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Hot Stuff: Would Climate Change Alter Transboundary Water Sharing Treaties?

Stefan Ambec* and Ariel Dinar†‡

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Abstract

By signing an international river sharing agreement (RSA), countries voluntary commit to release water in exchange for a compensation. We examine the robustness of such commitments to reduced water flows. We focus on RSAs that satisfy core lower bounds and fairness upper bounds. We characterize the constrained upstream incremental RSA as the core and fair RSA that is sustainable during the most severe droughts. It assigns to each country its marginal contribution to its followers, up to its maximal benefit from water extraction. It lexicographically maximizes the welfare of the most upstream countries in the set of core and fair RSAs. Its mirror image, the downstream incremental RSA, is not sustainable to drought at the river source.

Keywords: international river agreement, water, stability, core, fairness, global warming.

JEL codes: D74, Q25, Q28, Q54.

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1 Introduction

It has already been realized that the "global mean net effect of climate since 1750 has been one of warming" (IPCC 2007:3). The higher world temperatures are expected to increase the hydrological cycle activity, leading to a general change in precipitation patterns and increase in evapotranspiration. There is also high confidence that many semi-arid areas (e.g. Mediterranean region, western United States, southern Africa and northeast Brazil) will suffer a decrease in water resources due to climate change (Bates et al. 2008). A recent World Bank report (Alavian et al. 2009: xvii) summarizes state of the art projections for the 21st century in precipitation and droughts as follows: Increase (about 2% C) in total precipitations. High-latitude areas are generally projected to increase, while low-latitude areas are projected to decrease. Patterns are complex.

The hydrology of river basins is sensitive to changes in climatic conditions. Anthropogenic-induced climate change is expected to affect water resource cycles significantly. However, the stochastic nature of the changes in the water cycle is uncertain. As a result, much of the work by hydrologists, planners, engineers, and economists has globally been brought to the forefront in an attempt to assess the vulnerability of water supply systems to climate change and variability (Frederick, Major and Stakhiv 1997; Frederick 2002; Smith and Mendelsohn 2006; Miller and Yates 2005).

The present paper goes one step further by addressing the vulnerability of international water-sharing agreements to climate change. International basins that are shared by two or more countries are governed by treaties that allocate water among the riparian countries. Most treaties signed so far are determined by fixed allocation of the long-term flow based on historical data. Climate change is likely to modify long-term flow leading to reduced water supply. However, the magnitude of the future water shortage is uncertain and still debated among scientists. The resilience of the existing agreements based on past data to reduced water flows is an issue for the future of water management worldwide. Two global studies predict that 190/292 (Palmer et al. 2008) and 97/152 (Milly et al. 2005) of the rivers will face droughts in 2060, suggesting that the majority of the rivers they simulated may face reduction in water flows. Furthermore, Dinar et al. (2010) recorded complaints made during 1950-2005 regarding water sharing issues by states sharing international rivers. They found that a total of 112 complaints have been recorded regarding drought and floods between 1950-2005. One hundred and six of them regarding droughts and 6 regarding floods.. Several cases exist. We use the Jordan River to demonstrate the treaty fragility. While the Jordan-Israel water treaty of 1994 has mechanisms for dealing with shortages that cover a significant range of the possible shortages, there is no stated mechanism for sharing shortages, mainly in prolonged droughts and extreme shortages, when they occur. This was the case in the 1998-2000 drought. Israel stated that it would not be possible to allow Jordan its water allocation according to the agreement, and it would have to reduce it (Haddadin, 2002). Based on all the above, we focus our analysis on the water scarcity rather than on a water-abundant projection of change in future water flows. To address such issues in the paper, we analyze the design of river-sharing agreements based on mean flows, and their sustainability to unpredicted reduced water flows. We depart from the river sharing problem introduced by Ambec and Sprumont (2002) and extended by Ambec and Ehlers (2008). We first study a cooperative game in which countries negotiate a river sharing agreement (RSA) based on mean flows. It specifies an allocation of water and transfers among countries. The mean flow can be computed from historical data or from scientific assessment. In a negotiation among sovereign countries, the agreement should be accepted in a voluntary manner. In particular, countries are free to refuse any water sharing agreement at the river basin level if they are better off signing agreements with a partial number of riparians. To be accepted by all countries, the RSA should make any group of countries better-off than with any other partial agreement (including no agreement at all). In other words, it should be in the core of the cooperative game associated with the river sharing problem.

