maximizing aggregate profits requires including the external impact of upstream storage on the downstream nation in selecting x_1, and that s_1 be chosen for aggregate optimality after w is realized. If s_1 is chosen in this way, then the upstream dam will normally be larger, and the downstream smaller. The examples below illustrate this outcome.

For this analysis we focus on the conditions necessary for the downstream nation to contribute to the construction of the dam in the upstream nation, when the upstream nation controls the management of water storage. This contribution is rational when the expected benefit to the downstream nation of an increase in the size of the dam, relative to that size which the upstream nation would choose on its own, is positive. Mathematically, a contribution is rational when

$$\frac{\partial E_w(R_2)}{\partial x_1} = \frac{\partial E_w(r_2)}{\partial x_1} > 0. \tag{1}$$

This expression makes it clear that the rationality of a downstream contribution depends on how that contribution will affect expected downstream payoffs over the entire range of possible realizations of water flow and resultant second stage behavior. It is not sufficient to focus only on the benefits that will arise if a particular state – e.g. flood – occurs.

Any collaboration will require some contractual arrangement between the nations. One can identify a range of different contracts governing the downstream contribution, each of which will have implications for the total gains that can be realized and how they are distributed. The analysis of contract possibilities is left to future work. In what follows we explore the impact of changing parameter values on the rationality of a downstream contribution, as identified by equation (1). To simplify the analysis and interpretation of the results, we focus on an environment with only two states, low water flow (w_l) and high water flow (w_h). State w_l occurs with probability π, and state w_h with probability $1 - \pi$. If π is taken to be independent of decision variables – a reasonable assumption for weather events – then the condition for rational contribution can be written as

$$\frac{\partial E_w(r_2)}{\partial x_1} = \pi \frac{\partial r_2^l}{\partial x_1} + (1 - \pi) \frac{\partial r_2^h}{\partial x_1} > 0. \tag{2}$$

The rationality of a downstream contribution depends on the signs and relative sizes of $\partial r_2^l / \partial x_1$ and $\partial r_2^h / \partial x_1$. If flooding damage dominates consumption benefits with state w_h, then $\partial r_2^h / \partial x_1 \geq 0$. However, in state w_l, the sign of $\partial r_2^l / \partial x_1$ is indeterminant. If increasing upstream storage increases upstream consumption, then $\partial r_2^l / \partial x_1 < 0$. In contrast, if greater upstream storage does not affect upstream consumption, and there is no flood damage, then $\partial r_2^l / \partial x_1 = 0$. Finally, if upstream consumption is independent of upstream storage, and there is flooding damage, then $\partial r_2^l / \partial x_1 > 0$.

The point where the downstream nation is indifferent about contributing to the upstream dam occurs where

$$\frac{\partial r_2^l}{\partial x_1} = \left(\frac{1 - \pi}{\pi} \right) \frac{\partial r_2^h}{\partial x_1}. \tag{3}$$

In the following section, a parameterized version of the model is described. By varying the parameters of this system, the combinations that generate opportunities for joint contribution to the upstream dam are identified.

3. Examples

For example purposes, we use the following specific formulations

$$B_i(c_i) = c_i(A_i - B_i c_i) \tag{4}$$

$$C_i(s_i) = C_i s_i \tag{5}$$

$$D_i(s_1, s_2, w, k_i) = D_i \left[\max(0, w - \sum_{j=1}^{i} s_j - k_i) \right]^2 \tag{6}$$

$$F_i(x_i) = F_i x_i^2. \tag{7}$$

Parameters A_i, B_i, C_i, D_i, and F_i are all assumed to be positive. Two specific cases are considered. In one case the w_l state has lower water and relatively low flood damage and in a second the w_l state has higher

