Climate Change and the Stability of Water Allocation Agreements

Erik Ansink and Arjan Ruijs

NOTA DI LAVORO 16.2007

FEBRUARY 2007

ETA – Economic Theory and Applications

Erik Ansink and Arjan Ruijs, *Environmental Economics and Natural Resources Group Wageningen University*

Climate Change and the Stability of Water Allocation Agreements

Summary

We analyse agreements on river water allocation between riparian countries. Besides being efficient, water allocation agreements need to be stable in order to be effective in increasing the efficiency of water use. In this paper, we assess the stability of water allocation agreements, using a game theoretic model. We consider the effects of climate change and the choice of a sharing rule on stability. Our results show that both a decrease in mean river flow and an increase in the variance of river flow decrease the stability of an agreement. An agreement where the downstream country is allocated a fixed amount of water has the lowest stability compared to other sharing rules.

Keywords: Water Allocation, Stability, Climate Change, Game Theory

JEL Classification: C7, Q25

We thank Joel Bruneau and Hans-Peter Weikard for valuable comments, and we acknowledge financial support by the European Union FP6 Integrated Project AquaTerra (project no. GOCE 505428).

Address for correspondence:

Erik Ansink
Environmental Economics and Natural Resources Group
Wageningen University
P.O. Box 8130
6700 EW Wageningen
The Netherlands
Phone: +31 317 482 362
Fax: +31 317 484 933
E-mail: erik.ansink@wur.nl

1 Introduction

When multiple countries share a river, they compete over available water resources. The upstream country has the first option to use water, which may obstruct the overall efficiency of water use [5]. Cooperation between upstream and downstream countries—in the form of a water allocation agreement—may increase the efficiency of water use. Whether cooperation is stable, however, depends on the design of the water allocation agreement. The stability of water allocation agreements is the subject of this paper.

In the twentieth century, 145 international agreements on water use in transboundary rivers were signed; almost 50% of these agreements cover water allocation issues [43]. The majority of these water allocation agreements does not take into account the hydrologic variability of river flow [19]. This is a shortcoming because variability is an important characteristic of river flow. This variability will even increase in many river basins when the effects of climate change on temperature and precipitation proceed as projected by climate simulation models [23]. These effects are expected to increase the variability of the annual and seasonal flow patterns as well as the frequency of extreme events in many river basins [3, 13, 38, 40]. Recognition of flow variability in the design of water allocation agreements can increase the efficiency of these agreements.

Several studies have addressed this issue for two common sharing rules for water allocation: proportional allocation and fixed flow allocation [for an overview of sharing rules, see 15]. Fixed flow allocations are most common [43] but tend to be less efficient when flow variability increases. Bennett et al. [8] compared the efficiency of fixed flow allocations with proportional allocations and found that, in many situations, proportional allocations are more efficient. Kilgour and Dinar [26, 27] developed a sharing rule that ensures a Pareto-efficient allocation for every possible flow volume, where the level of compensation paid by receivers of water is subject to annual bargaining. Obviously, compared with a proportional or fixed flow allocation, this flexible allocation is more efficient, but it requires accurate predictions of annual river flow. In a case study of the Colorado river, Mendelsohn and Bennett [34] found that the loss of efficiency related to a change in mean river flow (e.g. because of climate change) is higher for a proportional allocation than for a fixed allocation, the main reason being that the initial proportions used were inefficient. Another result was that the largest impact of climate change on efficiency comes from changes in the mean of river flow, not from changes in its variance. Furthermore, in an analysis of U.S. interstate water allocation compacts, Bennett and Howe [7] found that agreement compliance is higher for proportional than for fixed flow allocations.

Apart from being efficient, water allocation agreements need to be stable in order to be effective instruments to increase the efficiency of water use. Efficiency and stability of agreements are not necessarily linked. Climate change, for instance, may increase the benefits of cooperation to one country while decreasing those of the other, leaving overall efficiency equal, but possibly giving the country with decreased benefits an incentive to leave the agreement. Because agreements are signed between sovereign nations, there is usually no higher level authority that can enforce compliance. The stability of agreements therefore depends on the distribution of the benefits of cooperation to the countries involved, which can be analysed using game theory. Recent studies [1, 41, 29, 20, 44] showed that water allocation agreements can improve the efficiency of water use and that—when benefits of cooperation are distributed properly—they can be attractive to all countries involved. This game theoretic literature, however, does not explicitly consider the effects of climate change on river flow and agreement stability.

The objective of this paper is to assess the stability of water allocation agreements when climate change affects river flow. This is done by constructing a game theoretic model of water allocation that analyses stability of three sharing rules for water allocation. Results show that both a decrease in mean river flow and an increase in variance of river flow decrease stability, and that an agreement where the downstream country is allocated a fixed amount of water has the lowest stability.

The remainder of this paper is organized as follows. In sections two and three we present our model and assess stability of cooperation. In section four we illustrate the effects of climate change on the stability of cooperation for different sharing rules, using a numerical example. In section five we assess stability effects of alternative punishment strategies and asymmetric countries. In section six we discuss the results using agreements in the Nile river basin, the Orange river basin, and the South Saskatchewan river basin as illustrations, and we conclude in section seven.

2 A model of cooperation

A river is shared by two countries $i \in \{u, d\}$, having its source in the upstream country u and subsequently flowing through the downstream country d. Q_t denotes the volume of river flow in year t that is available for use; it excludes the river flow necessary to sustain the environmental functioning of the river system and other vital services such as navigation. Q_t is defined by probability density function $f(Q)$ [cf. 28]; contributions to the river flow in d are negligible as are return flows. Climate change effects on river flow are included in the model by adapting the probability density function from $f(Q)$ to $f'(Q)$.

In year t, country i uses $q_{i,t}$ units of water. Because of the unidirectional flow of water, u has the first option to use water, which may limit water use by d. All water that was not used by u, is available for use by d:

$$0 \leq \quad q_{u,t} \quad \leq Q_t \tag{1}$$

$$0 \leq \quad q_{d,t} \quad \leq Q_t - q_{u,t} \tag{2}$$

Benefits $B_{i,t}(q_{i,t})$ from water use are concave with a maximum at $\bar{q}_{i,t}$. Clearly, if u maximizes benefits of water use, it does not have an incentive to pass water to d that has a positive marginal value to him. Yet, if the benefit to d of using more water outweighs the decrease in benefits to u, there is scope for cooperation, with u passing on water to d. There are many sharing rules to allocate water between countries. We analyse three common sharing rules:

Proportional allocation (PA): u receives αQ_t and d receives $(1-\alpha)Q_t$, with $0 < \alpha < 1$;

Fixed upstream allocation (FU): u receives $\min\{\beta, Q_t\}$ and d receives $\max\{Q_t - \beta, 0\}$, with $0 < \beta < E(Q_t)$;

Fixed downstream allocation (FD): u receives $\max\{Q_t - \gamma, 0\}$ and d receives $\min\{\gamma, Q_t\}$, with $0 < \gamma < E(Q_t)$.