Many river sharing agreement are in the core. One is the so-called downstream incremental introduced by Ambec and Sprumont (2002). It assigns to any country its marginal contribution to the set of predecessors in the river. Doing so, it maximizes lexicographically the welfare of the most downstream countries in the river in the set of core river sharing agreements. It thus favors downstream countries against upstream countries. We consider the river sharing opposite to the downstream incremental: the upstream incremental that assigns to each country its marginal contribution to its followers in the river. We show that it might not be in the core. We then posit a slight modification of the upstream incremental RSA by binding upward the welfare of countries. The welfare of any country is limited to its highest benefit from water extraction. That is the welfare it could achieve if it could extract as much water as it wants. The motivation for this upper bound on welfare is a fairness principle. Since by definition of water scarcity, it is impossible to assign the highest benefit from water extraction to all countries, by solidarity, no country should get strictly more than its highest benefit. The so-called constrained upstream incremental RSA assigns to any country its marginal contribution to its followers on the river, provided that it is lower than its highest benefit from water extraction. If not, the country obtains its highest benefit from water consumption, and the remaining welfare is transferred to the next downstream country in the river. We show that the constraint upstream incremental distribution is a core RSA. Both the downstream incremental and the constrained upstream incremental RSA turn out to satisfy two criteria that make them attractive for riparian countries: the core lower bounds and the fairness upper bounds.

We then examine the vulnerability of core and fair RSAs to defection in case of drought. A RSA agreement specifies some amount of water to be released in exchange for transfers. With water flows lower than mean, a country is obliged to consume less than its water allocation under the RSA in order to fulfill its commitment. Yet the payment it receives from the amount of water released is unchanged. With water being more valued by countries in case of drought, a country might be better off by not releasing the amount of water it committed, although at a cost of not getting the transfer from downstream countries. For a given level of reduced flow, a RSA is sustainable to some reduced water flows if no country chooses to defect by not releasing water. Among all core and fair RSAs, the constrained upstream incremental RSA is the most sustainable one in the sense that it maximizes the range of reduced flows for which no country defects. By maximizing payment for water released, it avoids defection in case of drought as much as possible. In contrast, since it assigns the lowest payment for water released, the downstream incremental RSA is the less sustainable core and fair RSA. It is indeed not sustainable to drought for the first country in the river.

The economic literature includes several works that focus on various aspects of international water sharing issues and their stability in a basin setting. Several studies analyze river sharing agreements but with deterministic water flows (Ambec and Sprumont, 2002; Ambec and Ehlers 2008). The impact of different water availability levels on stability of cooperation is assessed, using different approaches. Beard and McDonald (2007) assess the consistency of water allocation agreements over time if negotiations are held periodically with known flow prior to the negotiation. In a stylized model of two regions, wet and arid, Janmatt and Ruijs (2007) suggest that storage could enhance water scarcity, if upstream and downstream riparian countries find a beneficial allocation to sustain it. They find that the collaboration potential is greater in arid than in wet regions, but that there is little scope for capturing the gains from basin-level management if economic integration does not extend beyond water issues.

Yet, others introduce the water supply variability into their analysis. Kilgour and Dinar (2001) review several sharing rules that are common in international water treaties and demonstrate how they may not meet the treaty parameters under increased water variability. Alternative sharing rules are suggested and their sustainability is demonstrated, using the case of the annual flow of the Ganges River at Farkka, the flash point between India and Bangladesh. Focussing on interstate river compacts in the United States, Bennett et al. (2000) compare the efficiency of fixed versus proportional allocation of water with variable water flow. They compute the optimal fixed water allocation taking into account flow variability, whereas, here we consider fixed water allocation based on mean flow. They do not address the issue of sustainability in case of drought, since the federal government has coercive power to enforce interstate compacts. Ansink and Ruijs (2008) compare the performance of fixed and proportional agreements regarding their sustainability to reduce water flow. They rely on a two-country repeated game approach with self-enforcement constraints. Both types of agreements share the same division of welfare which translates into a payment from the downstream country to the upstream country. The authors show that fixed agreements are less sustainable than proportional agreements. Our paper departs from the last study in two features. First, we do not compare the performance of different types of agreements with similar exogenous surplus sharing rules (i.e. transfers) among countries. We rather focus on fixed agreement but endogenize the surplus sharing rule. We want to identify the surplus sharing rule (or equivalently the transfers among countries) that is more sustainable to drought. Our paper is thus more on the *design* of fixed water sharing agreements than on the comparison of different types of agreements. It aims to recommend transfers that are less vulnerable to defection in case of drought. Second, we do not restrict our analysis to bipartite agreements. We consider a river shared by $n \geq 2$ countries. Doing so, we allow for partial agreements in the river basin and coalition deviations during the negotiation. We also highlight the importance of the spatial structure in a river sharing problem. As suggested by Dinar (2008), geography is an important aspect that explains many of the outcomes of treaty stability as affected by water supply variability. We address the geography aspect in the design of the RSA.