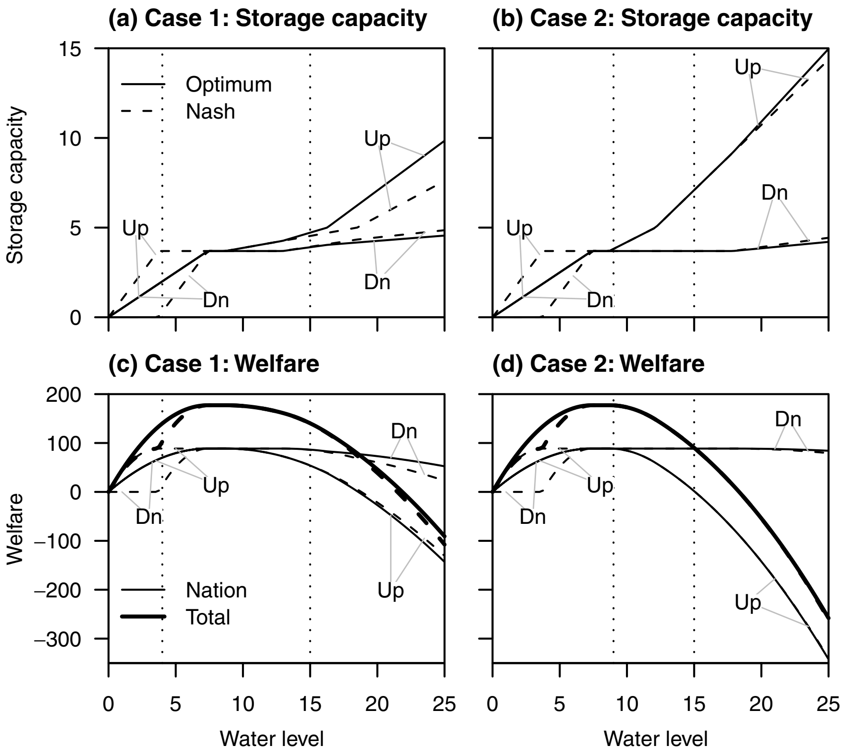

Figure 3. *Optimal and Nash equilibrium storage capacity and welfare by water level Notes: Labels 'Up' for upstream and 'Dn' for downstream identify the nation to which the lines apply. Heavy lines in panels (c) and (d) measure total welfare, with same patterns as individual nation lines. Dotted vertical lines mark water levels used for the two state examples developed below. For case 1, $D = 1$, while for case 2, $D = 4$.*

water and relatively high flood damage. These parametrizations are made to reflect a situation where a drought causes relatively greater hardship than a flood for a stylized arid region developing nation, and the converse is true for a stylized humid region developed nation. For all examples, $A_i = 50$ and $B_i = 5$. When not being varied, $C_i = 1$, $F_i = 1.5$, $k_i = 5$, and $w_h = 15$. For the arid region case, $w_l = 4$ and $D_i = 1$, while for the humid region, $w_l = 9$ and $D_i = 4$. The difference in the w_l values distinguishes between arid and humid, and the difference in D_i distinguishes developed and developing. The larger D_i value reflects destruction of more valuable infrastructure for flooding in developed nations.

Figure 3 plots the welfare maximizing and individually rational storage capacities, and resultant welfare levels, for a range of certain water flows. Panels (a) and (c) show the Nash and jointly optimal storage levels and selected and payoffs for each nation in the arid case. The vertical lines mark w_l and w_h. If w_l occurs, then at the Nash equilibrium, the upstream nation consumes most of the water flow. In this state, the downstream nation would gain with a smaller x_1. In contrast, in the w_h state, the upstream nation is choosing less than the optimal storage capacity. Here $\partial r_2/\partial x_1 > 0$. Whether the downstream nation will contribute to upstream storage construction depends on the relative probabilities of the two possible outcomes, as discussed below.

Panels (b) and (d) demonstrate the humid case. The higher w_l state water level results in $\partial r_2/\partial x_1 = 0$, as an increase in upstream storage capacity during this state will have no effect on downstream water consumption and payoff. During the w_h state, the downstream nation is able to free ride on the upstream nation's storage. The protection offered by the upstream storage lowers the marginal benefit of additional storage, either upstream or downstream, for the downstream nation to zero when it is certain that w_h will occur. However, if neither state is certain to occur, then the level of storage capacity chosen by the upstream nation will be reduced, creating room for gains for the downstream nation from increased upstream storage capacity. This is shown below.