For cooperation to be attractive to u, we need to include non-water transfers m_t paid by d to u. These non-water transfers may be monetary or in-kind transfers. There are ample examples of such non-water transfers related to river basin agreements [6]. We assume that non-water transfers are equal to the expected value of compensation of u for benefits foregone and a share ϵ of the additional benefits from cooperation. The non-water transfers, paid by d to u, are constant:

$$m^c = E\left(B^n_{u,t} - B^c_{u,t} + \epsilon\left[(B^c_{d,t} + B^c_{u,t}) - (B^n_{d,t} + B^n_{u,t})\right]\right) \quad \text{with} \quad 0 \le \epsilon \le 1 \tag{3}$$

where superscript c denotes cooperation, n denotes non-cooperation, and water use—and therefore benefits—depends on the sharing rule agreed upon.

This method to calculate non-water transfers is related to the Nash bargaining solution; a common solution concept from non-cooperative game theory. The Nash bargaining solution of a game maximizes $(x_u - z_u)(x_d - z_d)$, subject to $x_u, x_d \in F$, where F is the feasible set of payoff vectors and $z = (z_u, z_d)$ are non-cooperative payoffs [cf. 36]. Here, the calculated non-water transfers equal the asymmetric Nash bargaining solution.[1]

We analyse the stability of cooperation using an infinitely repeated game—a common approach in the analysis of international environmental agreements [cf. 17]—because water allocation agreements typically do not have a specified termination date. The stage game in year t is played as follows. First, a value of Q_t is realized from its probability distribution. Second, the countries observe Q_t and simultaneously choose their action: u chooses $q_{u,t}$ and d chooses m_t. If complying with the agreement, u plays $q_{u,t} = q^c_{u,t}$ according to the selected sharing rule, and earns $B^c_{u,t} = B_{u,t}(q^c_{u,t})$. If deviating, u plays $q_{u,t} = q^n_{u,t} = \min\{\bar{q}_{u,t}, Q_t\}$, and earns $B^n_{u,t} = B_{u,t}(q^n_{u,t})$. If complying with the agreement, d plays $m_t = m^c$. If deviating, d plays $m_t = m^n = 0$. Third, countries observe the strategy played by the other country and receive payoffs.[2]

[1] Two alternative methods to calculate non-water transfers are the Shapley value and Nucleolus, solution concepts from cooperative game theory.

[2] Alternatively, one could assume a Stackelberg game where u is the leader and d is the

The decision to cooperate or deviate in year t is based on the expected payoff stream:

$$E(\Pi_{i,t}) = \max\left(E(\Pi^c_{i,t}), E(\Pi^n_{i,t})\right) \tag{4}$$

We assume that both countries use trigger strategies: when a country deviates, it is punished by the other country in the form of p periods non-cooperative play of the stage game, after which countries return to cooperative play (i.e. agreement strategies). Hence, the expected payoff streams to u and d for compliance in year t equal:

$$E(\Pi^c_{u,t}) = B^c_{u,t} + m^c + \sum_{\tau=t+1}^{\infty} \delta^\tau [E(B^c_{u,\tau}) + m^c] \tag{5}$$

$$E(\Pi^c_{d,t}) = B^c_{d,t} - m^c + \sum_{\tau=t+1}^{\infty} \delta^\tau [E(B^c_{d,\tau}) - m^c] \tag{6}$$

where δ is the discount factor. The expected payoff streams to u and d for deviating in year t equal:

$$E(\Pi^n_{u,t}) = B^n_{u,t} + m^c + \sum_{\tau=t+1}^{t+p} \delta^\tau [E(B^n_{u,\tau})] + \sum_{\tau=t+p+1}^{\infty} \delta^\tau [E(B^c_{u,\tau}) + m^c] \tag{7}$$

$$E(\Pi^n_{d,t}) = B^c_{d,t} + \sum_{\tau=t+1}^{t+p} \delta^\tau [E(B^n_{d,\tau})] + \sum_{\tau=t+p+1}^{\infty} \delta^\tau [E(B^c_{d,\tau}) - m^c] \tag{8}$$

The differences, D_u and D_d, equal the net present value (NPV) of deviating to u and d:

$$D_u = B^n_{u,t} - B^c_{u,t} + \sum_{\tau=t+1}^{t+p} \delta^\tau [E(B^n_{u,\tau}) - E(B^c_{u,\tau}) - m^c] \tag{9}$$

$$D_d = m^c + \sum_{\tau=t+1}^{t+p} \delta^\tau [E(B^n_{d,\tau}) - E(B^c_{d,\tau}) + m^c] \tag{10}$$

follower. This would, however, not change the general results.

From equation (9) it follows that D_u is determined by the difference between benefits of non-cooperative and cooperative play in year t, plus a "punishment" term that has a constant (negative) expected value. From equation (10) it follows that D_d is independent from the level of Q_t, hence constant, for a given probability distribution of Q. Because D_d is negative at $Q_t = E(Q_t)$—an agreement would not be signed if $D_d \geq 0$ at the expected value of river flow—it is negative for any Q_t. Therefore, in the remainder of this paper, we will focus only on u's incentive to deviate.

The type of punishment used here differs from Bennett and Howe [7], who used monetary penalties in their analysis of cooperation between US states. We assume here that there is no authority that can issue this type of penalties when a dispute occurs between nations, a characteristic of many international agreements. In an overview of existing agreements on transboundary freshwater, Beach et al. [6] show that in half of the agreements, disputes are handled by advisory councils, governments' conflict-addressing bodies, the United Nations or other third parties. The other half of the agreements does not refer to any form of dispute resolution. The absence of a higher level authority that can issue penalties is clear; hence a reasonable punishment is non-cooperative behaviour by the other country.

3 Analysing stability

The folk theorem tells us that cooperation can be sustained in equilibrium as long as punishments are severe enough. When discounted payoffs of cooperation outweigh the sum of discounted payoffs of deviation in one year and Nash-payoffs during the subsequent punishment phase, an agreement is said to be stable.

Because of the uncertainty of payoffs in this model, through the stochastic variable Q, it is not possible to assess whether cooperation is stable or not. It is, however, possible to assess the probability of stability. To do this, we need to determine a threshold value of Q_t, for which the agreement is stable in year t; i.e. where both D_u and D_d are non-positive. Let $\hat{Q}$ be this threshold level. Because D_d is always negative, $\hat{Q}$ denotes the level of Q for which $D_u = 0$. From equation (9) it follows that $\hat{Q}$ depends on both u's benefit function and the punishment term and is therefore constant. We can safely assume that $\hat{Q} < E(Q_t)$ because an agreement would not be signed if $D_u \geq 0$ at the expected value of river flow. With $\hat{Q}$ known, we can express the probability of stability as $Pr[Q_t \geq \hat{Q}_t]$. Given that $f(Q)$ is the probability density function of Q, we can calculate $Pr[Q_t \geq \hat{Q}_t]$ as the area under $f(Q)$ where $Q \geq \hat{Q}$. Hence, the probability of stability of an agreement equals $1 - F(\hat{Q})$, see figure 1. In the remainder of this paper we will use this expression as our stability indicator and refer to it simply as "stability".