The paper proceeds as follow. We introduce the model in Section 2. We analyze the design of river sharing agreements in Section 3. In particular, we define the constrained upstream incremental river sharing agreement. We show that it is in the core and it is fair. In Section 4, we study the vulnerability of river sharing agreements to defection in case of drought. We show that the constrained upstream incremental river sharing agreement is the more sustainable river sharing agreement among those that are fair and in the core. We conclude the paper with an illustrative example.

2 The river sharing problem

A set $N = \{1, ..., n\}$ of countries are located along a river and share its water. We identify countries by their locations along the river and number them from upstream to downstream: $i < j$ means that i is upstream to j. A coalition of countries is a non-empty subset of N. Given two coalitions S and T, we write $S < T$ if $i < j$ for all $i \in S$ and all $j \in T$. Given a coalition S, we denote by $\min S \equiv \min_i S$ and $\max S \equiv \max_i S$, respectively, the smallest and largest members of S, i.e. $S = \{minS, ..., maxS\}$. Let $Pi = \{1, \ldots, i\}$ denote the set of predecessors of country i and $P^0 i = Pi \backslash \{i\}$ denote the set of strict predecessors of country i. Similarly, let $Fi = \{i, i+1, \ldots, n\}$ denote the set of followers of country i and let $F^0 i = Fi \backslash \{i\}$ denote the set of strict followers of i. A coalition S is connected if for all $i, j \in S$ and all $k \in N$, $i < k < j$ implies $k \in S$. For any n-dimension vector $y = (y_i)_{i \in N}$, we denote by $y_S = (y_i)_{i \in S}$ the vector of its components in S for any arbitrary $S \subset N$.

Each country $i \in N$ enjoys a benefit $b_i(x_i)$ from diverting x_i units of water from the river. We assume that the benefit function b_i is differentiable for all $x_i > 0$ and strictly concave. Furthermore, $b'_i(x_i)$ goes to infinity as x_i approaches 0 and there exists a satiation point $\hat{x}_i > 0$ such that $b'_i(\hat{x}_i) = 0$. In other words, $\hat{x}_i$ is country i's optimal water diversion and if it diverts more than $\hat{x}_i$, then it incurs a marginal loss (compared to diverting $\hat{x}_i$) from over-diversion.[1]

[1] The interpretation of a loss in the case of over diversion can be explained as damages of floods, which is the other extreme of the distribution of the annual flow. The hydrologic explanation to such damages is that the infrastructure in country i is fixed in the short run and cannot accommodate the extra amount of water.

Each country $i \in N$ controls a flow of water $e_i \geq 0$ with $e_1 > 0$ at the river source. It includes water supplied by tributaries or stored in a reservoir controlled by i. Moreover, it also includes the water flow that is not needed by upstream countries. More precisely, if the natural flows of water along the river at $e' \equiv (e'_1, ..., e'_n)$ is such $\sum_{j \in Pi} \hat{x}_j < \sum_{j \in Pi} e'_j$ for at least one i then we define the vector of controlled water flow as $e = (e_1, ..., e_n)$ by proceeding as follows. Let k be the more upstream agent in N such that $\sum_{j \in Pk} \hat{x}_j < \sum_{j \in Pk} e'_j$. The flow of water controlled by k is $e_k = \hat{x}_k$ and the remaining flow $e'_k - \hat{x}_k$ is transferred to $k + 1$. The flow of water controlled by $k + 1$ is $e_{k+1} = \min\{\hat{x}_{k+1}, e'_{k+1} + e'_k - \hat{x}_k\}$. If $\hat{x}_{k+1} < e'_{k+1} + e'_k - \hat{x}_k$ then $e_{k+1} = \hat{x}_{k+1}$ and the remaining water $e'_{k+1} + e'_k - \hat{x}_k - \hat{x}_{k+1}$ is transferred to $k + 2$ and so on until reaching country n. It implies that the controlled water flows e are such that $e_i \leq \hat{x}_i$ for every $i \in N$.[2]

