Investing in Arms to Secure Water

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Abstract. Where nations depend on resources originating outside their borders, such as river water, some believe that the resulting international tensions may lead to conflict. Homer-Dixon (1999) and Toset et al. (2000) argue such conflict is most likely between riparian neighbours, with a militarily superior downstream 'leader' nation. In a two stage stochastic game, solutions involving conflict are more common absent a leader, where a pure strategy equilibria may not exist. When upstream defensive expenditures substitute for water using investments, a downstream leader may induced an arms race to increase downstream water supplies. Water scarcity may not be a cause for war, but may cause a buildup in arms that can make any conflict between riparian neighbours more serious.

1. Introduction

Water scarcity is expected to be one of the most serious resource issues of the twenty-first century, particularly in the developing world (Rosegrant, 1997). In the literature on conflict and cooperation in water management, two separate schools of thought can be distinguished. One fears that as populations grow and demand expands, disputes over water allocation may lead to violent international conflict (Serageldin, 1995), particularly where water is already scarce (Falkenmark, 1990; Gleick, 1993; Sandler, 2000). In contrast, others argue that scarcity will promote increased cooperation (Giordano et al., 2002; Giordano and Wolf, 2003; Wolf et al., 2003; Dinar and Dinar, 2004), citing as support the absence of strong empirical evidence that past wars have been fought over water. The fears that wars will be fought over water seems to be borne out by the popular belief that wars are more common in arid regions. However, to reconcile this with the lack of evidence that water disputes have triggered wars, as an alternative we consider how disputes over water may set the conditions for war by encouraging military spending.

A very superficial examination of the data is weakly supportive of the hypothesis that the more sensitive an economy is to water scarcity, the greater the share of economic output spent on the military. Figure 1 plots, for all nations with World Resources Institute water availability data and World Bank military and development data, military expenditure as a share of GDP against the per capita renewable water supply, dependency - the share of the water used in a nation that comes in from outside, and the share of the national economy represented by agriculture. With an admittedly healthy dose of imagination, one can see that military spending decreases with water availability, increases with dependency, and with the importance of agriculture to the national economy. The effect appears strongest when water availability is low. However, the fact that the relationship is at best weakly apparent in the graphs suggests that there may be other effects or interactions not captured in this visual representation.

[Figure 1 about here.]

As there are almost certainly a range of variables that affect military expenditures, it is unlikely that the relationships will stand out strongly in a graph. The data can be explored in a bit more depth with regressions. Table 1 shows multiple regression results for two regressions using all the data, and two for nations with less than 10,000 m^3 of water available per year per person. Given the failure to account for political factors beyond corruption and stability, it is not surprising that the explanatory power of the models is very low. However, there is some weak evidence of a link between water availability and military spending. For all the data, increasing water availability correlates with a decrease in military spending, as a share of GDP, with statistical significance for nations where per capita water availability is low. Although not significant, the relationships between dependency and the share of agriculture's value in GDP are suggestive. As the dependency increases, military spending increases, whether we consider all the data or the more arid subset. As the importance of agriculture increases, military expenditure increase for the total dataset, but declines in the arid part of the dataset. To rationalize this, perhaps some nations, such as Kuwait and Saudi Arabia, are so arid that agriculture ceases to be an important component of the economy. A nation's military spending is certainly the result of a complex decision environment, so that it is not surprising that it is difficult to find any statistically significant results. However, they are not inconsistent with the idea that water scarcity and military spending are related, a relationship which we explore with the model developed in this paper.

[Table 1 about here.]

This casual empiricism suggests that military spending may be influenced by water availability. However, there is considerable doubt about whether water scarcity leads to international conflict. If military conflict is not a tool for securing water, then assuming these empirical results are valid, the question is why would water scarcity lead nations to have higher levels of military spending. Assuming that nations behave rationally, this military spending must result in a gain to nations involved, relative to one or both not doing so. We propose that such a mechanism exists, principally through the crowding out effect military spending can have on other investments that can consume more water. Thus, if a downstream nation can induce an upstream rival to spend on its military rather than on water using investments, it can secure more water for itself.

Although unable to explicitly identify water wars, the empirical evidence is not unequivocal. Some empirical research suggests that violent conflict between cultural groups can be an effort to capture resources, particularly when the risk of natural disasters is high (Ember and Ember, 1992). There is also evidence suggesting that population pressure is related to involvement in military conflicts (Tir and Diehl, 1998). Further, modern asymmetries in military technology may increase the attractiveness of using force on the part of the stronger adversary (Orme, 1997). Although agreeing that resource scarcity can increase conflict, Homer-Dixon (1991, 1994, 1999) argues violence is more likely to occur within, rather than between, nations as interest groups battle for resource access. According to Homer-Dixon, international wars over water are likely only when a downstream nation is highly dependent on a water source that an upstream nation can substantially disrupt, that there is a history of antagonism between the nations, and that the downstream nation has substantially superior military power[1]. Based on a review of the literature relating the environment and violent conflict, Gleditsch (1998) finds that to date, little research had effectively tested these relationships. In this paper we show that if a military superiority can be modelled as Stackleberg leadership in military expenditures, then the Homer-Dixon conjecture may be wrong.

Recent work has brought greater empiricism to bear on the water and conflict question. Giordano and Wolf (2003) and Wolf et al. (2003), on the basis of an extensive data base on international river basins, interpret the lack of obvious water wars as supporting the hypothesis that cooperation is enhanced when scarcity increases. They nuance this by arguing that water scarcity may both be a cause of conflict and stimulus to cooperation. Likewise Dinar and Dinar (2004), argue that although water wars have been rare, this does not mean that they will never occur, and emphasize that governance and scarcity interact to affect the degree of cooperation. Toset et al. (2000) and Gleditsch et al. (2004) bridge the difference between the 'water-war' and 'water-cooperation' schools. Using a database on international conflicts from 1880-1992, they find that the probability of international conflict increases in the presence of shared rivers. Further, they show that the presence of major powers results in a higher risk of conflict. However, they argue that "this is not evidence for 'water wars' but [that] shared water resources can stimulate low-level interstate conflict" (Gleditsch et al. (2004), p. 22). They agree with LeMarquand (1977), that upstream-downstream relationships are conflict prone and that "military threat and boycots routinely become part of bargaining behavior" (Toset et al. (2000), p.977). However, they suggest that this may be an incentive to cooperate. This paper contributes to this discussion by exploring theoretically how the likelihood of upstream-downstream disputes over scarce water resources are affected by the presence of a 'leader' nation, and conditions affecting military escalation or cooperation.

The Nile basin is commonly cited as a case where military posturing may influence water sharing. The Nile has the characteristics described by Homer-Dixon and Toset et al. (2000) as creating a situation particularly prone to dispute. Although the recent Nile Basin Initiative (NBI), aimed at more cooperative management of the Nile Basin, is cause for optimism, it is likely premature to conclude that aggressive acts have been banished forever. Egypt, at the bottom of the Nile, relies on the river for virtually all of its water needs. It also has the largest military, largest economy, and one of the largest populations of any nation in the basin (Dinar and Alemu, 2000; Rached et al., 1996). Ethiopia, among the poorest nations in the basin, is the source of over 70% of the water reaching Egypt. Following recent droughts, Ethiopia is keenly aware of how it could benefit by capturing and using more of the water that falls within its boundaries. It has been very hesitant to participate in any agreements that would commit it to a particular sharing arrangement (Swain, 1997). However, Egypt is also aware that any increase in storage capacity and water usage by Ethiopia may threaten its water security. Egypt has indicated it will take any action necessary, including military action, to defend its water supply, a key input into its economy (Gleick, 1993; Ndege, 1996; Wiebe,

[1]We will refer to this idea as the "Homer-Dixon conjecture." This terminology is, as far as we can tell, unique to this paper.

2001). It is within this context that the riparian nations of the Nile basin are seeking arrangements to share the Nile waters (Council of Ministers of Water Affairs of the Nile Basin States, 2001). There are a range of ways in which cooperative development of the Nile could benefit the riparian nations (Wichelns et al., 2003), but these would involve levels of political and economic integration that will be difficult to implement (Dinar and Wolf, 1994; Dinar and Alemu, 2000). Understanding the strategic issues that will impact on these negotiations is particularly important at this time, an understanding to which this paper contributes.