3.1. 'Arid region' developing nations

Figure 4 graphs the impact of changing a number of model parameters on the rationality of cooperation. In panel (a), the probability of being in state w_l is varied from 0 to 1. When the low water state is unlikely (low π), the Nash upstream storage is large enough that if w_l occurs, the downstream nation receives no water. Consequently, $\partial r_2^l/\partial x_1 = 0$, and the sign of $\partial r_2^h/\partial x_1$ determines the sign of $\partial E(R_2)/\partial x_1$. With flood damage in the w_h state, there is on balance a gain from increased upstream storage. As π is increased, upstream Nash storage capacity falls, until it is too low for the upstream nation to consume all the w_l water. From this point on, increases in upstream storage capacity harm the downstream nation. It is now no longer rational for the downstream nation to contribute to increasing upstream storage capacity. As one moves from left to right in panel (a), a drought probability threshold is reached, where it ceases to be rational to cooperate. The remaining panels identify parameter combinations which yield indifference, separating the parameter space into zones where a downstream contribution is rational and where it is not. With the large change in $\partial E(R_2)/\partial x$ when cooperation becomes non-rational, small differences in climatic conditions may result in large behavioral changes among neighbouring riparians. This suggests that climate change has the potential to induce some large changes in the nature of some international relationships.

In panels (b) through (f) pairs of parameters are varied. The indifference threshold is marked for w_l probabilities $\pi = \{0.25, 0.50, 0.75\}$, with shading indicating that it is not rational for the downstream nation to contribute to increasing upstream storage capacity. For graphical clarity, lines mark where $\partial E(R_2)/\partial x_1 = 0.01$. This ensures that the cooperative set does not include regions where $\partial E(R_2)/\partial x_1 = 0$, some of which are large. The storage cost parameter, C_i, is varied in panel (b). Negative values correspond to cases where storing water for later release increases nation i's payoff, even if the water is not consumed. For example, using the dam to generate electricity. In contrast, positive values apply when it is costly to use the