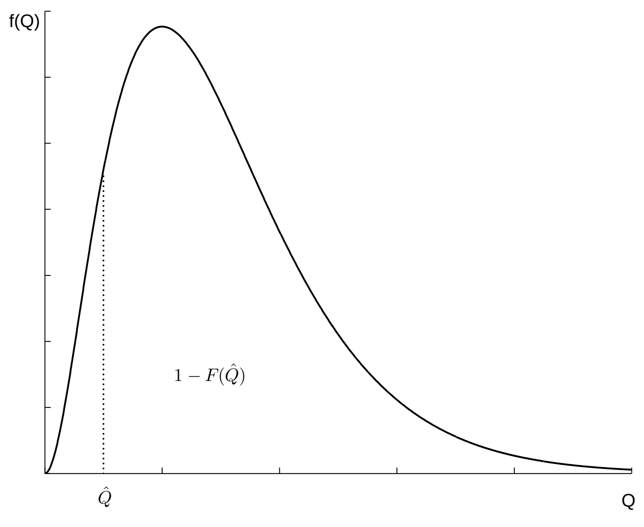


Figure 1: Stability is calculated as $1 - F(\hat{Q})$.

We are interested in probability density functions of Q without and with climate change. A comparison of the stability in each situation shows how climate change affects the stability of cooperation. Because $\hat{Q}$ is constant, we can compare stability of an agreement for $f(Q)$ (no climate change) and $f'(Q)$ (climate change). Stability in a situation with climate change is lower when $F'(\hat{Q}) > F(\hat{Q})$. Climate change is expected to affect river flow through the combined effects of changes in temperature, evaporation, soil moisture, and precipitation. Two general results of climate simulation models are (i) increased runoff variability, both within seasons and within years, and (ii) an increase of river flow in cold river basins and a decrease in warmer regions [cf. 3, 38]. For the probability distribution of Q this implies a change in the variance of river flow or a change in the mean of river flow. Their effects on stability depend on whether they affect the size of the area $1-F(\hat{Q})$. Both for a mean-preserving spread and for a decrease in mean river flow this area decreases in size, which negatively affects stability.

Result 1 *Stability of a water allocation agreement depends on the probability density function of river flow. It decreases if this density function changes by a mean-preserving spread or a decrease in mean river flow.*

We expect the stability of cooperation to be different for different sharing rules. To verify this expectation, we compare $\hat{Q}$ for the three sharing rules. In the comparison, we set $\alpha E(Q_t) = \beta = E(Q_t) - \gamma$, such that at $Q_t = E(Q_t)$ the water allocation is similar for each sharing rule. In calculating $\hat{Q}$ from equation (9) we can ignore the punishment term, because it is equal for all three sharing rules. We can also ignore $B^n_{u,t}$, because it is equal for all three sharing rules. Hence, we only have to compare cooperative benefits $B^c_{u,t}$. There are two situations when $B^c_{u,t}$ is not equal for all three sharing rules: if $Q_t < E(Q_t)$ and if $Q_t > E(Q_t)$. Because we assume that $\hat{Q} < E(Q_t)$, we only look at the situation where $Q_t < E(Q_t)$.

If $Q_t < E(Q_t)$, we have $Q_t - \gamma < \alpha Q_t < \beta$ and using equation (9) we find that $D_u^{FD} > D_u^{PA} > D_u^{FU}$ and hence $\hat{Q}^{FD} > \hat{Q}^{PA} > \hat{Q}^{FU}$. Because stability is defined as $1 - F(\hat{Q})$, we observe that stability is highest for FU and lowest for FD. This result is a direct consequence of the amount of risk connected to low flows that is allocated to u. For FU, this risk is minimized as u receives a fixed amount of water, constrained only by the amount of river flow available. For FD, the risk is maximized because if river flow decreases by one unit, the allocation to u may also decrease by one unit. For PA, the risk lies somewhere between those of FU and FD.

Result 2 *Stability of a water allocation agreement depends on the sharing rule. It is higher for fixed upstream allocation than for proportional allocation and lowest for fixed downstream allocation.*

Taking a closer look at FU, we find that D_u is maximized at $Q_t \geq \bar{q}_{u,t}$. To see this, using equation (9), note that we can ignore the punishment term because it is constant. Hence, we consider the maximization problem:

$$\max_{q_{u,t}} B^n_{u,t} - B^c_{u,t} \tag{11}$$

for FU. There are three possibilities:

1. if $Q_t < \beta < \bar{q}_{u,t}$ then $q^n_{u,t} = Q_t$ and $q^c_{u,t} = Q_t$;

2. if $\beta < Q_t < \bar{q}_{u,t}$ then $q^n_{u,t} = Q_t$ and $q^c_{u,t} = \beta$;

3. if $\bar{q}_{u,t} \leq Q_t$ then $q^n_{u,t} = \bar{q}_{u,t}$ and $q^c_{u,t} = \beta$.

Clearly, in the last situation, equation (11) is maximized. We argue that the last situation includes $Q_t = E(Q_t)$, because we assume that $\bar{q}_{u,t} \leq E(Q_t)$.

This assumption is based on the idea that in the short term, u's economy and infrastructure are not designed to abstract and use (much) more water than is expected in a given year.[3] Because we may assume that $D_u < 0$ for $Q_t = E(Q_t)$, we know that $D_u < 0$ for any level of Q_t. It follows that $\hat{Q}$ does not exist for FU. Hence $1 - F(\hat{Q})$ equals one; FU is stable.

Result 3 *Water allocation agreements with fixed upstream allocation are stable for any level of river flow.*

Because FU is stable for any level of river flow, we will focus on PA and FD only in the next section.

4 Numerical example

To illustrate the results of the model, we use the following numerical example:

$$B_{i,t} = aq_{i,t} - bq_{i,t}^2 \qquad E(Q_t) = 40$$
$$a = 80 \qquad \alpha = 0.5$$
$$b = 1.5 \qquad \beta = 20$$
$$\delta = 0.95 \qquad \gamma = 20$$
$$n = 5 \qquad \epsilon = 0.5$$

The values for α, β, and γ are chosen such that at $Q_t = E(Q_t)$ the water allocation is similar for each sharing rule. Because the countries have symmetric benefit functions, the allocation is optimal when $Q_t = E(Q_t)$.[4] Further-

[3] If $\bar{q}_{u,t} \gg E(Q_t)$, FU is unstable for Q_t large enough.

[4] Because the countries have symmetric benefit functions in this example, PA will provide a more efficient allocation than FU or FD when climate change effects occur: the total benefits of water use are maximized. This property of the model is similar to results from efficiency studies that were surveyed in the introductory section of this paper [cf. 8].

more, for each sharing rule, cooperation is attractive to both countries for $Q_t = E(Q_t)$, because countries would never agree to cooperate if there was no expected gain from cooperation.