Our analysis builds on the resource capture games literature, which examines when cooperation can be sustained between agents who can steal from each other, in an environment absent a regulator. Military expenditures enter a *conflict function*, which determines the likelihood of successful resource capture. Skaperdas (1992) highlights the importance of the relative productivity of military investment in determining whether an equilibrium without engagement can be supported. Hirshleifer (1995) develops a resource capture model to evaluate the relative stability of 'anarchy', defined as a situation "in which contenders struggle to conquer and defend durable resources, without effective regulation by either higher authorities or social pressures (Hirshleifer, 1995, p. 27)." It is shown that changes in the effectiveness of military power or relative strength are important factors in determining whether 'anarchy' is stable. A particularly interesting result is that when one nation can act as a leader, it is able to gain in absolute terms, but in relative terms the follower gains more. Cothren (2000) integrates these approaches. In his model, the only impact of military accumulation is through the conflict function. Nash equilibria exist where both nations have sufficient military capacity to deter potential attacks by their rival, with both nations indifferent between attacking and not attacking.

Our analysis adds to the conflict versus cooperation debate by explicitly examining the role of leadership. In particular, we focus on the "Homer-Dixon conjecture," whereby conflict is more likely when nations are militarily asymmetric. Our approach is similar to Cothren, in its use of an anarchy environment and a tradeoff between productive and military expenditures. We extend this approach with characteristics of a riparian system, and explore the difference between a simultaneous and sequential move game. The paper proceeds as follows. In the next section we describe a two period, two nation model, where nations first decide how to divide an endowment between a productive activity and military expenditures, and then one decides whether or not to attack. A numerical demonstration follows, illustrating the impact of simultaneous versus sequential 'leadership' play. The final section concludes the paper with a discussion of model extensions and implications.

2. Model

We consider a model of two riparian neighbors, both dependent on a shared river, which originates within the upstream neighbour. If w_1 and w_2 are the water volumes used by the upstream and downstream nations respectively, and V is the total water, then $0 \le w_1 \le V$ and $0 \le w_2 \le V - w_1$.[2] The water each nation captures for use depends on a capital stock K_i. The function $g_i(K_i)$ measures the share of the river's

[2]For simplicity, the hydrological dynamics of the river are not considered. In fact, w_i represents the difference between the water uptake and return flow into the river. The analysis of a more complex environment is left to future work.

flow nation i is able to capture. The capture function is assumed continuous, with continuous derivatives to at least the second order, and satisfying $\partial g_i/\partial K_i > 0$, $\partial^2 g_i/\partial K_i^2 < 0$, $g_i(0) = 0$ and $\lim_{K_i\to\infty} g_i(K_i) = 1$. This last assumption ensures that with finite capital stocks, the downstream nation always receives some water. With these definitions, $w_1 = Vg_1(K_1)$ and $w_2 = V[1 - g_1(K_1)]g_2(K_2)$, which gives us that $\partial w_2/\partial K_1 < 0$.

Water is the only input constraining production, and the only factor affecting water capture is capital. Water enters a production function $f_i(w_i)$, assumed continuous to at least two derivatives, satisfying $\partial f_i/\partial w_i > 0$ and $\partial^2 f_i/\partial w_i^2 < 0$. For simplicity, we write $F(K_1)$ and $G(K_1, K_2)$ for the upstream and downstream nations' production functions. For functions with partial derivatives, subscripts will index the argument with respect to which the derivative is taken. Using the definitions of w_i, it quickly follows that $F_1 > 0$, $F_{11} < 0$, $G_1 < 0$, $G_{11} > 0$, $G_2 > 0$, $G_{22} < 0$ and $G_{12} < 0$. Welfare is a function of output, which depends on capital, but not military spending. To concentrate on the decision to start a military conflict, we focus exclusively on the relationship between capital and military investment when a downstream riparian neighbor can choose to attack its upstream neighbor's capital stock. For simplicity, we do not consider the case when the upstream nation can attack the downstream nation.

Like Cothren (2000), military expenditures affect the probability of a successful attack, using resources that could otherwise be invested in production. We too compare Nash equilibria with and without a military attack. However, we extend the Cothren analysis in the following ways. First, the interaction of our nations rests on a shared resource, rather than the potential to capture the rival's output. Second, the attack option is targeted at capital affecting resource availability, rather than at capturing output. Thirdly, we use a more complicated production function that captures critical features of the resource process integrating the nations of our model. We will also consider solutions to three investment choice game structures, a simultaneous move game, and two sequential move games.

We develop the simultaneous investment game as a baseline to compare with the sequential investment games. The analysis proceeds in four steps. First we characterize the equilibria for two degenerate games, one where an attack never occurs in the second period and the second where it always occurs. We then show how the reaction functions are affected by allowing a second stage attack choice. The relationships demonstrated allow us to prove that a game of this form cannot have pure strategy equilibria where the downstream nation is indifferent between attacking and not attacking. Finally, we argue that in most situations of this type, an attack would be less likely with a downstream leader than with no leader.

If the only choice facing each nation is the investment level, then each nation would invest its endowment, with the downstream nation enduring lower returns as a consequence of the water captured by the upstream nation. The welfare function for the two nations is $W_1 = F(K_1)$ and $W_2 = G(K_1, K_2)$ if there is no attack. The assumptions on the water capture and production functions together ensure that W_1 and W_2 satisfy strict quasi-concavity over the range of available K_1 and K_2 values, allowing us to make the following proposition:

Proposition 2.1. *For the ranges $0 \le K_1 \le \mu_1$ and $0 \le K_2 \le \mu_2$, where μ_i is the endowment available to nation i, and assuming each nation seeks to maximize* *its welfare, the best response functions for the two nations are* $K_1(K_2) = \mu_1$ *and* $K_2(K_1) = \mu_2$*, absent an attack option.*

Proof. The proof is straightforward. For the upstream nation $W_1 = F(K_1)$. Since $F_1 > 0$ for all values of K_1, it immediately follows that $\partial W_1/\partial K_1 > 0$, so that to maximize welfare, the upstream nation will choose $K_1 = \mu_1$. Similarly, for each value of $K_1 \in [0, \mu_1]$, we have that $G_2 > 0$ ensuring that $\partial W_2/\partial K_2 > 0$. Therefore, downstream welfare is maximized by choosing $K_2 = \mu_2$. □

The result which follows from this proposition is that the Nash, upstream leader and downstream leader equilibria all coincide at $K_1 = \mu_1$ and $K_2 = \mu_2$. For completeness then,

Corollary 2.2. *For two nations engaged in a non-cooperative simultaneous move, upstream leader, or downstream leader game, with strategies and payoffs as in Proposition 2.1, all three games have the same solution,* $K_1 = \mu_1$ *and* $K_2 = \mu_2$*.*

Proof. Since $K_1(K_2) = \mu_1$ and $K_2(K_1) = \mu_2$, where $K_i(K_j)$ denotes the best response of nation i to strategy K_j, the result immediately follows. □

This game is rather uninteresting, as the downstream nation cannot influence the decision of the upstream nation. We therefore extend the game by allowing a second stage decision for the downstream nation, to attack the upstream nation's capital stock.

For the extended game, we focus exclusively on the use of military expenditure to influence the probability of a successful attack. A successful downstream attack reduces the upstream capital stock to $\underline{K}_1$. Conceptually, K_1 is considered to be a structure such as a dam, and an attack either reduces the dam capacity to a specific low level or does nothing. The scale of the engagement is not explicitly modelled. The probability of a successful attack, the *conflict function* (Clarke, 1993) is $\phi(M_1, M_2)$, where M_i is the military stock held by country i. $\phi(M_1, M_2)$ is assumed continuous to at least two derivatives, with $\partial\phi/\partial M_1 < 0$, $\partial\phi/\partial M_2 > 0$, $\partial^2\phi/\partial M_1^2 > 0$, and $\partial^2\phi/\partial M_2^2 < 0$. The derivatives in M_1 reflect increasing upstream military expenditures increasing the probability of successful defense, while those in M_2 reflect increasing downstream military expenditures increasing attack success probability. Both types of expenditures have diminishing returns. We also assume that $\phi(\epsilon, 0) = 0$ and $\phi(0, \epsilon) = 1$ for all positive ϵ. With no downstream military, very little defense is needed, while with no upstream military, attack success is guaranteed with very little downstream military expenditure. Finally, with endowment μ_i split such that $K_i + M_i = \mu_i$, then the conflict function is $\pi(K_1, K_2) = \phi(\mu_1 - K_1, \mu_2 - K_2)$, satisfying $\pi_1 > 0$, $\pi_{11} < 0$, $\pi_2 < 0$ and $\pi_{22} > 0$.