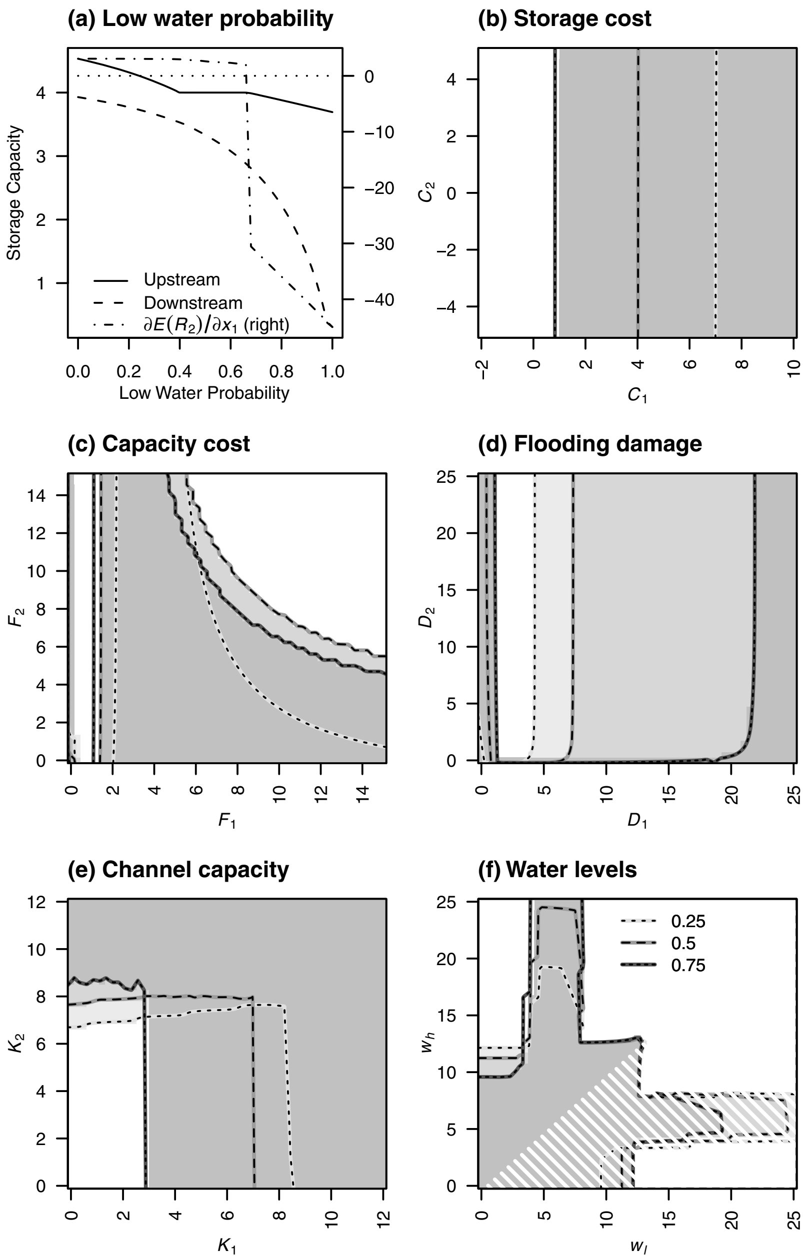

Figure 4. *Arid region case*
Notes: In panels (b) through (f), lines mark parameter combinations where the downstream nation just becomes indifferent about contributing a marginal unit to increasing upstream storage capacity, for $\pi = \{0.25, 0.50, 0.75\}$. *On the shaded side of the line the downstream nation will not contribute,* $\partial E(R_2)/\partial x_1 \leq 0$. *For graphical clarity, lines drawn at* $\partial E(R_2)/\partial x_1 = 0.01$.

storage capacity of the dam. These would be the maintenance costs for a dam which is mainly used for irrigation and flood control. When storage is profitable, the upstream nation will use as much of its storage capacity as it can. This ensures that additional upstream storage capacity will be used when the w_h state occurs, conferring the flood protection benefit on the downstream nation. It becomes irrational to contribute only in the positive cost region, and first for higher w_l probabilities.

The capacity cost parameter, F_i, is varied in panel (c). For high costs, upstream capacity is not large enough for the downstream nation to free ride, so contributing to increasing upstream capacity is rational. As upstream capacity costs fall, the chosen capacity increases, leading to a reduction in the marginal flooding damage avoided downstream and an increase in the lost consumption benefit. Contributing becomes irrational. As costs fall further, upstream capacity rises to the point where no w_l flow reaches the downstream nation. Since there remains a benefit to flood control, contributing again becomes rational. Finally, with further decreases in upstream capacity cost, upstream capacity reaches a level where the downstream nation fully free rides, and has no incentive to contribute to increasing upstream capacity.

In panel (d) flooding damage, D_i, is varied. For very low upstream damage, it is not rational to contribute as the extra capacity will not be used. The avoided upstream damage does not cover the cost of using the storage capacity. If this is the case, reducing the cost of using the storage can serve to make it rational for the downstream nation to contribute. For intermediate flooding damage costs, the upstream nation will use a marginal increase in storage capacity. However, for high enough upstream damage, the downstream nation need not contribute as the upstream nation will build and use enough capacity to allow the downstream nation to free ride.

Panel (e) shows the impact of changing the capacity, K_i, of the river channel, the amount of flow that can occur without causing flooding. When upstream channel capacity is high, storage is not needed and will not be used. It is therefore not rational to contribute. Likewise, if downstream channel capacity is high, flood damage is low, and there is no benefit from increasing upstream storage. Finally, panel (f) shows the impact of changing w_l and w_h. The lower right region is hashed, as $w_l > w_h$ is not reasonable. The plot itself essentially reflects over a 45° line through the origin, with π replaced by $1 - \pi$. When w_l and w_h are both high, flooding damage dominates, and contributing is rational. When w_h is high and w_l is low, the downstream nation receives no water in the w_l state and it is again rational to contribute on the basis of flooding damage reduced. However, for intermediate values, it is not rational to contribute.

3.2. 'Humid region' developed nations

Figure 5 varies the parameters for the humid region case. Except when varied, the base values are $w_l = 9$, and $D_i = 4$, with the remaining parameters as for the earlier case. Panel (a) shows the upstream and downstream storage capacity, and the derivative $\partial E_w(r_2)/\partial x_1$. With the higher flood damage and higher value for w_l, $\partial E_w(r_2)/\partial x_1$ is never negative. However, when