A feasible allocation of water is a vector $x = (x_1, ..., x_n)$, which satisfies the following resource constraints at any location i along the river for every $i \in N$:

$$\sum_{j \in Pi} x_j \leq \sum_{j \in Pi} e_j. \tag{1}$$

Countries might perform unbounded transfers among themselves. A *river sharing agreement* (RSA) based on controlled water flows $e = (e_1, ..., e_n)$ is a tuple (x, t) where $x = (x_1, ..., x_n)$ is a feasible allocation of water and $t = (t_1, ..., t_n)$ is a vector of transfers that satisfies the following budget-balance constraint:

$$\sum_{i \in N} t_i = 0.$$

Without any cooperative agreement among countries, each country diverts as much water as possible up to the satiation point. More precisely, the *free-access* exploitation of water in the river defines a non-cooperative game in which countries sequentially decide how much to extract given the available flow in the river. The sequence of extraction is defined by the localization on the river starting from country 1 to country n. At the subgame perfect Nash equilibrium of the sequential water extraction game, each country i chooses the level of extraction that maximizes its own benefit b_i, given the amount of water extracted upstream to it. Since the controlled flow

[2] While our paper focuses on one main, through border, geography, there is another important, border creator, geography, that may lead to different results. This is left for future research. For insight see Dinar S. (2008) and Kilgour and Dinar (2001).

is by definition lower than the satiated level $e_i \leq \hat{x}_i$ for every $i \in N$, each country i extracts e_i at the subgame Nash equilibrium of the free-access extraction game. Hence the free-access water allocation is simply the controlled water flow e. For instance, in the particular case of water supplied only in the river source (no tributaries), the water flow $\sum_{j=1}^{k} e_j$ is extracted in turn by several countries. Each country $i < k$ extracts its controlled share $\hat{x}_i = e_i$, country k extracts what is left $e_k \leq \hat{x}_k$ leaving nothing to downstream countries $j > k$.

As long as water is scarce at some location i (or for country i) in the sense that $\sum_{j \in Pi} \hat{x}_j < \sum_{j \in Pi} e_j$, i.e., there is not enough water to satisfy the demand of all countries upstream of i (including i), the free-access allocation of water is inefficient. Given the concavity of the benefit function and since some downstream agents get less than their optimal diversion $\hat{x}_i$, the total welfare, defined as the sum of benefits of the basin countries, can be increased if upstream countries divert less water to supply downstream agents.[3] They would agree to refrain from diverting water if they are compensated by downstream agents in some ways, e.g. through side payments. This is the idea of a water sharing agreement, in which the upstream countries agree to let more water flow in the river in exchange of some monetary from the downstream countries.[4]

In what follow we examine two aspects of river sharing agreements, namely their design based on controlled water flows e and their sustainability to reduced water flows $e' \leq e$, where the sign " $\leq$ " means $e'_j \leq e'_j$ for every $j \in N$ and $e'_i < e_i$ for one $i \in N$ at least. This change of mean flow is somehow "unexpected" in the sense that each country or group of countries considers its own welfare under mean flow as an objective function. We analyze the river sharing agreement, which is designed in a deterministic world in which the realized flow is mean flow before moving to its sustainability to water flow lower than mean flow.

[3] In practice, the above welfare improvement is potentially high, since under most known cases of cross border basins marginal value product of water in the downstream country is higher than in the upstream country. For example in the case of South Africa and Lesotho on the Orange River.

[4] An actual case is the Bishkent agreement on the Syr Darya River between Tajikistan (upstream) and Uzbekistan and Kazakhstan (downstream), where some winter water, usually used by the upstream country for creation of electricity is stored, and released only in the summer for irrigation by the downstream countries. That exchange has an agreed monetary value expressed in terms of non-renewable energy resources of gas and oil (Dinar et al. 2007).