Before considering the two stage game, we describe the features of the game when an attack always occurs. In this case the expected welfare functions are

$$W_1^A(K_1, K_2) = \pi(K_1, K_2)F(\underline{K}_1) + [1 - \pi(K_1, K_2)]F(K_1) \tag{1}$$

$$W_2^A(K_1, K_2) = \pi(K_1, K_2)G(\underline{K}_1, K_2) + [1 - \pi(K_1, K_2)]G(K_1, K_2) - C_2 \tag{2}$$

where $\underline{K}_1$ is the level to which a successful downstream attack reduces upstream capital, and C_2 is the cost of that attack to the downstream nation. This cost measures impacts to the downstream nation that would not occur if the nation did not choose to attack. This could be the cost of the military equipment used, the impact of sanctions imposed by the international community, or any other cost that would not be experienced absent an attack. A defense cost for the upstream nation could also be included. However, as the upstream nation is not choosing whether or not to defend, such a cost is irrelevant to the upstream nation's choice. It is therefore not explicitly included. With $\partial W_1^A/\partial K_1\big|_{K_1=\underline{K}_1} = (1-\pi)F_1 > 0$ for all K_2, it follows that $K_1(K_2) > \underline{K}_1$. By assuming that for $K_1 \leq \underline{K}_1$, $F(\underline{K}_1) = F(K_1)$ and $G(\underline{K}_1, K_2) = G(K_1, K_2)$, then if $K_1 < \underline{K}_1$, an attack has no effect. No attack will therefore occur if $K_1 \leq \underline{K}_1$. For conciseness, we define $\underline{F} = F(\underline{K}_1)$, $\overline{F} = F(K_1)$, $\underline{G} = G(K_1, K_2)$ and $\overline{G} = G(\underline{K}_1, K_2)$. Since the upstream nation's output is increasing in K_1, and since K_1 does not crowd out consumption, the upstream nation will therefore never choose $K_1 < \underline{K}_1$. Thus, we only need to consider values of K_1 that lie between $\underline{K}_1$ and μ_1. Using the assumptions outlined above, it is relatively easy to show that (1) is strictly concave with respect to K_1 and that (2) is strictly concave with respect to K_2. The convexity of the welfare functions when an attack always occurs ensures that the best response function is single valued. The derivative conditions and boundary conditions also ensure that it will be interior. We state this as a proposition.

Proposition 2.3. *For all values of $K_2 \in [0, \mu_2)$, the best response function $K_1(K_2)$ satisfies $0 < K_1(K_2) < \mu_1$, and for all values of $K_1 \in (\underline{K}_1, \mu_1]$,the best response function $K_2(K_1)$ satisfies $0 < K_2(K_1) < \mu_2$, provided that $\underline{G}_2 + \pi_2(\overline{G} - \underline{G}) < 0$. Also, $K_1(\mu_2) = \mu_1$ and for $K_1 \in [0, \underline{K}_1]$, $K_2(K_1) = \mu_2$.*

Proof. Since both welfare functions are concave, by virtue of the assumptions on the component functions, we only need toshow that over the indicated ranges, the welfare functions are increasing on the lower boundary and decreasing on the upper boundary. For the upstream nation, $\partial W_1^A/\partial K_1\big|_{K_1=\underline{K}_1} = (1-\pi)F_1 > 0$ and, as $\pi(\mu_1, K_2) = 1$ for all $K_2 < \mu_2$, $\partial W_1^A/\partial K_1\big|_{K_1=\mu_1} = \pi_1(\underline{F} - \overline{F}) < 0$. This establishes the first result. For the downstream nation, $\partial W_2^A/\partial K_2\big|_{K_2=0} = \pi\overline{G}_2 + (1-\pi)\underline{G}_2 > 0$ and $\partial W_2^A/\partial K_2\big|_{K_2=\mu_2} = \pi_2(\overline{G} - \underline{G}) + \underline{G}_2$ when $K_1 \in (\underline{K}_1, \mu_1]$. Thus, if $\pi_2(\overline{G} - \underline{G}) + \underline{G}_2 < 0$, an interior maximum exists. When $K_2 = \mu_2$, $\pi(K_1, \mu_2) = 0$, so that $K_1(\mu_2) = \mu_1$. Finally, when $K_1 \in [0, \underline{K}_1]$, $\partial W_2^A/\partial K_2 = G_2 > 0$ for all K_1, so that $K_2(K_1) = \mu_2$. □

The additional condition $\underline{G}_2 + \pi_2(\overline{G} - \underline{G}) < 0$ means that the change in expected gain resulting from a reduction in K_2 (increase in military expenditure), $\pi_2(\overline{G} - \underline{G})$, must be greater than the loss in output, $\underline{G}_2$, when $K_2 = \mu_2$. If this were not the case, then it would never be worthwhile investing in the military, reducing the exercise to the solution for proposition 2.1.

Corollary 2.4. *A game with payoff functions as in equations 1 and 2, with $\pi_2(\overline{G} - \underline{G}) + \underline{G}_2 < 0$, must have an interior pure strategy Nash equilibrium.*

Proof. Proposition 2.3 establishes that the best responses are interior, relative to their arguments, over the range $K_1 \in (\underline{K}_1, \mu_1]$ and $K_2 \in [0, \mu_2)$. Continuity assumptions on the components of the welfare functions result in the best response functions being continuous in both arguments in this region. The assumption that $\partial W_1^A/\partial K_1\big|_{K_1=\underline{K}_1} > 0$, which implies that $K_1(K_2) > \underline{K}_1$ everywhere, ensures that the upstream best response does not pass through the discontinuity in the downstream best response at $\underline{K}_1$. All the requirements of Kakutani's fixed point theorem are therefore strictly satisfied on the restricted range $(\underline{K}_1, \mu_1] \times [0, \mu_2]$, which confirms the result. □

When the second stage attack decision is part of the game, and the downstream nation is assumed to attack whenever this is expected return maximizing, then the investment choice space can be partitioned into those investment pairs that will result in an attack and those that will not. Let the attack set be called Q^A, which is defined as

$$Q^A = \{(K_1, K_2) \in [0, \mu_1] \times [0, \mu_2] | \pi\overline{G} + (1-\pi)\underline{G} - C_2 > \underline{G}\}$$

Also let $Q^A(K_1)$ be the subset of Q^A where the value of K_1 is fixed. Further let $\overline{Q}^A$ be the complement of Q^A, the set of strategy combinations where an attack will not occur. The fact that Q^A is open on the interior of the strategy space means that $\overline{Q}^A$ is closed on the interior. Both sets are closed along the boundary of the strategy space. See figure 2 for a graphical presentation of these set definitions.

[Figure 2 about here.]

Notice that so long as $C_2 > 0$, it follows immediately that Q^A will not contain the boundaries $K_1 = 0$, $K_2 = 0$ and $K_2 = \mu_2$. To see this, consider each case in turn. First, when $K_1 = 0$, $\pi\overline{G} + (1-\pi)\underline{G} - C_2 = \underline{G} - C_2$, because $\underline{G} = \overline{G}$ when $K_1 = 0$. Since $\underline{G} - C < \underline{G}$ for all $C > 0$, we have the first result. When $K_2 = 0$, $\underline{G} = \overline{G} = 0$, so that $\pi\overline{G} + (1-\pi)\underline{G} - C = -C < 0$, establishing the second result. Finally, when $K_2 = \mu_2$, then $\pi = 0$, which leads to $\pi\overline{G} + (1-\pi)\underline{G} - C = \underline{G} - C < \underline{G}$ for all $C > 0$, completing the set. Using these facts, we can conclude that the downstream best response curve must have a discontinuity in the two stage game, and that the upstream best response cannot include points in the interior of $\overline{Q}^A$. We state these results as two propositions.