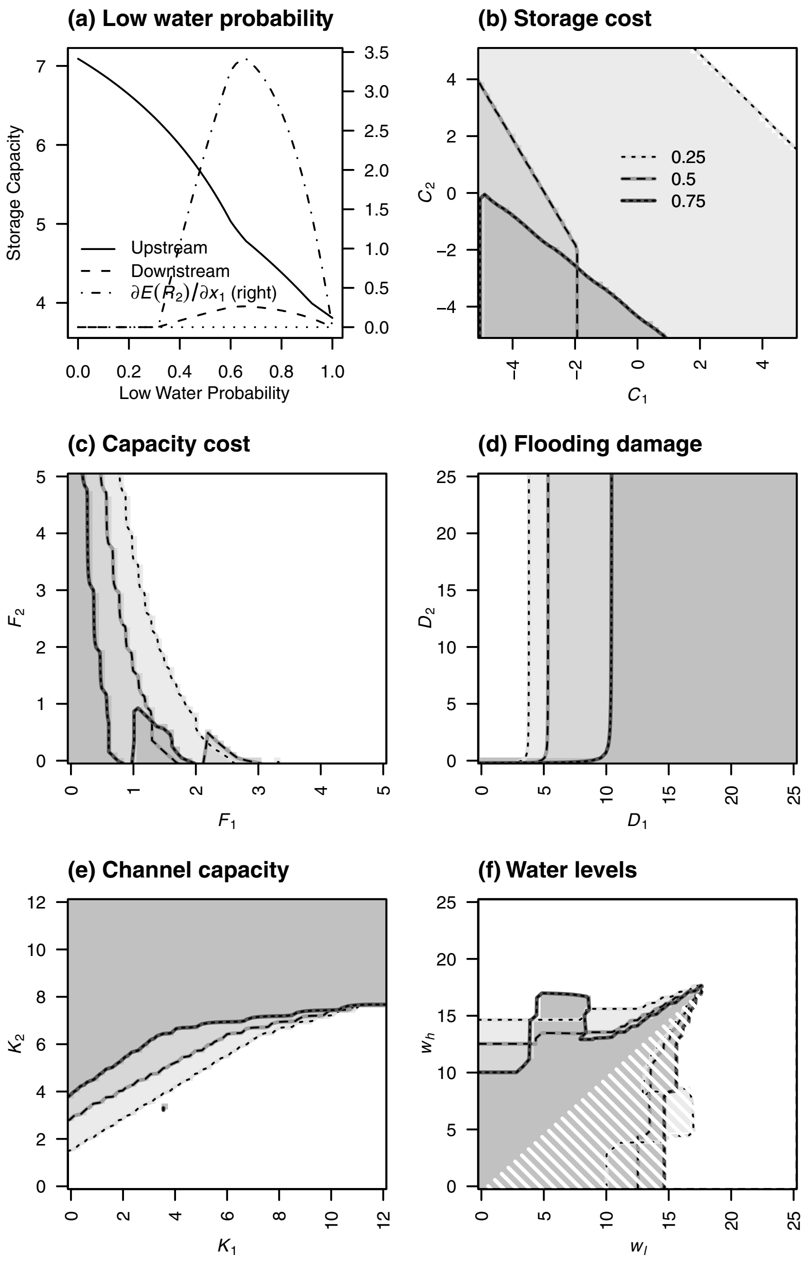

Figure 5. *Humid region case*

Notes: In panels (b) through (f), lines mark parameter combinations where the downstream nation just becomes indifferent about contributing a marginal unit to increasing upstream storage capacity, for $\pi = \{0.25, 0.50, 0.75\}$*. On the shaded side of the line the downstream nation will not contribute,* $\partial E(R_2)/\partial x_1 \leq 0$*. For graphical clarity, lines drawn at* $\partial E(R_2)/\partial x_1 = 0.01$*.*

w_h is more likely – low π – upstream storage is adequate to provide all downstream flood protection. It is not rational to contribute to upstream storage, as it has no impact on the downstream nation.

Panel (b) shows the impact of changing C_i. In contrast to the arid region case, the rationality of a downstream contribution decreases with decreasing storage cost. With relatively high water levels and profitable storage, increased upstream storage now reduces the downstream benefit from storage. With respect to hydroelectricity, this may be somewhat unrealistic, as upstream generation does not preclude downstream generation using the same water. However, the timing of upstream releases may not be ideal for downstream generation. Further, a large upstream storage reservoir may be managed to maximize recreation and fisheries benefits, which could adversely impact these same values in a downstream reservoir.

Panels (c) and (d) show the impact of changing construction costs and flooding damage (F_i and D_i). The higher average water level reduces the downstream loss during the w_l state for the downstream nation. This increases the region where contribution is rational, relative to that shown in panel (c) of figure 4. With higher flooding damage and higher average water levels, the upstream nation builds more storage, independent of any downstream contribution. This reduces the region of contribution, relative to the arid case.