3 The design of water sharing agreements

We first consider the design of a water sharing agreement (RSA) based on water flows e among countries, assuming that any country or group of countries is free to sign it or not. In particular, a group of countries would reject a basin-wide RSA, if it can be better off by signing its own RSA. We need to define the welfare that a coalition of countries can achieve by itself with its own sub-basin RSA. It depends on the behavior of the countries outside the coalition. For instance, a coalition can "free-ride" on outsiders' cooperation if a country upstream from the coalition agrees to release more water to supply its downstream partners. The cooperative game associated with the river sharing problem is a cooperative game with externalities. Following Ambec and Ehlers (2008), we assume that the members of a coalition expect the outsiders to play non-cooperatively when they compute their highest welfare (they do not coordinate their water extraction). More precisely, they expect that the outsiders will extract up to be satiated which is the worse that can credibly happen to coalition S as shown in Ambec and Ehlers (2008). Denoted by $v(S, e)$, this welfare is the highest that coalition S can secure by signing its own RSA with water flows e.[5]

Consider a coalition $S \subset N$. Since countries upstream to coalition S behave non-cooperatively by extracting water under free-access, each country i diverts its controlled water flow e_i. Hence, the most upstream country in S labeled as $minS$ has access to e_{minS} units of water. This first observation allows us to define the secured welfare of any connected coalition $S \subset N$:[6]

$$
\begin{aligned}
v(S,e) = \max_{x_S} \quad & \textstyle\sum_{i \in S} b_i(x_i), \\
& \text{subject to} \\
& \textstyle\sum_{j \in Pi \cap S} x_j \leq \sum_{j \in Pi \cap S} e_j \\
& \text{for every } i \in S.
\end{aligned}
$$

For a disconnected coalition S, we need to decompose S into its connected components. Let $\mathcal{C}(S) = \{T_k\}_{k=1}^{K}$ denote the set of connected components of S, i.e. $\mathcal{C}(S)$ is the coarsest partition of S such that $T_k \in \mathcal{C}(S)$ is connected for $k = 1, ..., K$ with $T_k < T_{k+1}$ for $k = 1, ..., K-1$. Members of coalition S expect that if they release some water downstream to a connected

[5]Note that $v(S, e)$ can be viewed as the payoff to coalition S in the subgame perfect equilibrium of an non-cooperative extraction game played by the coalitions in the partition $\{S, \{i\}_{i \in N \setminus S}\}$ (see Ambec and Ehlers, 2008, for a more general analysis).

[6]Recall that S is connected if for any $i, j \in S$ and all $k \in N$, $i < k < j$ implies $k \in S$.

component $T_k \in \mathcal{C}(S)$ to supply the next connected component $T_{k+1} \in \mathcal{C}(S)$, countries located in-between T_k and T_{k+1} would divert water up to their satiated level. Formally, for any water allocation x_S within S, each country $l \in N \backslash S$ outside S diverts:[7]

$$x_l^{ncS} \equiv \min\{\hat{x}_l, \sum_{j \in Pl} e_j - \sum_{i \in Pl \cap S} x_l - \sum_{k \in Pl \backslash S} x_k^{ncS}\}. \tag{2}$$

Therefore the highest welfare that any coalition of countries $S \subset N$ can secure by signing its own RSA is:

$$\begin{aligned} v(S,e) = \max_{x_S} \quad & \textstyle\sum_{i \in S} b_i(x_i), \\ & \text{subject to} \\ & \textstyle\sum_{j \in Pi \cap S} x_j \leq \sum_{j \in Pi \cap S} e_j - \sum_{k \in Pi \cap S} x_k - \sum_{l \in Pi \backslash S} x_l^{ncS}, \\ & \text{for every } i \in S. \end{aligned} \tag{3}$$

where x_l^{ncS} is defined by (2) for every $j \in N \backslash S$. The solution of (3) that we denote x_S^S is the efficient allocation of water among members of S, given that the countries outside S divert water up to their satiated level. Its computation follows a backward induction mechanism described in Ambec and Ehlers (2008). It is uniquely defined. It yields to coalition S a secured welfare of

$$v(S,e) = \sum_{i \in S} b_i(x_i^S).$$

An important property of the secured welfare v that will be useful later is its superadditivity: for any $S, T \in N$, since the water allocation (x_T^T, x_S^S) can be implemented in $T \cup S$, $v(T \cup S, e) \geq v(T,e) + v(S,e)$ for any e_N.