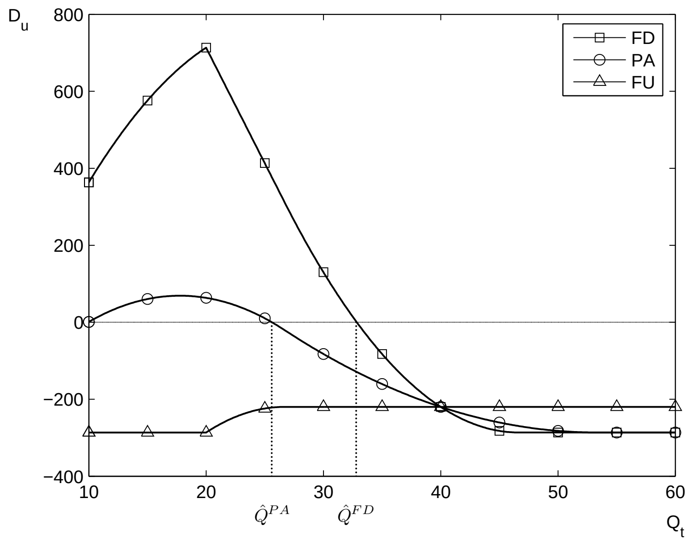
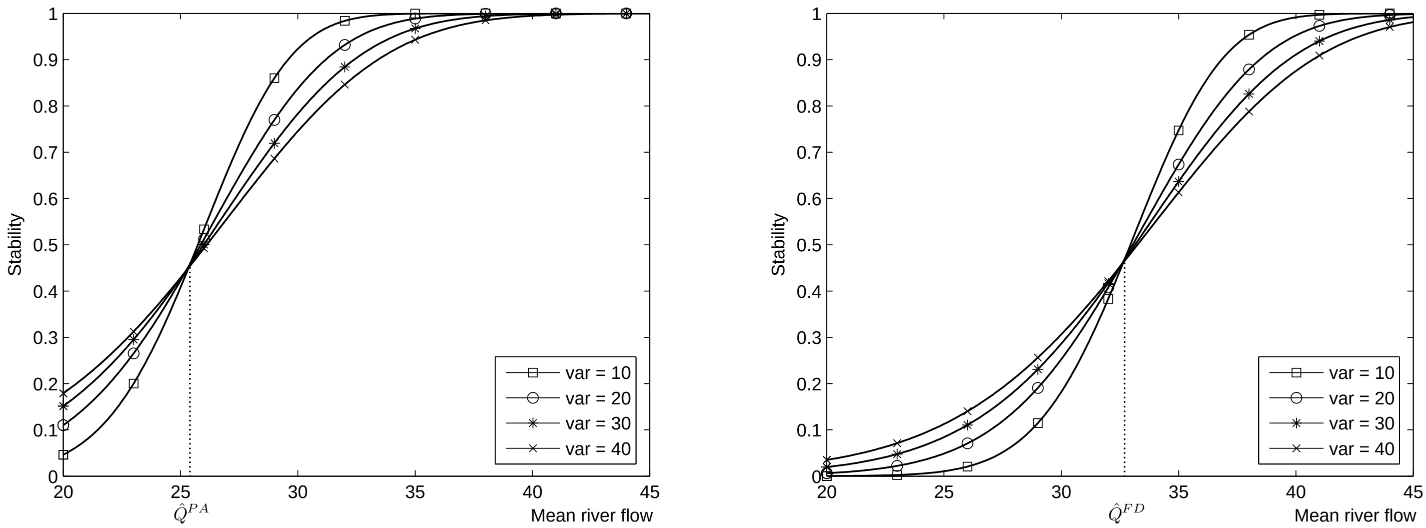


Figure 2: D_u (NPV of deviating to u) for different levels of Q_t and different sharing rules.

Figure 2 plots D_u for different levels of Q_t, for the three sharing rules. Two interesting aspects can be observed in figure 2. First, looking at the FU curve, we can observe that indeed $D_u < 0$ for any level of Q_t and that D_u is maximized at $Q_t \geq \bar{q}_{u,t}$. Second, we observe that the point where the FD curve crosses the horizontal axis ($\hat{Q}^{FD} = 32.9$) lies to the right of the point where the PA curve crosses the horizontal axis ($\hat{Q}^{PA} = 25.6$), hence, PA is more stable than FD. The decrease of D_u for Q_t less than ±20 is caused by the decreasing gain of deviation relative to the punishment.

The stability of cooperation depends on the probability distribution of Q. In this example we use the gamma distribution to describe $f(Q)$ and $f'(Q)$, which is an appropriate and commonly applied distribution in the literature on probabilistic hydrological forecasting [9, 33].

The effect of a change in the mean or variance of river flow on the stability of cooperation is shown in figure 3, for both PA and FD. The mean river flow refers to the mean of $f'(Q)$, the probability density function of Q_t when climate change effects occur.[5] Two interesting aspects can be observed in figure 3. First, the figure illustrates for selected levels of mean and variance that FD is less stable than PA. Second, when the mean flow is higher than $\hat{Q}_t$—which seems realistic given that $E(Q) = 40$—both a decrease in mean river flow and an increase in variance of river flow decreases stability.



(a) Proportional allocation

(b) Fixed downstream allocation

Figure 3: Stability ($1 - F(\hat{Q})$) of an agreement when climate change affects the mean river flow or the variance of river flow. Mean and variance are based on $f'(Q)$, the probability density function of Q_t when climate change effects occur.

[5]The calculation of expected benefits is still based on $E(Q) = 40$—the mean of the original probability density function $f(Q)$—because the agreement will not be immediately adapted at the first signs of climate change effects on river flow. Governments need reliable information before they are willing to change conditions of this type of agreements; long-term observations are needed before a change in the probability distribution of river flow can be assessed.

5 Punishment and asymmetry

In this section, we assess the effects on stability of two interesting factors: alternative punishment strategies, and asymmetry in benefit functions and political power. For both factors we assess how they affect stability.

5.1 Alternative punishment strategies

We have argued that the only possible punishment for deviation by the other country is a trigger strategy of non-cooperative play for p periods. Variations on this type of punishment are possible. A first example is tit-for-tat, where the period of punishment depends on the behaviour of the other country. If u deviates p consecutive years, the punishment period is also p years. A second example is a grim trigger strategy where the period of punishment is infinite. Both strategies and other variations, however, are similar to the strategy described above, with $p = 1$ and $p = \infty$ respectively.

More interesting punishment strategies may arise when the issue of water allocation is linked to an other transboundary issue between the two countries [18]. In the game on water allocation, d is the country that benefits most from cooperation. For issue linking to be most effective, this game should be linked to a game where u can benefit more than d [25], a good example of which is the facilitation of river transport by d to u. It is clear that the punishment term may increase when the two games are linked, as long as the benefits of river navigation to u are sufficiently large.

From these examples it becomes clear that alternative punishment strategies change the size of the punishment term (denoted by θ). To assess the effect of alternative punishment strategies, we take the derivative of equation (9) with respect to this term:

$$\frac{\partial D_u}{\partial \theta} = 1 \tag{12}$$

An increase of θ leads to a similar increase of D_u, decreasing the stability for each level of river flow.[6] This result holds for each sharing rule. The implication of this result is that for any agreement, the higher the absolute value of the punishment term, the higher the stability of cooperation.

5.2 Asymmetry

We consider both asymmetry in political power and asymmetry in benefit functions.

Asymmetry in political power As exemplified by the Nile basin and described by LeMarquand [30], the distribution of political power has implications for the incentives for cooperation. In this model, we can incorporate this aspect through the level of ϵ, which we define here to be a measure of political power for the upstream country. When benefit functions are symmetric, Kilgour and Dinar [27] have shown that in an efficient situation, the surplus benefit is equally shared between the two countries; in our model this implies that $\epsilon = 0.5$.