The channel capacity and water level effects are shown in panels (e) and (f). In panel (e), increasing downstream channel capacity reduces the benefit of upstream storage as for the previous case. However, since increasing upstream channel capacity reduces upstream storage, more water flows to the downstream nation. As this results in flooding damage, the downstream nation would benefit from an increase in upstream storage. From panel (f) it is seen that as water levels are increased, the region where contribution is rational increases. In contrast to the arid case, the higher flood damage leads to an increase in storage. This reduces the region where upstream storage is crowding out downstream consumption, increasing the water values for which a contribution is rational.

When the two cases are compared, the relative difficulty of developing collaborative infrastructure projects in arid regions stands out. These results are not inconsistent with casual observation. Relatively humid and developed regions of the globe, Europe and northern North America, tend to have amicable, if not cooperative, relations with respect to river management. In more arid but developed regions, it has been difficult to achieve cooperation. However, in some cases the threat of the imposition of agreements from outside, such as by the federal court in the US with respect to the Colorado, has led to a level of collaboration. Finally, arid and less developed regions are characterized by adversarial relations, in spite of the large gains that are possible if collaboration were to occur.

3.3. Welfare effects

Figure 6 shows how individual nation and aggregate welfare varies with low water probability, for the two example cases. For the arid region case there is a substantial difference between optimal and Nash aggregate

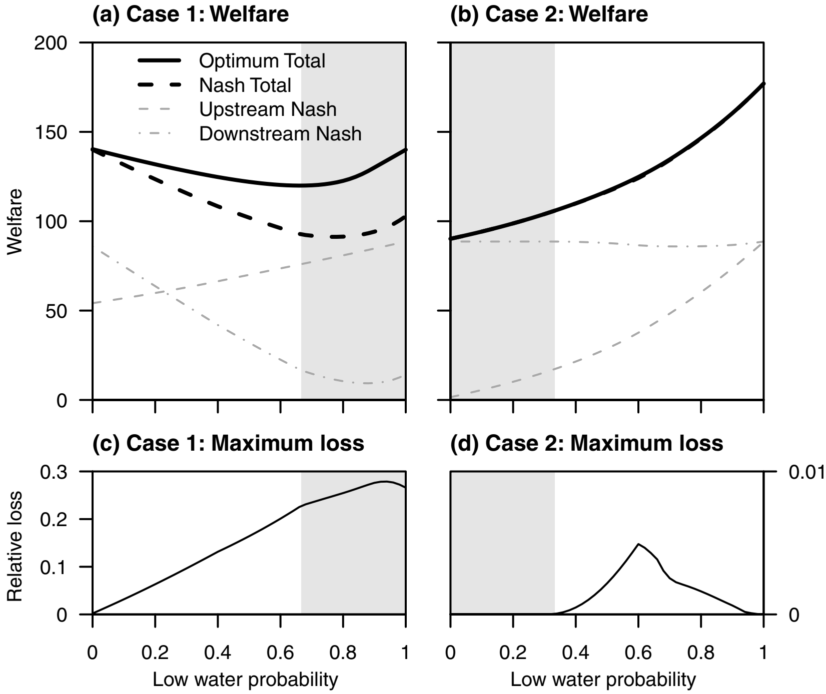

Figure 6. *Welfare effects when low water probability is varied*
Notes: Shaded region identifies where downstream contribution is not rational. Maximum loss measures difference between optimal (first best) and Nash outcome. Outside region where cooperation is not rational, some cooperation may be sustained, and actual losses should not be as large.

payoffs. However, the largest difference occurs when w_l is very likely, which is also when it is not rational for the downstream nation to contribute to increasing upstream capacity. The unequal distribution of water generates a higher marginal return to water in the downstream nation than upstream. A reduction in upstream water use during the w_l state increases downstream return and aggregate return. However, absent an enforceable agreement governing the distributing payoffs on realization of the water state, it is not sub-game perfect for the optimal (smaller) upstream storage capacity to be constructed.

In contrast, for the humid region case, the gains to be had if optimal water management were implemented are relatively small. When the w_l state is unlikely, the upstream nation builds the optimal amount of storage. The downstream nation free rides on the flood protection. The point of interest is the large inequity between the payoffs. A downstream contribution is not rational here as neither aggregate payoff nor the return to the downstream nation can be increased. There is the potential for gain when the w_l state is more likely, as now the upstream storage is insufficient to maximize aggregate expected returns. However, the gains are not very large.