Proposition 2.5. *For the two stage game, the downstream best response function in the first stage, applying sub-game perfection to the second stage, has at least one discontinuous break.*

Proof. Let $K_2^A(K_1)$ be the best response conditional on an attack always occurring. Proposition 2.1 establishes that the best response functions when there is no attack are $K_1 = \mu_1$ and $K_2 = \mu_2$. Thus, when the sub-game does not result in an attack, which occurs for all K_1 where $Q^A(K_1)$ is empty or where $W_2^A(K_1, K_2^A(K_1)) \leq W_2(K_1, \mu_2)$, then the best response is $K_2 = \mu_2$. When $W_2^A(K_1, K_2^A(K_1)) > W_2(K_1, \mu_2)$, proposition 2.3 shows that $K_2(K_1)$ is interior. At values of K_1 when $W_2^A(K_1, K_2^A(K_1)) = W_2(K_1, \mu_2)$, the best response consists of two K_2 values, $K_2 = \mu_2$ and a K_2 value in the interior of $Q^A(K_1)$. This latter point must be true because with $G_2 > 0$, which leads to $\partial W_2/\partial K_2 > 0$, there must be a region between $K_2^A(K_1)$ and μ_2 where $\partial W_2^A/\partial K_2 < 0$ or we could not have that $W_2^A(K_1, K_2^A(K_1)) \geq W_2(K_1, \mu_2)$. Since one best response is interior to $Q^A(K_1)$ and the boundary is not in $Q^A(K_1)$, there must be a discontinuous break. □

This proposition establishes that there must be a gap between points b and c in figure 2. Beginning at point b, the return to the downstream nation falls as K_2 is reduced. Likewise, beginning from c, the return falls as K_2 is increased. The return is lowest at the boundary between Q^A and $\overline{Q}^A$. Since K_1 is equal at points b and c, and the return to the downstream nation is greatest for this level of K_1 at points b and c, only points b and c can be in the best response $K_2(K_1)$.

Proposition 2.6. *For the two stage game, the upstream best response function in the first stage, applying sub-game perfection to the second stage, is either on the boundary of* $\overline{Q}^A$ *or contains strategy combinations in the interior of* Q^A.

Proof. Assume that $C > 0$, so that $\overline{Q}^A$ has an interior. For all strategy combinations in $\overline{Q}^A$, $W_1 = F(K_1)$. Since $F_1 > 0$ for all K_2, for any points not on the boundary of $\overline{Q}^A$, W_1 can be increased by increasing K_1. Notice that the $K_1 = 0$ cannot be in a best response. The best response will be $\{K_1 \in \overline{Q}^A(K_2) | K_1 = \max[\overline{Q}^A(K_2)]\}$, the boundary of $\overline{Q}^A$, except where $F(\max[\overline{Q}^A(K_2)]) <$ $\max_{K_1 \in Q^A(K_2)} W_1^A(K_1, K_2)$. In this latter case, the best response is interior to Q^A. □

Propositions 2.5 and 2.6 establish the conditions sufficient to show that there cannot be a pure strategy Nash equilibrium for games of this form where, at the equilibrium, the downstream nation is indifferent between attacking and not attacking. If attacking is ever a best response, any pure strategy Nash equilibrium without an attack must be on this boundary. Thus, with the asymmetry introduced by the riparian environment, the armed standoff equilibrium common in resource capture games does not occur. By establishing that such equilibria do not exist, we can then conclude that if there is a Nash equilibrium, it must be a mixed strategy equilibrium, and our function definitions ensure that these mixed strategy equilibria cannot put zero weight on realizations not in Q^A. Using this result we can then argue that in many such situations, leadership will not lead to attack while not having a leader has a nonzero attack probability. This contradicts Homer-Dixon's conjecture.

Let Γ be a two stage game where payoffs are either $F(K_1)$ and $G(K_1, K_2)$ or as in equations 1 and 2, with properties as outlined earlier. Player two chooses which payoff functions will apply in the second stage of the game, after both players have chosen values for K_1 and K_2. We state the non-existence result as a theorem.

Theorem 2.7. *For any two stage, two player game with the form of* Γ, *a pure strategy Nash equilibrium where the payoff choosing player is indifferent between second stage choices does not exist.*

Proof. Proposition 2.6 establishes that the upstream best response is either on the boundary outside Q^A, inside Q^A, or equal to μ_1. Along the boundary of $\overline{Q}^A$, adjacent to Q^A, $W_2(K_1, K_2) = W_2^A(K_1, K_2)$. Proposition 2.1 shows that when $(K_1, K_2(K_1)) \in \overline{Q}^A$, $K_2(K_1) = \mu_2$. When $C > 0$, so that $\overline{Q}^A$ has an interior, μ_2 cannot be in the set of points that define the boundary of $\overline{Q}^A$ adjacent to Q^A. Therefore, since the gap(s) in the downstream best response occur where $G(K_1, K_2(K_1)) = G(K_1, \mu_2)$ (proposition 2.5), these gaps must span the boundary. Since pure strategy Nash equilibria with the downstream nation indifferent about attacking must lie on the boundary, no such Nash equilibria can exist. □

Graphically, the gap between points b and c in figure 2 cannot contact the boundary between $\overline{Q}^A$ and Q^A. As a result, an equilbria cannot exist where the downstream nation is just indifferent between attacking and not attacking. The only Nash equilibria possible for this game are therefore mixed strategy equilibria. Further, since the structure introduces a non-concavity into the payoff functions of the overall game, there is no guarantee that there will be a mixed strategy equilibria either (see Osborne and Rubenstein 1994 for existence conditions for Nash equilibria). It can be shown that the upstream nation's payoff functions both with and without an attack are strictly quasi-concave for the arguments K_1 and K_2. Strict quasi-concavity means that for any set of K_2 values and probability distribution over those values, there will be a single K_1 value that maximizes the expected payoff. Therefore, the upstream nation will only have a pure strategy best response to any mixed strategy played by the downstream nation if the realizations are either all in Q^A or all in $\overline{Q}^A$. Since $K_2(K_1)$ is also single valued in these regions, no mixed strategy equilibria can exists which does not generate realizations in both Q^A and $\overline{Q}^A$. This means that if we observed a large number of independent replications of this game, when a mixed strategy Nash equilibrium exists, we would expect to see the attack option being exercised in some realizations.

With reference to the proposal that water wars are more likely when there is a downstream leader, to support it we must show that a downstream leader would play a strategy that is more likely to lead to an attack. A downstream leader chooses K_2, incorporating the upstream best response $K_1(K_2)$. There are three cases to consider, when the upstream best response lies entirely outside the attack region, when there is a Nash equilibrium inside the attack region, and when there is no Nash equilibrium, but a portion of the upstream best response function lies in the attack region. In the first case, clearly, when $K_1(K_2)$ is entirely in $\overline{Q}^A$, all downstream leader outcomes will involve $(K_1, K_2) \in \overline{Q}^A$, which will never result in an attack. Thus, in these cases the likelihood of a downstream leader attacking cannot exceed that for the simultaneous move game. For the second case, note that when a pure strategy Nash equilibrium exists for the simultaneous move game, it will always involve an attack in the second stage. As such, in this situation, a downstream leader cannot increase the likelihood of an attack.

The only cases where downstream leadership may increase the risk of violence is when the upstream best response includes a segment inside Q^A not intersecting $K_2(K_1)$ inside Q^A. The downstream leader may now prefer a point on $K_1(K_2)$ where attacking is rational, while without a leader it need not always involve an attack. Unfortunately for our analysis, within this region, whether or not it is rational for the downstream nation to attack depends on the forms for the production and attack success functions. To explore this, consider a case where a downstream leader is indifferent between attacking and not attacking. Let $K_1 = K_1(K_2)$ when K_2 maximizes $G(K_1, K_2)$ for K_2 in $\overline{Q}^A$, and let $K_1^A = K_1(K_2^A)$ when K_2^A maximizes $W_2(K_1^A, K_2^A)$ in Q^A. To simplify the exposition, let $\pi = \pi(K_1, K_2)$, $\pi^A = \pi^A(K_1^A, K_2^A)$, $G = G(K_1, K_2)$, $\underline{G} = G(\underline{K}_1, K_2)$, $G^A = G(K_1^A, K_2^A)$ and $\underline{G}^A = G(\underline{K}_1, K_2^A)$.