When $\epsilon < 0.5$, d has more political power than u and therefore a stronger bargaining position. As a result, the non-water transfer from d to u is lower than in a situation with equally distributed political power. To assess the effect of political power on stability, we take the derivative of equation (9)

[6] Note that θ is negative, so an increase of θ is a lower punishment.

with respect to ϵ:

$$\begin{aligned}\frac{\partial D_u}{\partial \epsilon} &= \sum_{\tau=t+1}^{t+p} \delta^{\tau} \left[-\frac{\partial m^c}{\partial \epsilon} \right] \\ &= \sum_{\tau=t+1}^{t+p} \delta^{\tau} E\left[\left(B^n_{d,\tau} + B^n_{u,\tau} \right) - \left(B^c_{d,\tau} + B^c_{u,\tau} \right) \right] < 0 \end{aligned} \tag{13}$$

Equation (13) yields a negative value because for d, the expected cooperative benefits outweigh the expected non-cooperative benefits. An increase of ϵ leads to a decrease of D_u, increasing the stability for each level of river flow. This result holds for each sharing rule. The implication of this result is that for any agreement, the larger the political power of u relative to the political power of d, the higher the stability of cooperation. The intuition behind this result is that when ϵ is high, the non-water transfer is high, and therefore cooperation is attractive to u. Changes in the distribution of political power after an agreement has been signed have no effect on stability because the effect of ϵ on D_u works via m^c, which has been fixed.

Asymmetry in benefit functions Asymmetry in benefit functions between countries is assessed using the same functional form of the benefit function as the one introduced in section 4. The effect of asymmetric benefit functions is simulated by scaling u's benefit function by a factor η. Hence, $B_{u,t} = \eta \left(a q_{u,t} - b q^2_{u,t} \right)$ and $B_{d,t} = a q_{d,t} - b q^2_{d,t}$. To assess the effect on stability, we analyse how η affects D_u by taking the derivative of equation (9) with respect to η:

$$\begin{aligned}
\frac{\partial D_u}{\partial \eta} &= \frac{\partial B^n_{u,t}}{\partial \eta} - \frac{\partial B^c_{u,t}}{\partial \eta} + \sum_{\tau=t+1}^{t+p} \delta^\tau \left[\frac{\partial E(B^n_{u,\tau})}{\partial \eta} - \frac{\partial E(B^c_{u,\tau})}{\partial \eta} - \frac{\partial m^c}{\partial \eta} \right] \\
&= \left(aq^n_{u,t} - b(q^n_{u,t})^2\right) - \left(aq^c_{u,t} - b(q^c_{u,t})^2\right) \\
&\quad + \sum_{\tau=t+1}^{t+p} \delta^\tau E\left[\left(aq^n_{u,\tau} - b(q^n_{u,\tau})^2\right) - \left(aq^c_{u,\tau} - b(q^c_{u,\tau})^2\right)\right] \\
&\quad - (1-\epsilon) \sum_{\tau=t+1}^{t+p} \delta^\tau E\left[\left(aq^n_{u,\tau} - b(q^n_{u,\tau})^2\right) - \left(aq^c_{u,\tau} - b(q^c_{u,\tau})^2\right)\right] \\
&= \left(aq^n_{u,t} - b(q^n_{u,t})^2\right) - \left(aq^c_{u,t} - b(q^c_{u,t})^2\right) \\
&\quad + \epsilon \sum_{\tau=t+1}^{t+p} \delta^\tau E\left[\left(aq^n_{u,\tau} - b(q^n_{u,\tau})^2\right) - \left(aq^c_{u,\tau} - b(q^c_{u,\tau})^2\right)\right] > 0 \qquad (14)
\end{aligned}$$

Equation (14) yields a positive value because for u, the non-cooperative benefits outweigh the cooperative benefits, both at current and expected levels of river flow. An increase of η leads to an increase of D_u, decreasing the stability for each level of river flow. This result holds for each sharing rule. The implication of this result is that for any agreement, the higher the benefits of water use to u compared with those to d, the lower the stability of cooperation.

Changes in η after an agreement has been signed can also be calculated. Such a change may occur because of demographic or economic developments. This effect does not influence m^c, because m^c has been fixed in the agreement. Therefore, to assess the effect on stability, we analyse how η affects D_u by taking the derivative of equation (9) with respect to η, similar to equation (14), but assuming that m^c is fixed:

$$\frac{\partial m^c}{\partial \eta} = 0 \qquad (15)$$

Combining equations (14) and (15) gives:

$$\frac{\partial D_u}{\partial \eta} = \left(aq^n_{u,t} - b(q^n_{u,t})^2\right) - \left(aq^c_{u,t} - b(q^c_{u,t})^2\right) + \sum_{\tau=t+1}^{t+p} \delta^\tau E\left[\left(aq^n_{u,\tau} - b(q^n_{u,\tau})^2\right) - \left(aq^c_{u,\tau} - b(q^c_{u,\tau})^2\right)\right] > 0 \quad (16)$$

Equation (16) also yields a positive value. An increase of η after an agreement has been signed leads to an increase of D_u, decreasing the stability for each level of river flow. This result holds for each sharing rule. The implication of this result is that for any agreement, if benefits to u increase after the agreement has been signed, the stability of cooperation decreases.

6 Discussion

The analysis presented here shows that climate change affects the stability of water allocation agreements. The precise effect on stability depends on (i) the characteristics of the river basin: its hydrological regime and the effects of climate change on river flow, and (ii) the characteristics of the agreement: in particular the sharing rule, the countries' benefit functions, and the distribution of political power. Because the results show that stability decreases when water becomes more scarce, this result is mostly relevant for arid regions. It is less relevant for humid regions and not relevant for regions facing (only) water quality issues: the impact of climate change on water quality is too complicated in hydrological terms to be captured in a simple model as the one presented here.

To show how the results can be used we discuss existing water allocation agreements in three river basins, the Nile river basin, the Orange river basin, and the South Saskatchewan river basin. For each agreement we identify some key characteristics. Based on these characteristics, we provide conclusions on the stability of these agreements, building on the results of this paper.

Nile river basin The Nile river basin knows cooperation in water allocation between Sudan (upstream) and Egypt (downstream), in the form of the Nile Waters Agreement, signed in 1929 and 1959. Although the vast majority of river flow is generated in Ethiopia, a lack of infrastructure and a dispute on its historical rights makes that Ethiopia hardly uses Nile water, leaving the majority for Egypt and Sudan. The average available river flow of 74 000 million cubic meters per year (MCM/yr) is allocated using a sharing rule that mixes fixed and proportional allocations [35]. Based on acquired rights, 48 000 MCM/yr is allocated to Egypt and 4 000 MCM/yr to Sudan. Of the remaining flow, 34% is allocated to Egypt and 66% to Sudan. In an average year this gives Egypt 55 500 MCM/yr. Because almost 90% of this expected allocation is fixed, we can safely consider this a FD sharing rule.

Egypt, being the downstream country, is not paying a non-water transfer to Sudan. In 1959, Egypt paid Sudan a one-time transfer of 15 million Egyptian Pounds compensation for increased storage in the Sudd el Aali reservoir that was required in the agreement [35]. Until 1977, however, Sudan could not fully use its entitlement, so it decided to make "water loans" to Egypt of up to 1 500 MCM/yr until 1977. This is the first of two factors that might explain why Egypt is not paying Sudan anything for passing through the majority of the Nile water; non-water transfers equal zero. The second factor is the distribution of political power in the Nile basin. It is evident that Egypt is the strongest country in the Nile basin, in political, economic and military terms. In fact, the military threat that Egypt poses to Sudan can be viewed as an equivalent to a non-water transfer [cf. 24].