4. Discussion

The analysis presented in the previous section characterized a hierarchical relationship between two nations sharing a river, in an environment without tradable water rights or a mechanism for agreeing to storage capacity reductions. Upstream storage capacity enhances the 'rule of capture' gains available to the upstream nation, which leads to an inefficient distribution of water when it is scarce. However, upstream storage also provides a public benefit, flood protection, when water is excessive. If water levels are high, the under-provision of the flood protection public good by the upstream nation creates the possibility for aggregate gain from a downstream contribution towards increasing upstream storage capacity. However, when water is scarce, the downstream nation may benefit from a reduction in upstream capacity, making a contribution to increasing upstream capacity irrational.

When water flows are uncertain, and storage capacity is constructed prior to realization of water flows, then it is the balance between expected damage avoided due to flood protection and expected lost water consumption benefits that determines if participation in jointly funded upstream storage capacity is rational for the downstream nation. The water flow distribution plays a key role in determining whether or not a downstream contribution is rational, with an increasing likelihood of water scarcity reducing expected gains from this contribution. There are two distinct situations where it is rational for the downstream nation to participate in increasing upstream storage capacity. The first occurs when upstream storage capacity is so large that a further increase will not impact downstream consumption during water scarce periods, leaving avoided flood losses as the only effect. The second occurs when upstream storage is too small for an increase to cause a large enough drop in marginal expected consumption benefits to offset avoided flood losses. Increases in the cost of storage capacity construction tend to increase the gains from jointly funded upstream capacity, as without it the upstream nation builds less storage capacity. However, increases in flood damage costs may reduce joint funding by creating the opportunity for the downstream nation to free ride on the upstream nation's flood protection investments.

The analysis focuses on the difference between the construction and management of dams in the international context. We abstract away from the water management problem itself. Over the life of a reservoir, inflows will vary. Managing reservoir levels and carryover between periods adds a dynamic element. If inflow uncertainty is optimally managed with a larger reservoir, the likelihood of cooperation will be further reduced in arid regions. In contrast, in humid regions where flood control is the determining factor, inflow – flood severity – uncertainty may further enhance cooperation. Confirmation of this conjecture is left for future work.

Barrett (1994) emphasized the importance of 'self-enforcing' international environmental agreements, and demonstrated that the larger the potential gains from cooperation, the less likely large cooperating coalitions can be sustained. Barrett's model nations were identical, and identically affected by a pollution externality. In this paper's model, we focus on two nations, and increase the complexity of their relationship. Sub-game perfection here is consistent with self-enforcement. As for the Barrett result, when the gains from cooperation are largest, we find that it is not rational for the downstream nation to participate.

In many contexts, repetition of a finite horizon game can sustain greater cooperation than predicted by sub-game perfection. In this context, the combination of a long time horizon and the essentially irreversible nature of the infrastructure investment should preclude most of these Folk Theorem type effects. Somewhat perversely, the stronger the structure, the less likely it is to be built cooperatively. Some research empirically supports this. Before durable, large-scale structures were the norm, communities along some rivers would share the burden of building basic water diversion structures, and share the water diverted. When permanent structures were built, with the assistance of central governments or aid agencies, the water sharing arrangements collapsed (Lam, 1996). Overall welfare may be better served by assisting the downstream nation in increasing its water use efficiency, which will increase the amount of water that can be consumed upstream before it induces downstream hardship. If large, long-lived, and essentially irreversible projects can be replaced by smaller, short-term structures, then a one shot game may be turned into a repeated game, possibly inducing greater cooperation.

Instead of repetition of the dam construction game, a degree of economic integration can result in mutual interdependencies that make cooperation more likely. In Europe and North America, negotiated agreements over shared management and shared infrastructure are generally adhered to. The negotiation of the North American Free Trade Agreement may have provided some impetus for greater cooperation between the US and Mexico (Frisvold and Caswell, 2002). In some cases (see Just *et al.*, 1997), water projects paired across countries may set up retaliation tools that can support cooperation. In contrast, where international relations are less friendly, military actions can play a role. A downstream nation may seize upstream territory or threaten to do so. The threat itself may divert upstream investment away from water using activities, without actual engagement (Janmaat and Ruijs, 2006). Political and cultural realities are also likely to affect prospects for cooperation. Dinar and Wolf (1994) argue that strict economic rationality is not an adequate criterion for judging potential arrangements in the Middle East. Galassi (2002) suggests that when water is scarce, cooperation is discouraged and it is difficult to build social capital. In contrast, excess water encourages cooperation and facilitates building social capital.