When the downstream leader is indifferent between choosing K_1 and K_1^A, it must be true that $G = \pi^A \underline{G}^A + (1 - \pi^A)G^A - C_2$. Since (K_1, K_2) is on the boundary of $\overline{Q}^A$, it must also be true that $G = \pi \underline{G} + (1 - \pi)G - C_2$. This second relation requires that at the boundary, $G = \underline{G} - C_2/\pi$. Taking this result together with the indifference conditions, it follows that $\pi^A \underline{G}^A + (1 - \pi^A)G^A = \underline{G} - C_2(1/\pi - 1)$, or that $\pi^A(G^A - \underline{G}^A) + (\underline{G} - G^A) = C_2(1/\pi - 1)$. Whether or not this can be satisfied depends on the forms of π and G.

The critical question is whether this condition can be satisfied while a Nash equilibrium does not exist. To do this, we consider a limiting case, that where there is only one interior point in $K_1(K_2)$. In figure 2 in this case, points d and f and points e and g coincide. When this is true, $\underline{G}^A = \underline{G}$, so that indifference for the downstream leader requires that $(1 - \pi^A)(\underline{G} - G^A) = C_2(1/\pi - 1)$. Since $\underline{G} > G^A$ ($K_2$is fixed) and $\pi^A < 1$, there is no contradition. All that is required is the right functional forms. If this point is to be a Nash equilibrium, it must also satisfy $K_2 = K_2(K_1^A)$. Since there is nothing about the indifference along K_2 that requires K_2 to also maximize W_2 at K_1^A, in particular for K_2 in $Q^A(K_1^A)$, it is entirely possible that it may be rational for a leader to choose to attack while no Nash equilibrium exists. Whether or not this is the case then depends on the functional forms involved. For the numerical example shown below, no such cases were found. Consequently, if downstream leadership is to increase the likelihood of interstate military conflict, relative to the case with no leader, a rather specific set of relationships must be in place. Thus, although we are unable to rule out downstream leadership on a river increasing the likelihood of war in some circumstances, we can rule out the conclusion that the presence of a militarily superior downstream riparian in itself increases the likelihood of military conflict over water.

3. Numerical Example

To illustrate the analytical results, we use a numerical example. The assumptions on the water capture functions are satisfied by implementing them as

$$\begin{aligned} w_1 &= P(1 - e^{-g_1 K_1}) \\ w_2 &= (P - w_1)(1 - e^{-g_2 K_2}) \end{aligned}$$

where P is the precipitation in the upstream nation and g_i is the effectiveness of investment at water capture. This water enters a production function

$$\begin{aligned} F_1(K_1) &= [w_1(K_1)]^{\alpha_1} \\ F_2(K_1, K_2) &= [w_2(K_1, K_2)]^{\alpha_2} \end{aligned}$$

where $0 < \alpha_i < 1$ ensures diminishing marginal productivity. The conflict function, identical to that used by Cothren (2000), is

$$\pi^K(K_1, K_2) = \frac{\mu_2 - K_2}{(\mu_1 - K_1) + (\mu_2 - K_2)}$$

with $\pi(\mu_1, \mu_2) = 0$. Figure 3 shows the production and conflict functions, both defined in terms investment levels K_1 and K_2, with parameters $\mu_1 = \mu_2 = 10$, $P = 10$, $g_1 = g_2 = 0.5$, and $\alpha_1 = \alpha_2 = 0.75$. Notice that with symmetric parameter values, $F_1(K_1) = F_2(0, K_1)$, so that the upstream production function can also be seen in figure 3, where $K_1 = 0$. All results and graphics were generated using R (Ihaka and Gentleman, 1996).

[Figure 3 about here.]

Figure 4 shows the best response functions for the two nations, for four different attack costs. In all cases, a portion of the upstream nation's best response curve follows the boundary between the regions where a second stage attack is rational and where it is not. With low attack cost ($C_2 = 0.5$), a large segment of the upstream best response lies inside the attack region. A pure strategy Nash equilibrium exists, and is located inside the attack region, at the intersection of the best response curves. The sequential game equilibria, both with pure strategies, lie close to the Nash equilibria. The investment levels and expected payoffs are given in table 2.

[Figure 4 about here.]

With costs at $C_2 = 1.0$, the share of the upstream best response located along the boundary of the attack region increases. A pure strategy Nash equilibrium in the attack region no longer exists. Although not a Nash equilibria in a one shot game, the average of a best response cycle is indicated in the figure. A best response cycle is a sequence of strategy profiles, where each strategy profile is the best response for each player to the rival's strategy in the previous point in the cycle. For this cycle, an attack is rational for approximately 63% of cycle strategy combinations. For both sequential games, attacking is not rational. When the upstream nation leads, it selects the largest K_1 such that the downstream nation chooses $K_2 = \mu_2$, where an attack is not rational. With a downstream leader, K_2 is chosen along $K_1(K_2)$ to maximize downstream welfare. This occurs for a point on the attack region boundary, again where an attack is not rational. Notice that relative to the cycle average, the downstream leader has reduced investment (increased its military) which induces lower upstream investment (larger upstream military), resulting in greater downstream welfare. Thus, this downstream lead 'arms race' has increased downstream welfare and reduced upstream welfare.

[Table 2 about here.]

Further increasing the attack cost to $C_2 = 2.0$ closes the discontinuity in the upstream best response. The upstream best response now coincides with the boundary of the attack region. The upstream nation now only responds with investment levels that make it irrational for an attack in the second stage. However, the discontinuity in the downstream best response curve is such that no pure strategy Nash equilibrium exists. If the upstream nation leads, it chooses the largest K_1 such that the downstream response is $K_2 = \mu_2$ and no attack. If the downstream nation leads, it chooses the point along the boundary of the attack region where its welfare is maximized. Even without an attack, military spending again exceeds the cycle average, while increasing downstream welfare.

Finally, panel (d), plots the $C_2 = 6.0$ case. Now there is only a small set of strategy pairs where an attack is optimal. The cycle average continues to have a relatively high attack rate at 60%. If the upstream nation chooses its investment first, it is able to increase its return by keeping $K_2 = 10$. However, when the downstream nation leads, it is unable to increase its welfare relative to the cycle average. Downstream leadership now has no advantage.

Since leadership by either nation is questionable when both nations are identical, we also consider three cases where downstream leadership is more credible. These are shown in figure 5, with numerical values in table 3. Panel (a) reproduces the results of panel (b) in figure 4. In panel (b), the downstream endowment has been increased to $\mu_2 = 30$. As a share of endowment, the upstream best response has shifted down; with a larger endowment, a larger share is devoted to the military. Conceptually, the larger endowment increases the relative marginal productivity of military spending, used to 'liberate' upstream water. With the downstream leader, the solution does not involve an attack. Further, relative to the cycle average, a 56% reduction in productive investment, from 22.7 units down to 9.99 units, results in a

43% increase in welfare, from 5.29 to 7.59 units. This compares to a 43% reduction in investment generating a 26% increase in return for the $\mu_2 = 10$ case. With a larger endowment, a downstream leader is again better off not attacking, and gains more in relative terms than when endowments are equal.

[Figure 5 about here.]

[Table 3 about here.]

Panel (c) increases the effectiveness of the downstream water capture investment. As for the endowment increase, the downstream best response shifts down. This results in a greater share of water released by an attack being captured. There is again no interior Nash equilibrium for the simultaneous move game. However, the downstream leader is still better off choosing a strategy that does not lead to an attack. In this case, a 1.3% reduction in capital investment, from 2.98 to 2.94, increases downstream return by 37%.