Agriculture is the main water using sector in both Egypt and in Sudan. Because developments in irrigation techniques are nearly complete in Egypt, while Sudan still lacks the resources to expand its irrigated area [42], average yields are much higher in Egypt [16]. Hence, benefits of water use are higher in Egypt than in Sudan.

Studies of climate change effects on the hydrology of the Nile river basin find different results. Some models predict decreases while others predict increases in river flow [22]. Arnell [2] and Voss et al. [40] predict that the expected increase of precipitation exceeds the effect of the expected increase of evaporation in the Nile basin, resulting in a small increase of river flow by 2050. Results of a study by Arora and Boer [4], by contrast, show a decreased annual mean flow. Effects on the variance of river flow are indeterminate.

Putting these observations into the perspective of the model developed in this paper, we can conclude that the stability of cooperation in the Nile basin between Egypt and Sudan is negatively affected by its FD sharing rule. A second negative effect on stability is Egypt's high political power compared to Sudan. A positive effect on stability is Egypt's high benefits of water use compared to those of Sudan. The stability of this agreement in the future depends crucially on the effects of climate change, which are uncertain. Projected increases in population growth, and possible future water claims made by Ethiopia [42] are two factors that are likely to decrease stability. Population growth will increase benefits of water use to Sudan, increasing its incentive to deviate. When, somewhere in the future, Ethiopia is also allocated a share of the Nile water, increased scarcity in Sudan and Egypt will increase Sudan's incentive to deviate even further.

Orange river basin The Orange river basin covers areas of Lesotho, The Republic of South Africa (RSA), Botswana, and Namibia. The Lesotho Highlands Water Project (LHWP), signed in 1986, concerns cooperation in the upper basin between Lesotho (upstream) and RSA (downstream) on water transfers from the Orange river (known as Senqu in Lesotho) to cover RSA water deficits. Under the agreement, Lesotho and RSA construct a number of dams, reservoirs and channel capacity that enable diversions to RSA as well as capacity to generate hydropower [39]. Lesotho receives the benefits from hydropower, while RSA receives a minimum allocation of water that increases over the years, as the project moves forward, from 57 MCM/yr in 1995 to 2 200 MCM/yr after 2020 [32]. On top of this minimum allocation, additional water is delivered to RSA when possible, using a fixed formula to calculate the water-price.

RSA pays non-water transfers to Lesotho, increasing from € 14 million in 1998, when actual deliveries started, to € 24 million in 2004, averaging € 30 000 per MCM [31]. Revenues from hydropower generation are substantial but should not be classified as non-water transfers, because Lesotho has financed this part of the project infrastructure.

Lesotho's geographical location, being completely surrounded by RSA, makes the country highly dependent on RSA. RSA has more political power and higher benefits of water use than Lesotho. The development of Lesotho's economy is cumbersome; the country cannot use all its available water resources and there are only limited plans to further develop irrigation works. Turton [39] states: *"The LHWP can, therefore, be seen as a* *viable way for Lesotho to add value to the water that would otherwise flow onto RSA's soil. . . "*.

In general, predictions of climate change effects in Southern Africa indicate reduced precipitation and an increase of evaporation [22]. There is, however, some uncertainty for the Orange river basin. Although Arnell [2] finds that there is a great reduction in runoff by the year 2050 in Southern Africa, predictions for the Orange river basin do not clearly indicate whether and how mean and variance of river flow will change [21]. Nevertheless, current river flow in the Orange river basin knows already large variability [14].

Putting these observations into the perspective of the model developed in this paper, we can conclude that the stability of cooperation in the Orange river basin between Lesotho and RSA could be negatively affected by its FD sharing rule, but it is not, because Lesotho's demand for water lies far below its available resources. Positive effects on stability are provided by (i) the hydropower benefits that Lesotho generates within the project, (ii) Lesotho's dependence on revenues from RSA's non-water transfers, and (iii) RSA's high benefits of water use compared to Lesotho. The stability of this agreement in the future can only be affected by climate change if Lesotho's economy develops such that its demand for water increases sharply.

South Saskatchewan river basin The South Saskatchewan river is shared by the Canadian provinces of Alberta (upstream) and Saskatchewan (downstream). Although the river basin is not an international one, the provinces in Canada have a high level of autonomy, which allows for a discussion of our results. The Master Agreement on Apportionment provides guidelines for the sharing of the waters of eastward flowing inter-provincial streams, including the South Saskatchewan river. The agreement comprehends a proportional allocation of the river flow, with 50% allocated to each province, subject to a mimimum flow requirement at the boundary of 42.5 m^3/s [37].

Saskatchewan is not paying a non-water transfer to Alberta. There is no need for such a transfer because up to now, water use in the South Saskatchewan river basin has not been limited by water availability. Alberta, therefore, has always met its obligation to pass on 50% of river flow. In recent years, however, water use is getting close to 50% of river flow in Alberta, partly due to Alberta's fast growing economy. Water use in Saskatchewan is much lower and increasing at a lower rate.

Two distinct trends affect water availability in the basin. On the one hand, climate change effects are projected to decrease mean river flow by 4–10% and to decrease low flow levels by 14–22% by 2046. On the other hand, the combined effects of population growth, economic growth, and increasing irrigation efficiency are projected to increase water use. With lower water availability and increasing water use, Alberta is expected to face water shortage in the coming decades [11].

Political power of Alberta and Saskatchewan, both being Canadian provinces, can be considered equal. Benefits of water use are higher in Alberta because of its larger demand for water. Putting these observations into the perspective of the model developed in this paper, we can conclude that the current stability of cooperation in the South Saskatchewan river basin between Alberta and Saskatchewan is high, because both provinces are not using their total allocation. In the coming decades, however, the 50% constraint to Alberta will become binding, giving the province an incentive to deviate. Because the agreement does not have an enforcement mechanism and no non-water transfer is being paid by Saskatchewan, Alberta is likely to deviate and use more than 50% of river flow; the agreement's stability is decreasing. Renegotiation of the treaty seems desirable, with either Alberta being allocated a larger share of river flow or, if Saskatchewan insists on its 50% share, Saskatchewan paying for its share of water.

Besides economic gain, there are other issues that influence the allocation of water to riparian countries and hence the stability of cooperation. First, as the example of the Nile river basin points out, acquired water rights can be important determinants in the allocation of river water. A sharing rule based on acquired rights is not expected to be optimal from the points of view of efficiency and stability. Second, risk aversion might play a role. A country receiving a fixed allocation faces a lower risk of flow variability than a country that receives a non-fixed allocation or a proportional allocation [cf. 8]. We expect stability to be positively affected by risk aversion as risk averse countries would appraise the certitude of cooperative benefits above non-cooperative benefits more than risk neutral countries.

Two approaches could be used to decrease the risk associated with low flows and generate more stable agreements. First, both u and d could decide to invest in reservoir capacity. When managed properly, reservoirs can provide a buffer in water supply, decreasing the dependency on river flow in low flow years. Second, a water market could be coupled to an agreement to enable water trading during low flow years [cf. 10]. Water markets can improve the efficiency of existing water allocations such that both countries would benefit. Both approaches reduce the incentive to break an existing agreement.