Investments that increase the peak flow that the river can accommodate without flooding, increasing the river's channel capacity, may create another strategic interaction. For the investing nation, increasing channel capacity can substitute for flood storage. However, unlike storage, no benefit is conveyed on nations downstream. For downstream flood protection, similar investments must be made. The upstream option to make such investments may encourage downstream cooperation. In contrast, downstream investment in channel capacity can substitute for investment in upstream storage. In the extreme, downstream nation dikes may create a bottleneck effect, leading to increased flooding upstream. This bottleneck effect occurred during the Red River Flood in Winnipeg, Manitoba, Canada in 1997 and in the Mississippi River Floods in the USA in 1993. Where floods are common, such effects create a tool that the downstream nation can pursue to increase upstream storage.

Lastly, a large portion of water resource economics research has focused on water rights and water markets. Considerable evidence on the exchange of water within nations suggests that where market mechanisms exist, the efficiency of water use is enhanced (Howitt, 1994; Rosegrant and Binswanger, 1994; Hearne and Easter, 1996; Miller, 1996; Thobani, 1997; Tsur and Dinar, 1997; Crase *et al.*, 2000). Some suggest that inter-state and inter-nation water markets can be valuable tools as well (Whittington *et al.*, 1995; Lord and Kenney, 1995). Gains occur even when inflows are uncertain, and even when there are correlated supply shocks in different parts of an area with a water market (Janmaat, 2006). To date, securing tradable water rights across international boundaries has been difficult, even for developed nations (Canadian Department of Foreign Affairs and International Trade, 1999, for example). The promise of water markets is therefore unlikely to be realized in the international context.

The inability to attain the cooperative solution when scarcity is common is particularly troubling since this is where human suffering is often great. The barrier to cooperation suggested by this analysis is the absence of a mechanism to enforce mutually beneficial management of storage capacity. To enhance cooperation therefore requires building those enforcement mechanisms. Efforts to develop such mechanisms are unlikely to succeed if two nations only relate around a shared river. However, if the riparian game can be embedded in a larger game, then trade-offs may exist which enable greater cooperation. Many cases of emergent cooperation (see Dinar and Loehman, 1995) can be interpreted as a consequence of growing issue integration. The reduction of trade barriers and greater integration of basin-wide economies may enlarge the scope for exchanges. However, if the trade barriers are themselves a consequence of disputes related to water, then it is unclear how to initiate such changes.

Finally, and possibly the least likely solution, is formation of a semi-autonomous agency to manage the entire river, rather than leaving the management to *ad-hoc* arrangements between basin nations. Such arrangements exist in developed countries, and have been quite successful. However, these nations are more consistent with situations where excess water is a problem, rather than where water is scarce. Given that nations in drought-prone river basins are currently unwilling to cooperate, it is not clear how they will agree to hand authority to a separate agency.

5. Conclusion

Cooperative management of international rivers can be quite successful (St. Lawrence, Rhine) or a virtual failure (Tigris, Euphrates, Nile). In this paper we suggest that an important factor in determining whether nations will collaborate in managing a shared river is the likelihood that actions taken after expensive infrastructure is built are consistent with such collaboration. When flood damage is relatively more common than losses due to drought, collaboration is facilitated. During floods, storage capacity constraints lead to increases in damage, so that downstream nations are willing to help build storage capacity in upstream nations. However, when droughts are common, excess upstream storage capacity can lead the upstream nation to consume more water, adversely affecting the downstream nation. Rather than joint construction of upstream storage, the downstream nation will seek to prevent upstream storage being built. Increases in the cost of constructing storage capacity tend to increase the likelihood of coordination, as it reduces the amount of storage that upstream nations will unilaterally build. However, increases in upstream flood damage may reduce collaboration, as the unilateral investment by the upstream nation is large enough to allow the downstream nation to free ride. Where water is scarce, cooperation can be facilitated if the likelihood of enforceability of management is increased. The potential gains from cooperative river management in arid regions are substantial and easy to identify. However, it is precisely in these environments that strategic interactions act to make cooperation less likely. The nature of large-scale water control investments is inconsistent with international cooperation if water management is the only basis for that cooperation. Those seeking means of realizing the potential gains may be more successful if they first seek to expand the scope of integration between riparian neighbors, thus creating the potential for a larger set of trade-offs than those directly related to the shared river.

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