The secure welfare $v(N,e)$ of the "grand" coalition N is the highest total welfare that can be achieved at the basin level. The solution x^* of (3) for the grand coalition $S = N$ is the efficient allocation of the controlled flows e. It is unique and described in Ambec and Sprumont (2002) (see also Kilgour and Dinar 2001) as follows. There exists a partition $\{N_k\}_{k=1,\dots,K}$ of N and a list $(\beta_k)_{k=1}^K$ of non-negative numbers such that:

$$N_k < N_{k'} \text{ and } \beta_k > \beta_{k'} \text{ whenever } k < k'$$

$$b_i'(x_i^*) = \beta_k \text{ for every } i \in N_k \text{ and every } k = 1, \dots, K$$

[7]The definition of x_l^{ncS} applies for all l countries outside S: those upstream S, in-between two connected component of S and downstream S.

$$x_i^* \leq \hat{x}_i \text{ for all } i \in N$$

$$\sum_{i \in N_k} (x_i^* - e_i) = 0 \text{ for every } k = 1, \ldots, K-1.$$

In other words, the efficient allocation of water equalizes marginal benefits whenever possible. If not, it bounds the feasibility constraints, which defines the subsets in which marginal benefits are equals. The marginal benefit is the shadow value of water at that river location, which reflects its scarcity. Marginal benefit is decreasing when moving from one subset downstream to the next one because water is less scarce when the river is supplied by tributaries along its stream. Marginal benefits are indeed equals in rivers without tributaries or in canals supplied by a reservoir in country 1 because the same amount of water is available for all countries in the river. In this particular case, $N_1 = N$. Yet a tributary might supply say country i with water. Therefore, more water is available for country i and all countries $j > i$ downstream i. Then it might be that the feasibility constraint is binding in i. Therefore the shadow value of water and the marginal benefit of countries is higher upstream of i than downstream of i.

A coalition S of countries is better off with the basin-wide RSA (x, t) than under a partial agreement among members of S if its welfare $\sum_{i \in S}(b_i(x_i) + t_i)$ is at least what it could secure by its own $v(S, e)$. Therefore, in order to be accepted by sovereign countries, a basin-wide RSA should satisfy the following core lower bounds.[8]

Definition 1 *A RSA (x, t) associated with the river sharing problem (N, b, e) is a core RSA if and only if it satisfies the following core lower bounds for every $S \subset N$:*

$$\sum_{i \in S} (b_i(x_i) + t_i) \geq v(S, e). \tag{4}$$

The core lower bound for the "grand coalition" N at the basin level implies that the water allocation in a core RSA must be efficient. Thus the core lower bound for $S = N$ uniquely defines the allocation of water $x = x^*$. By contrast, several transfer schemes are in the core, in the sense that they satisfy the core lower bounds with the efficient allocation of water x^*. A transfer scheme defines a distribution z of the total welfare $v(N, e) = \sum_{i \in N} b_i(x_i^*)$ with

[8] The terminology borrowed from Ambec and Ehlers distinguishes between two core lower bounds: the cooperative and non-cooperative ones, depending if players outside S play cooperatively or non-cooperatively. Our core lower bounds correspond to their non-cooperative core lower bounds. The core lower bounds define the core of the cooperative game associated with the river sharing problem.

$z_i = b_i(x_i^*) + t_i$ for $i =, ..., N$. Ambec and Ehlers (2008) show that the downstream incremental distribution defined by $z_i^d \equiv v(Pi, e) - v(P^0 i, e)$ for every $i \in N$ satisfies all core lower bounds. It assigns to each country its marginal contribution to the set of predecessors. The welfare distribution z^d defines the downstream incremental transfer scheme $t_i^d \equiv v(Pi, e) - v(P^0 i, e) - b_i(x_i^*)$ for $i = 1, ..., n$. The downstream incremental RSA (x^*, t^d) is therefore in the core of the cooperative game associated with any given river sharing problem (N, b, e).

The downstream incremental RSA obviously favors downstream countries. Indeed the most downstream country n gets its marginal contribution to the total welfare $z_n^d = b(x_n^*) + t_n^d = v(N, e) - v(N \backslash \{n\}, e)$, the second one $n-1$ obtains its marginal contribution to remaining welfare $v(N \backslash \{n\}, e)$ to be shared, that is $b_2(x_2^*) + t_2^d = v(N \backslash \{n\}, e) - v(N \backslash \{n, n-1\}, e)$, and so forth up to the first country which gets its stand-alone welfare $v(\{1\}, e)$. Among the RSAs that belong to the core, the downstream incremental RSA lexicographically maximizes the welfare of n, $n-1$, ..., 1.