In theory, the use of punishment strategies enhances cooperation in a repeated game. In our model, however, punishment of u by d also decreases benefits to d, because the non-cooperative outcome gives d lower benefits than the cooperative outcome. Shortening the period of punishment is therefore always beneficial to d, which undermines its credibility of actually going to punish in case of deviation by u. It is this lack of credibility of punishment strategies that might obstruct the effective use of punishment strategies in international agreements on water allocation [12]. Ideally, punishment is implemented in a linked game, which does not affect the benefits of the punishing country. Again, the facilitation of river transport by d to u is a good example.

Mendelsohn and Bennett [34] find that the impact of climate change on the mean of river flow is a far more important determinant for efficiency than its impact on the variance of river flow. For both the Nile and Orange river basin discussed above, where model predictions on the mean river flow are not distinct, this implies that the expected efficiency of the agreement is not expected to change because of climate change. Our model suggests that, although this conclusion may hold for efficiency, it does not hold for the stability of cooperation. Stability is affected by changes in both mean and variance of river flow. Hence, both the mean and variance of river flow have to be taken into account when negotiating agreements on water allocation.

7 Conclusions

The objective of this paper is to assess the stability of water allocation agreements when climate change affects river flow. A game theoretic model is constructed that analyses the stability of cooperation in water allocation between two countries for three sharing rules. The stability of cooperation is expressed in terms of the probability that one of the two countries deviates from the specified agreement actions, given that the countries maximize their expected payoff stream (consisting of benefits of water use and non-water transfers).

Deviation from agreement actions is found unattractive to the downstream country (d) for each sharing rule. Therefore, stability only depends on the probability of deviation by the upstream country (u). Of the three sharing rules that were analysed, the fixed upstream allocation was found stable for any level of river flow (Q_t). For low levels of Q_t, however, both with fixed downstream allocation and proportional allocation, u may have an incentive to deviate. The stability of agreements with these sharing rules depends on the probability distribution of Q. Results showed that both a decrease in mean river flow and an increase in variance of river flow decrease the stability of cooperation. Agreements with PA are in general more stable than agreements with FD, because with FD, u bears a larger part of the risk connected to low flows.

In addition to the probability distribution of Q and the sharing rule, three other factors are identified to affect stability of cooperation. The stability of cooperation is higher (i) if the absolute value of the punishment term is higher, (ii) if u's political power is large relative to d's political power, and (iii) if u's benefits of water use are low relative to d's benefits.

This paper shows that the stability of water allocation agreements can be affected by climate change. This paper adds to the analysis of water allocation agreements by focusing on stability aspects, where others have focused on efficiency aspects. Where Bennett et al. [8] found that proportional allocations are more efficient in many situations, we find that proportional allocations are less stable than fixed upstream allocations. Where Mendelsohn and Bennett [34] found that the largest impact of climate change on efficiency comes from changes in the mean of river flow, we find that both changes in mean and variance affect stability. Because water allocation agreements need to be stable in order to increase the efficiency of water use, the results of this paper are important for the design of water allocation agreements and especially the selection of a sharing rule.

References

[1] Ambec, S. and Y. Sprumont (2002). Sharing a river. *Journal of Economic Theory 107*(2), 453–462.

[2] Arnell, N. W. (1999a). Climate change and global water resources. *Global Environmental Change-Human and Policy Dimensions 9*, S31–S49.

[3] Arnell, N. W. (1999b). The effect of climate change on hydrological regimes in Europe: a continental perspective. *Global Environmental Change-Human and Policy Dimensions 9*(1), 5–23.

[4] Arora, V. K. and G. J. Boer (2001). Effects of simulated climate change on the hydrology of major river basins. *Journal of Geophysical Research-Atmospheres 106*(D4), 3335–3348.

[5] Barrett, S. (1994). Conflict and cooperation in managing international water resources. World Bank Research Working Paper 1303.

[6] Beach, H. L., J. Hammer, J. J. Hewitt, E. Kaufman, A. Kurki, J. A. Oppenheimer, and A. T. Wolf (2000). *Transboundary freshwater dispute resolution: theory, practice, and annotated references*. Tokyo, Japan: United Nations University Press.

[7] Bennett, L. L. and C. W. Howe (1998). The interstate river compact: Incentives for noncompliance. *Water Resources Research 34*(3), 485–495.

[8] Bennett, L. L., C. W. Howe, and J. Shope (2000). The interstate river compact as a water allocation mechanism: efficiency aspects. *American Journal of Agricultural Economics 82*(4), 1006–1015.

[9] Bobee, B. and F. Ashkar (1991). *The gamma family and derived distributions applied in hydrology*. Water Resources Publications, Littleton, Colorado.

[10] Booker, J. and R. Young (1994). Modeling intrastate and interstate markets for Colorado river water resources. *Journal of Environmental Economics and Management 26*(1), 66–87.

[11] Bruneau, J. F. and B. Toth (2006). The impact of economic growth on water scarcity under climate change in the SSRB: a tale of three cities. Paper presented at the Climate Change and Water in the Prairies Conference, June 21–23 2006, Saskatoon, Canada.

[12] Carraro, C., C. Marchiori, and A. Sgobbi (2005). Applications of negotiation theory to water issues. Nota di Lavoro 65.2005, FEEM.

[13] Chalecki, E. L. and P. H. Gleick (1999). A framework of ordered climate effects on water resources: A comprehensive bibliography. *Journal of the American Water Resources Association 35*(6), 1657–1665.

[14] Conley, A. H. and P. H. van Niekerk (2000). Sustainable management of international waters: the Orange river case. *Water Policy 2*, 131–149.

[15] Dinar, A., M. W. Rosegrant, and R. Meinzen-Dick (1997). Water allocation mechanisms: principles and examples. World Bank Policy Research Working Paper 1779.

[16] FAO (2006). FAOSTAT data. availabe at http://www.fao.org/, last accessed May 2006.

[17] Finus, M. (2002). Game theory and international environmental cooperation: any practical application? In C. Bohringer, M. Finus, and C. Vogt (Eds.), *Controlling global warming: perspectives from economics, game theory and public choice*. Cheltenham, UK: Edward Elgar, Cheltenham, U.K.

[18] Folmer, H., P. Mouche, and S. Ragland (1993). Interconnected games and international environmental problems. *Environmental and Resource Economics 3*(4), 313–335.

[19] Giordano, M. A. and A. T. Wolf (2003). Sharing waters: post-Rio international water management. *Natural Resources Forum 27*(2), 163–171.

[20] Heintzelman, M. D. (2004). Thirsty dogs: bargaining over interstate rivers. Canadian Resource and Environmental Economics Study Group, 14th Annual Meeting.

[21] Hulme, M., R. Doherty, T. Ngara, M. New, and D. Lister (2001). African climate change: 1900-2100. *Climate Research 17*, 145–168.

[22] IPCC (2001a). *Climate Change 2001: Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

[23] IPCC (2001b). *Climate Change 2001: The scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

[24] Janmaat, J. and A. Ruijs (2006). Investing in arms to secure water. Paper presented at the International Conference on Economics of Poverty, Environment and Natural Resource Use, 17–19 May 2006, Wageningen, The Netherlands.

[25] Just, R. E. and S. Netanyahu (2000). The importance of structure in linking games. *Agricultural Economics 24*, 87–100.