Panel (d) puts the upstream nation at a technological disadvantage, in terms of water capture effectiveness, by setting $\alpha_1 = 0.5$. The effect appears in table 3 as an increase in K_1 and a reduction in W_1, relative to the panel (a) results. No portion of the upstream best response curve is now in the interior of the attack region, so that the downstream leader can only choose points that will not result in an attack. In this case, a 43% reduction in investment relative to the cycle average results in a 28% increase in return. This is the smallest increase in return, but still larger than the 26%, from 4.24 to 5.78, increase in return when both technology parameters are equal. In all four panels, if the upstream nation is the leader, it will choose a strategy that results in $K_2 = \mu_2$ and no attack.

In both figure 4 and figure 5, strategy combinations that generate greater expected welfare for both nations than the Nash equilibrium or cycle average are identified. The existence of these strategy combinations in all four panels shows that this game has aspects of a prisoner's dilemma. This highlights that there is scope for Folk theorem results, where repetition permits cooperation, allowing Pareto improvements to be realized. From the point where the upstream best response function becomes continuous, the range of strategy combinations which support such cooperation increases as costs increase, with none involving an attack. When the upstream best response is not continuous, the set of mutually advantageous strategies increases as costs fall. However, some lie in the attack region. With cheap attack costs, strategies can be coordinated to increase mutual gain while, somewhat perversely, the downstream nation continues to attack the upstream nation's infrastructure.

Beyond pure and mixed strategy Nash equilibria, there are other solution concepts. Best response cycles with various belief structures may generate equilibria. Naive expectations, adaptive expectations and moving average expectations were tried in this numerical example, always resulting in periodic attacks. A version of this model, focusing only on the simultaneous move form, was implemented as an experiment (Janmaat, 2004). Subjects playing repeated rounds were unable to coordinate on no attack solutions, although average behavior tended to lie between the attack always Nash equilibrium and a no attack point consistent with the Folk Theorem. Further experiments will explore the impact of leadership, and seek to identify relevant solution concepts.

4. Discussion

In this paper we constructed a model in which two countries are connected by a natural resource, water, and able to invest in military hardware. Downstream military investment creates a threat to the upstream nation, while upstream military investment provides protection against that threat. In both cases, military investment provides no direct utility or productivity impact. Thus military expenditure is costly in terms of foregone production, and provides no benefit beyond its impact on attack success probabilities.

One general result is that for a one shot two stage game where a downstream 'leader' nation's threat can persuade an upstream neighbour to consume less water, the likelihood of an attack occurring is likely less than absent a leader. This contrasts with Homer-Dixon (1999) and Gleditsch et al. (2004), who argue that militarily and economically superior nations, such as Egypt with respect to its upstream neighbors, are more likely to resort to force than when there is no such dominance. Historically, Egypt was well known for threatening to use force to protect its water security. However, perhaps it is the credibility of this threat that provides Egypt with water security, relative to a situation where its superiority is not so apparent.

Although motivated by the Nile basin example, our results may be relevant in other cases where resources are sequentially shared between nations. An example without clear leadership is the dispute between India and Pakistan over the Kashmir region. Even though this region is an important headwater for the Indus, the existence of a water sharing treaty suggests water is not an immediate cause of the wars these nations have fought. However, the results of this paper suggest that the military buildup may be in part caused by concerns over water security. Several other river systems, such as the Jordan, the Tigris and Euphrates, the Ganges and Brahmaputra, the Danube and the Rhine, also flow from one country to another. The Ganges and Brahmaputra have been identified as potentially vulnerable for conflict, negotiations have recently been taking place around the Jordan and the Tigris and Euphrates (Wolf et al., 2003). In contrast to arid region rivers, nations along the Rhine and Danube have a long history of cooperation. Other sequential resource movements, such as animal migration or dispersion patterns, may also fit this framework. The recent 'Turbot War' between Canada and Spain, surrounding fishing immediately outside Canada's territorial water, is a possible example (Missios and Plourde, 1996). Likewise, for trans-boundary aquifers or oil reserves, military buildup may enable the nation more vulnerable to rapid drawdown of the reservoir to induce a slower extraction rate by its neighbour.

Military investment decisions are made in a far more complex environment than that captured in a one shot game. Generally, the interaction is repeated. Following the Folk theorem, if this game was repeated, we expect nations to be able to coordinate on a strategy where both are better off. As attacks destroy capital, the repeated game equilibrium is less likely to include an attack. Further, with the accumulation of military capital, an upstream leader may attack a downstream rival so as to reduce its military stock, or reduce the economic output needed to produce this military stock. For the numerical example, the sequential move game almost never involves an attack, regardless of who leads. With repetition, an attack is probably less likely yet. In line with the dynamics of repetition, capital and military assets are normally accumulated over time. The opportunity cost of capital destruction is greater, in terms of time to rebuild. This likely increases the incentive for the upstream nation to invest in defense, and the effectiveness of the downstream threat. It is expected that the interaction of these effects will further reduce the likelihood of war. We leave the details of these dynamic analyses for future work.

While long run expected river discharge can be considered constant, for other resources this is not true. For example, an oil field is analogous to an aquifer, with no natural recharge. A key variable for analyzing these situations is the size of the resource pool, which declines over time with extraction. Although not presented, increasing the resource supply to divide increases the likelihood of war in the numerical example. With greater resource abundance, provided abundance does not generate costs (see Janmaat and Ruijs, 2004 for impact of flooding risk on cooperation), capture investment has a larger expected return, as the gain to a successful attack is greater. The key role of the value that can be captured implies that resource wars are most likely to occur when scarcity has sufficiently increased the value of disputed resource reserves, with enough left to make it worth fighting over. Therefore, rather than mayhem and anarchy when oil supplies approach exhaustion, as some pundits suggest, it may occur sooner, when supplies are relatively abundant but of high value.

Our results indicate that water scarcity need not cause international violent conflict, and that when one riparian is dominant, violence is unlikely. However, in most equilibria the downstream nation is indifferent between war and peace. In the symmetric model of Cothren (2000), nations are also indifferent between attacking and not attacking at the Nash equilibrium. Hauge and Ellingsen (1998) and Toset et al. (2000) found a positive relationship between domestic conflict and environmental scarcity. However, they also found that military expenditure was the best predictor of the severity of conflict. "The sources of civil conflict are not necessarily closely related to the severity of the conflict. Although environmental scarcity is a cause of conflict, it is not necessarily also a catalyst (Hauge and Ellingsen, 1998, p. 314)". In the current model, water scarcity stimulates arms accumulation, but not necessarily violent conflict. Stochastic effects that change the economic or military positions may upset this delicate balance and trigger violence. Consequently, international military conflicts may be more common where states are resource dependent, even though not directly triggered by resource scarcity. In this vein, Tir and Diehl (1998) find a strong interaction between military capacity and population growth as predictors of involvement in military conflict, while Toset et al. (2000) and Gleditsch et al. (2004), examining the relation between factors such as water scarcity, leadership, regime type and conflict, find results consistent with ours.

The current model also highlights the critical role played by the cost of the attack to the attacking nation. If the cost is low relative to the expected gain, then an attack is rational, while if the cost is high, it is neither rational to attack nor to invest in the military. These costs may play a key part in determining what triggers can transform an arms race into a war. In particular, the prospect of sanctions or other economic censure from the international community may serve to increase the costs. This would reduce the need for the upstream nation to invest in its military, allowing an increase productive capital investment.

Dynamically, productive capital accumulation stimulates economic growth, while the impact of military accumulation on growth is less clear. A number of studies have examined the relationship between economic growth and military expenditures. At a theoretical level (Zou, 1995; Blomberg, 1996; Shieh et al., 2002; Gong and Zou, 2003), this work suggests that the effects are ambiguous. Military expenditures may crowd out more productive investments - as in the model we develop - and thereby reduce economic growth. However, this investment may also enhance growth by building human capital, providing social stability, etc. Empirical analyses of this relationship - many of which preceeded the theoretical work - find similarly inconclusive results (LaCivita and Frederiksen, 1991; Looney, 1993; Kusi, 1994; Blomberg, 1996; Dakurah et al., 2001). Several authors conclude that this is a consequence of the importance of context. Our results support this by highlighting the role of one element of that context, where a nation lies in a watershed. For an upstream nation, increasing military expenditure is likely to reduce economic growth by crowding out productive investment. In contrast, downstream military expenditure may, via its threat effect, lead to more water reaching the downstream nation. Thus, whether military spending stimulates or retards economc growth may depend on riparian position.