The RSA opposite of the downstream incremental in the set of core RSAs is the *upstream incremental* RSA. It assigns to any country i its marginal contribution to the set Fi of followers in the river. Denoted by (x^*, t^u), it divided the total welfare $v(N, e)$ by assigning $z_i^u = b(x_i^*) + t_i^u \equiv v(Fi, e) - v(F^0 i, e)$ to agent i for $i = 1, ..., n$. It defines the upstream incremental transfer scheme t^u with $t_i^u \equiv v(Fi, e) - v(F^0 i, e) - b_i(x_i^*)$ for $i = 1, ..., n$. It favors upstream countries over downstream countries by lexicographically maximizing the welfare of countries 1, 2, ..., n. The first country 1 obtains its marginal contribution to the welfare $z_1^u = b_1(x_1^*) + t_1^u = v(N, e) - v(N \backslash \{1\}, e)$, the second one $n-1$ obtains its marginal contribution to the remaining welfare $v(N \backslash \{1\}, e)$ to be shared, that is $z_2^u = b_2(x_2^*) + t_2^u = v(N \backslash \{n\}, e) - v(N \backslash \{1, 2\}, e)$, and so forth up to the last country which enjoys its stand alone welfare $v(\{n\}, e)$. Hereafter, we often omit set brackets for sets and write i instead of $\{i\}$ or $v(i, j, e)$ instead of $v(\{i, j\}, e)$.

Although the upstream and downstream RSAs are constructed in a symmetric way, surprisingly, the upstream incremental RSA fails to satisfy the core lower bounds for rivers shared by more than two countries.[9]

Proposition 1 *The upstream incremental RSA fails to satisfy the core lower bounds for* $n > 2$.

[9] It is easy to show that upstream incremental RSA satisfies the core lower bounds for $n = 2$. Indeed, it assigns $z_1^u = v(1, 2, e) - v(2, e) \geq v(1, e)$ by subadditivity of v and , $z_2^u = v(2, e)$, which imply $z_1^u + z_2^u = v(1, 2, e)$.

The above result points out the importance of satiated water consumption in the benefit functions. Indeed with always increasing and concave benefits, i.e. with $\hat{x}_i = +\infty$ for every $i \in N$, Ambec and Sprumont (2000) have shown that the cooperative game associated with the river sharing problem is convex. It implies that the upstream incremental distribution z^u satisfies all core lower bounds. Proposition 1 shows that it is not true with more general concave benefit functions with finite satiated water consumption.

To identify a RSA in the core that favors lexicographically the most upstream countries, we introduce an additional requirement. We impose that no country should enjoy a welfare higher than its satiated benefit $b_i(\hat{x}_i)$. This requirement is inspired by a fairness principle introduced by Moulin (1990) for games with externalities. Since water is scarce in the sense that not all countries can consume their satiated level and, therefore, enjoy its satiated benefit, by solidarity, no country should get strictly more than its satiated level. A country i that enjoys a strictly higher welfare than $b_i(\hat{x}_i)$ is able to extract more welfare with scarce water at the expense of the other countries. This principle defines upper bounds on countries' individual welfare.[10]

Definition 2 *A RSA (x, t) of the river sharing problem (N, b, e) is a fair RSA if and only if it satisfies the satiated benefit upper bounds:*

$$b_i(x_i) + t_i \leq b_i(\hat{x}_i) \text{ for all } i \in N. \tag{5}$$

We restrict our attention to core and fair RSAs. Ambec and Ehlers (2008) show that the downstream incremental RSA satisfies upper bounds more stringent than the satiated benefit, namely the aspiration welfare upper bounds. It is therefore fair in addition to being a core RSA. It is the RSA that maximizes lexicographically the welfare of country n, $n-1$,..., 1 in the set of fair and core RSAs. The RSA opposite of the downstream incremental RSA in the set of fair and core RSAs is the *constrained upstream incremental* RSA. It is the core and fair RSA that lexicographically maximizes the welfare of country 1, 2,..., n. Denoted with the superscript "cu", the constrained upstream incremental RSA (x^*, t^{cu}) assigns to country 1 a welfare $z_1^{cu} = b_1(x_1^*) + t_1^{cu} \equiv \min\{v(F1, e) - v(F^01, e), b_1(\hat{x}_1)\}$. If $v(F1, e) - v(F^01, e) > b_1(\hat{x}_1)$,

[10]With similar concave and single peak benefit functions but with equal access to water, Ambec (2008) has shown that the Walrasian allocation with equal division of water might assigns to some agents more than their satiated benefits. It therefore violated the below fairness upper bounds.