[26] Kilgour, D. M. and A. Dinar (1995). Are stable agreements for sharing international river waters now possible? World Bank Policy Research Working Paper 1474.

[27] Kilgour, D. M. and A. Dinar (2001). Flexible water sharing within an international river basin. *Environmental and Resource Economics 18*(1), 43–60.

[28] Krzysztofowicz, R. (2001). The case for probabilistic forecasting in hydrology. *Journal of Hydrology 249*, 2–9.

[29] Kucukmehmetoglu, M. and J. M. Guldmann (2004). International water resources allocation and conflicts: the case of the Euphrates and Tigris. *Environment and Planning A 36*(5), 783–801.

[30] LeMarquand, D. (1977). *International Rivers: The Politics of Cooperation*. Vancouver, B.C.: Westwater Research Centre, University of British Colombia.

[31] LHDA (2005). Annual Report 2004/2005. Lesotho Highlands Development Authority.

[32] LHWP (1986). Treaty on the Lesotho Highlands Water Project between the government of the Republic of South Africa and the government of

the Kingdom of Lesotho. Lesotho Highlands Water Project, available at http://www.transboundarywaters.orst.edu/.

[33] Markovic, R. D. (1965). *Probability functions of best fit to distributions of annual precipitation and runoff*. Fort Collins, Colorado State University.

[34] Mendelsohn, R. and L. L. Bennett (1997). Global warming and water management: water allocation and project evaluation. *Climatic Change 37*(1), 271–290.

[35] NWA (1959). Agreement between the government of the United Arab Republic and the government of Sudan for the full utilization of the Nile waters. Nile Waters Agreement, available at http://www.transboundarywaters.orst.edu/.

[36] Osborne, M. J. and A. Rubinstein (1994). *A course in game theory*. MIT Press.

[37] PPWB (1969). Master Agreement on Apportionment. Prairie Provinces Water Board, available at http://www.iigr.ca/.

[38] Raisanen, J., U. Hansson, A. Ullerstig, R. Doscher, L. P. Graham, C. Jones, H. E. M. Meier, P. Samuelsson, and U. Willen (2004). European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Climate Dynamics 22*(1), 13–31.

[39] Turton, A. R. (2003). An overview of the hydropolitical dynamics of the Orange river basin. In M. Nakayama (Ed.), *International waters in Southern Africa*. United Nations University Press.

[40] Voss, R., W. May, and E. Roeckner (2002). Enhanced resolution modelling study on anthropogenic climate change: changes in extremes of

the hydrological cycle. *International Journal of Climatology 22*(7), 755–777.

[41] Wang, L. Z., L. Fang, and K. W. Hipel (2003). Water resources allocation: a cooperative game theoretic approach. *Journal of Environmental Informatics 2*(2), 11–22.

[42] Wichelns, D., J. Barry, M. Müller, M. Nakao, L. D. Philo, and A. Zitello (2003). Co-operation regarding water and other resources will enhance economic development in Egypt, Sudan, Ethiopia and Eritrea. *Water Resources Development 19*, 535–552.

[43] Wolf, A. (1998). Conflict and cooperation along international waterways. *Water Policy 1*(2), 251–265.

[44] Wu, X. and D. Whittington (2006). Incentive compatibility and conflict resolution in international river basins: a case study of the Nile basin. *Water Resources Research 42*, W02417.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:

http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm
http://www.ssrn.com/link/feem.html
http://www.repec.org
http://agecon.lib.umn.edu
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2007

NRM	1.2007	*Rinaldo Brau, Alessandro Lanza, and Francesco Pigliaru*: How Fast are Small Tourist Countries Growing? The 1980-2003 Evidence
PRCG	2.2007	*C.V. Fiorio, M. Florio, S. Salini and P. Ferrari:* Consumers' Attitudes on Services of General Interest in the EU: Accessibility, Price and Quality 2000-2004
PRCG	3.2007	*Cesare Dosi and Michele Moretto*: Concession Bidding Rules and Investment Time Flexibility
IEM	4.2007	*Chiara Longo, Matteo Manera, Anil Markandya and Elisa Scarpa*: Evaluating the Empirical Performance of Alternative Econometric Models for Oil Price Forecasting
PRCG	5.2007	*Bernardo Bortolotti, William Megginson and Scott B.* Smart: The Rise of Accelerated Seasoned Equity Underwritings
CCMP	6.2007	*Valentina Bosetti and Massimo Tavoni*: Uncertain R&D, Backstop Technology and GHGs Stabilization
CCMP	7.2007	*Robert Küster, Ingo Ellersdorfer, Ulrich Fahl* (lxxxi): A CGE-Analysis of Energy Policies Considering Labor Market Imperfections and Technology Specifications
CCMP	8.2007	*Mònica Serrano* (lxxxi): The Production and Consumption Accounting Principles as a Guideline for Designing Environmental Tax Policy
CCMP	9.2007	*Erwin L. Corong* (lxxxi): Economic and Poverty Impacts of a Voluntary Carbon Reduction for a Small Liberalized Developing Economy: The Case of the Philippines
CCMP	10.2007	*Valentina Bosetti, Emanuele Massetti, and Massimo Tavoni*: The WITCH Model. Structure, Baseline, Solutions
SIEV	11.2007	*Margherita Turvani, Aline Chiabai, Anna Alberini and Stefania Tonin*: Public Policies for Contaminated Site Cleanup: The Opinions of the Italian Public
CCMP	12.2007	*M. Berrittella, A. Certa, M. Enea and P. Zito*: An Analytic Hierarchy Process for The Evaluation of Transport Policies to Reduce Climate Change Impacts
NRM	13.2007	*Francesco Bosello, Barbara Buchner, Jacopo Crimi, Carlo Giupponi and Andrea Povellato*: The Kyoto Protocol and the Effect of Existing and Planned Measures in the Agricultural and Forestry Sector in the EU25
NRM	14.2007	*Francesco Bosello, Carlo Giupponi and Andrea Povellato*: A Review of Recent Studies on Cost Effectiveness of GHG Mitigation Measures in the European Agro-Forestry Sector
CCMP	15.2007	*Massimo Tavoni, Brent Sohngen, and Valentina Bosetti*: Forestry and the Carbon Market Response to Stabilize Climate
ETA	16.2007	*Erik Ansink and Arjan Ruijs*: Climate Change and the Stability of Water Allocation Agreements

(lxxxi) This paper was presented at the EAERE-FEEM-VIU Summer School on "Computable General Equilibrium Modeling in Environmental and Resource Economics", held in Venice from June 25th to July 1st, 2006 and supported by the Marie Curie Series of Conferences "European Summer School in Resource and Environmental Economics".

2007 SERIES	
CCMP	*Climate Change Modelling and Policy* (Editor: Marzio Galeotti)
SIEV	*Sustainability Indicators and Environmental Valuation* (Editor: Anil Markandya)
NRM	*Natural Resources Management* (Editor: Carlo Giupponi)
KTHC	*Knowledge, Technology, Human Capital* (Editor: Gianmarco Ottaviano)
IEM	*International Energy Markets* (Editor: Matteo Manera)
CSRM	*Corporate Social Responsibility and Sustainable Management* (Editor: Giulio Sapelli)
PRCG	*Privatisation Regulation Corporate Governance* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*