There are at least three empirical implications of this model that can be explored. First, where resources are scarce and shared, the level of militarization is likely to be high. Second, international conflicts are also likely to be more frequent and more violent where heirarchical resource dependencies exist, even though it may be difficult to directly identify that resource scarcity is a cause. Toset et al. (2000) and Gleditsch et al. (2004) find support for this hypothesis. Third, as outlined above, the correlation between economic growth and military expenditure will depend on whether a nation provides a critical resource to a neighbour or depends on a neighbour for a critical resource. In the former case it would be negative, while in the latter positive. We leave detailed empirical analyses to the future.

Finally, this work points to the importance of considering the broader context within which international conflict develops. Arms accumulation may be a response to water scarcity and dependence, while escalations may not directly flow from the resource. The military balance may actually contribute to maintaining sharing arrangements, by making defection sufficiently costly. Unwinding this delicate web requires recognition of the resource underpinning. Embedding arms reduction agreements in broader arrangements including trade and resource access is more likely to be successful than focusing on arms alone. Further expanding to regional arrangements may both increase the cost to downstream riparians of an attack, while putting greater pressure on upstream riparians to respect resource sharing arrangements. The Nile Basin Initiative may represent a move in this direction, and we hope it proves successful.

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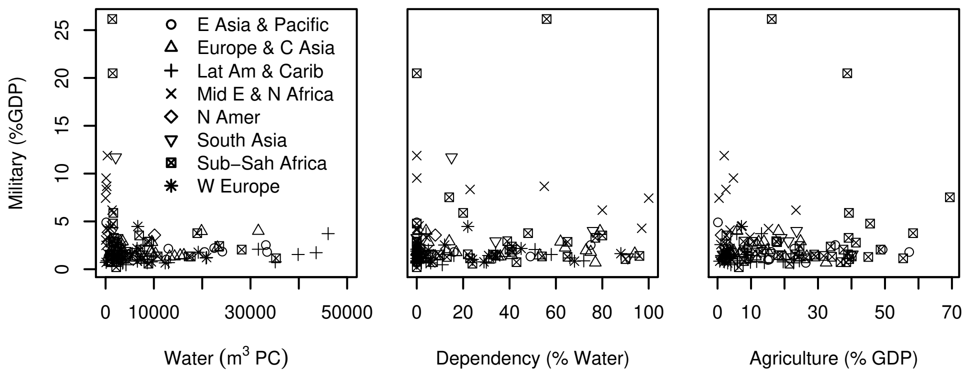


FIGURE 1. Military expenditures as affected by per capita water availability, water dependency, and share of economic output represented by agriculture. Source: World Resource Institute Earthtrends data (www.wri.org) and World Bank World Development Indicators (www.worldbank.org).

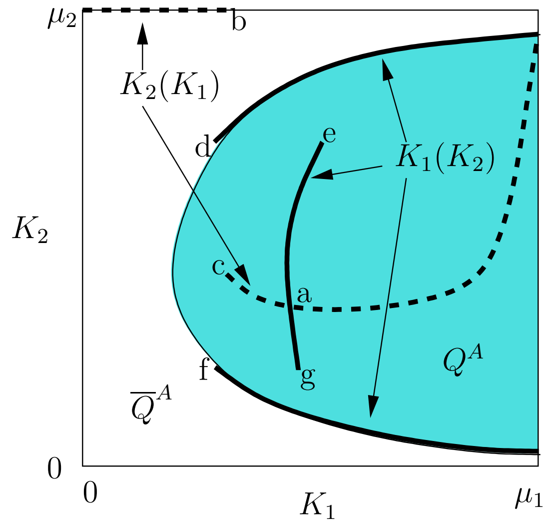


FIGURE 2. Graphical representation of key sets. $K_1(K_2)$ and $K_2(K_1)$ are best response functions for investment level. Q^A is the attack region, the combinations of K_1 and K_2 where it is rational for the downstream nation to attack. $\overline{Q}^A$ is its complement. Point a is a Nash equilibrium. Points b and c are endpoints of $K_2(K_1)$, at which the return to the downstream nation are equal. Points d, e, f, and g are endpoints for $K_1(K_2)$, at which the return to the upstream nation are equal.

FIGURE 3. Production and conflict functions, in terms of K_1 and K_2. Parameters set at $\mu_1 = \mu_2 = 10$, $P = 10$, $g_1 = g_2 = 0.5$, and $\alpha_1 = \alpha_2 = 0.75$.

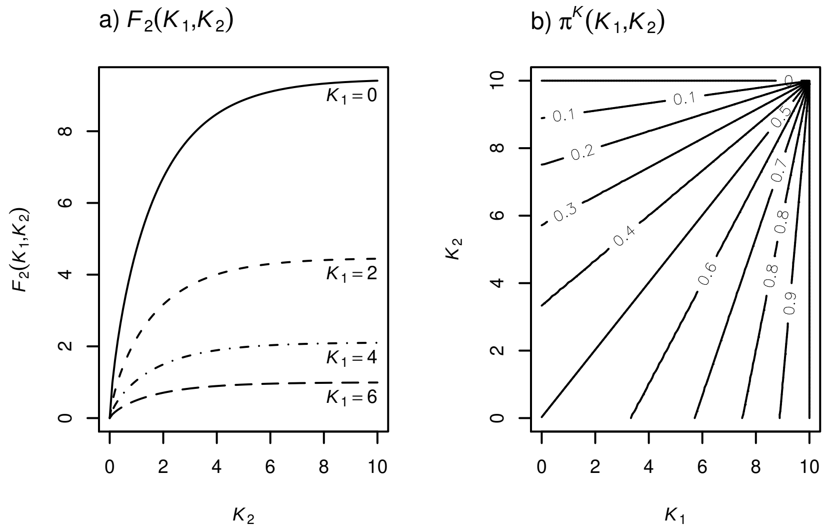


FIGURE 4. Best response functions, Nash equilibria, and equilibria with upstream or downstream nation as leader. Lightly shaded region marks investment combinations where the downstream nation will attack, while darkly shaded regions are investment combinations that leave both nations better off than at the Nash equilibrium or cycle average.

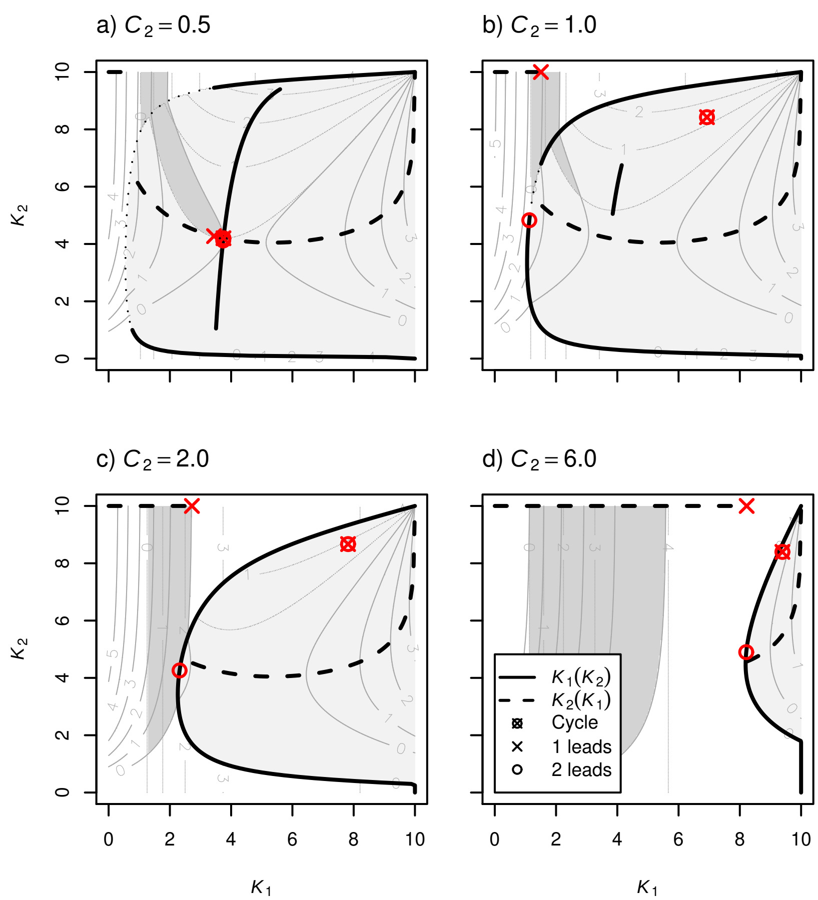
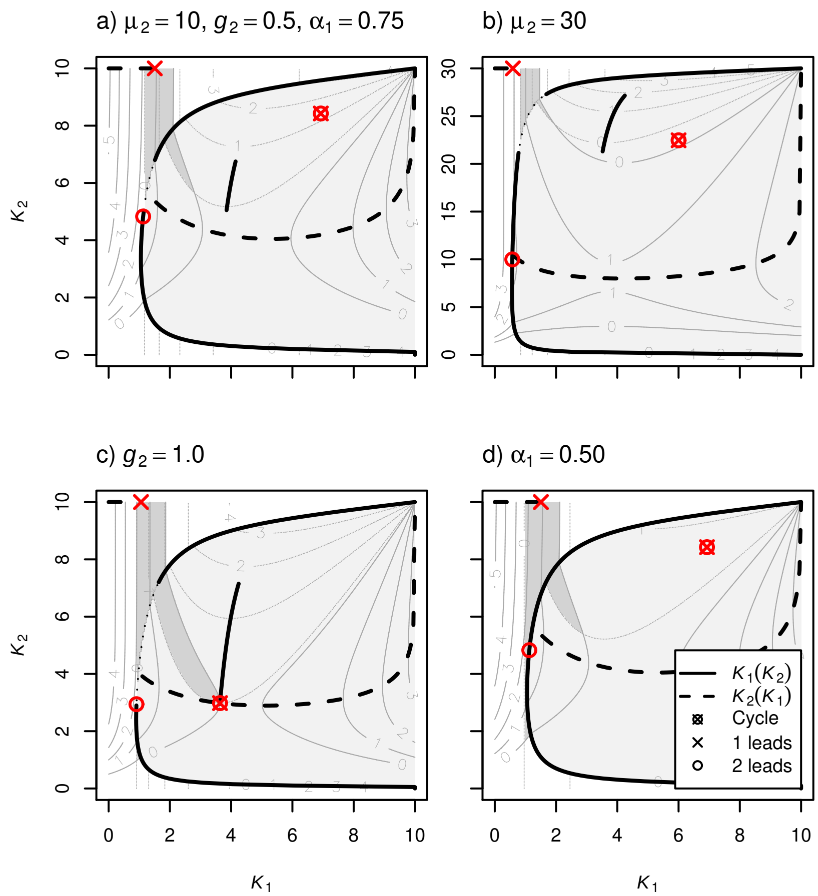


FIGURE 5. Best response and attack regions for cases where the downstream nation has a larger endowment, has better capture technology, and is more productive in its use of water. Parameter values are $C_2 = 1$, $\mu_1 = \mu_2 = 10$, $g_1 = g_2 = 0.5$ and $\alpha_1 = \alpha_2 = 0.75$ unless otherwise indicated.



List of Tables

TABLE 1. Regression results, Est. reports parameter estimates, and S.E. their standard error. Variables are per capita renewable water, water dependency ratio, agriculture value share of GDP, per capita GDP, the World Bank's corruption index and political stability index. Per capita renewable water parameter has been scaled to units of 1000 m^3 per person per year, and GDP has been scaled to 1000 US$ per person per year. Figures in bold are significant at the 5% level.

	All Data				Per Capita Water < 10,000 m^3			
Variable	Est.	S.E.	Est.	S.E.	Est.	S.E.	Est.	S.E.
Water_PC	-0.013	0.010	-0.011	0.009	**-0.400**	**0.145**	**-0.365**	**0.151**
Dependency	0.000	0.001	0.001	0.009	0.007	0.013	0.007	0.014
Ag_Value	0.013	0.019	0.010	0.025	-0.001	0.030	-0.018	0.043
GDP_PC			-0.065	0.047			-0.069	0.068
Corruption			**1.205**	**0.724**			0.820	1.106
Stability			**-0.930**	**0.502**			-0.582	0.748
Intercept	**2.576**	**0.494**	**2.915**	**0.653**	**4.108**	**0.828**	**4.624**	**1.031**
n			132		87		87	
R^2			0.053		0.085		0.103	

TABLE 2. Equilibrium strategies and payoffs for various attack costs. When a Nash equilibrium does not exist, the average for a best response cycle passing through (μ_1, μ_2) is reported. For the cycles, length is the number of moves before the same point is returned to, st. dev is the standard deviation of the payoff for the cycle, and attack indicates what portion of the points along the cycle result in a second stage attack. For '1 leads' and '2 leads' results, the leading nation chooses its investment level, using the pure strategy best response of the other nation in place of taking the other nation's strategy as fixed.

	Upstream		Downstream			Cycle	
	K_1	W_1	K_2	W_2	Length	St. Dev	Attack
$C_2 = 0.5$							
Nash	3.75	4.80	4.20	4.56	1	0.00, 0.00	1.00
1 leads	3.44	4.81	4.27	4.63	-	-	1.00
2 leads	3.74	4.78	4.12	4.57	-	-	1.00
$C_2 = 1.0$							
Cycle	6.93	5.14	8.42	4.24	8	3.90, 2.64	0.63
1 leads	1.51	5.87	10.0	5.35	-	-	0.00
2 leads	1.13	5.03	4.83	5.78	-	-	0.00
$C_2 = 2.0$							
Cycle	7.82	5.34	8.67	3.42	8	3.36, 2.27	0.63
1 leads	2.72	7.57	10.0	3.40	-	-	0.00
2 leads	2.32	7.13	4.26	3.61	-	-	0.00
$C_2 = 6.0$							
Cycle	9.39	5.04	8.40	1.16	10	0.78, 2.14	0.60
1 leads	8.22	9.34	10.0	0.43	-	-	0.00
2 leads	8.21	9.34	4.90	0.41	-	-	0.00

TABLE 3. Equilibrium strategies and payoffs when endowment, capture success and output elasticity are varied. When a Nash equilibrium does not exist, the average for a best response cycle passing through (μ_1, μ_2) is reported. For the cycles, length is the number of moves before the same point is returned to, st. dev is the standard deviation of the payoff for the cycle, and attack indicates what portion of the points along the cycle result in a second stage attack. For '1 leads' and '2 leads' results, the leading nation chooses its investment level, using the pure strategy best response of the other nation in place of taking the other nation's strategy as fixed.

	Upstream		Downstream			Cycle	
	K_1	W_1	K_2	W_2	Length	St. Dev	Attack
$C_2 = 1.0$							
Cycle	6.93	5.14	8.42	4.24	8	3.90, 2.64	0.63
1 leads	1.51	5.87	10.0	5.35	-	-	0.00
2 leads	1.13	5.03	4.83	5.78	-	-	0.00
$\mu_2 = 30$							
Cycle	6.26	4.40	22.7	5.29	8	4.39, 9.60	0.49
1 leads	0.59	3.40	30.0	7.58	-	-	0.00
2 leads	0.57	3.33	9.99	7.59	-	-	0.00
$g_2 = 1.0$							
Nash	3.64	4.45	2.98	4.70	1	0.00, 0.00	1.00
1 leads	1.06	4.85	10.0	6.36	-	-	0.00
2 leads	0.91	4.44	2.94	6.46	-	-	0.00
$\alpha_1 = 0.5$							
Cycle	7.14	2.79	8.51	4.15	8	3.90, 2.64	0.63
1 leads	1.51	3.25	10.0	5.34	-	-	0.00
2 leads	1.13	2.94	4.83	5.78	-	-	0.00