i.e. country 1's marginal contribution to its followers is strictly higher than its satiated benefit, the remaining welfare $r(1) \equiv \min\{z_1^{cu} - b_1(\hat{x}_1), 0\}$ is assigned to the next country in the river. Country 2 obtains $z_2^{cu} = b_2(x_2^*) + t_2^{cu} \equiv \min\{v(F2, e) - v(F^0 2, e) + r(1), b_2(\hat{x}_2)\}$. And so on and so forth for the next downstream countries. More generally, the constrained upstream incremental distribution assigns $z_i^{cu} = b_i(x_i^*) + t_i^{cu} \equiv \min\{v(Fi, e) - v(F^0 i, e) + r(i-1), b_i(\hat{x}_i)\}$ to each country $i \in N$ where $r(i-1) \equiv \min\{z_{i-1}^{cu} - b_{i-1}(\hat{x}_{i-1}), 0\}$ for every $i \in N \backslash \{1\}$ and $r(0) = 0$. The constrained upstream incremental transfer scheme t^{cu} is thus defined by $t_i^{cu} = z_i^{cu} - b_i(x_i^*)$ for $i = 1, ..., n$. It satisfies the satiated benefit upper bounds by construction. The next proposition establishes that it is a core RSA.

Proposition 2 *The constrained upstream incremental RSA* (x^*, t^{cu}) *satisfies the core lower bounds.*

We now turns to the sustainability of RSAs to reduced water flows.

4 The sustainability of water sharing agreements

We examine compliance with an RSA under reduced water flows $e' \leq e$. By signing an RSA (x^*, t), a country commits to release water against money. More precisely, country 1 commits to release $e_1 - x_1^*$ to supply downstream countries in exchange for a transfer t_1. Country 2 receives $e_1 - x_1^*$ units of water in exchange for t_1. It commits to release $e_1 + e_2 - x_1^* - x_2^*$ units of water downstream in exchange for $t_2 + t_1$. More generally, each country $i > 1$ receives $\sum_{j \in P^0 i}(e_j - x_j^*)$ units of water from upstream countries in exchange of a payment $\sum_{j \in P^0 i} t_j$. Each country $i < n$ agreed to release $\sum_{j \in Pi}(e_j - x_j^*)$ units of water to supply downstream countries in exchange for $\sum_{j \in Pi} t_j$.

The RSA (x^*, t) commits countries to release water independently of the realized water flows. When the realized water flows are mean flows $e_i' = e_i$, then country i enjoys a welfare $b_i(x_i^*) + t_i$ by fulfilling its duties providing that everyone else do the same. However, if the realized water flow e' is lower than the mean for country $i < n$, i.e. $e_i' < e_i$, then i is forced to consume less than its allocation x_i to fulfill its commitment. More precisely, from the water flow it controls $e_i' + \sum_{j \in P^0 i}(e_j - x_j^*)$, country i must release $\sum_{j \in Pi}(e_j - x_j^*)$ which limits its consumption to $e_i' - e_i + x_i^* < x_i^*$. It therefore enjoys a welfare of $b_i(e_i' - e_i + x_i^*) + t_i < b_i(x_i^*) + t_i$.

It might be tempted not to release the water it had committed to, but at a cost of renouncing to be paid by downstream countries. Doing so, it can consume $e'_i + \sum_{j \in P^0 i}(e_j - x^*_j)$ units of water. It thus achieves a welfare of $b_i(\min\{e'_i + \sum_{j \in P^0 i}(e_j - x^*_j), \hat{x}_i\})$. [11] For a given RSA (x^*, t), let us denote country i's water consumption under the realized water flow e'_i at i by

$$x'_i \equiv e'_i - e_i + x^*_i \tag{6}$$

and the water flow controlled by country i by

$$E'_i \equiv \min\{e'_i + \sum_{j \in P^0 i}(e_j - x^*_j), \hat{x}_i\} \tag{7}$$

for every $i \in N$. We assume $x'_i \geq 0$: the realized flow of water allows any country i to fulfill its duties.[12]

Definition 3 *An RSA (x^*, t) is sustainable under realized water flow $e' \leq e$ if it satisfies the following no-defection constraints for every $i \in N$:*

$$b_i(x'_i) + t_i \geq b_i(E'_i) - \sum_{j \in P^0 i} t_j.$$

The no-defection constraints insures that all countries release what they committed to. They obviously hold when the realized water flow is the mean flow $e' = e$ for any core RSA. Furthermore, the no-defection constraint for the most downstream country n always holds because it does not have to release water.[13] Symmetrically, since the most upstream country in the river does not receive any water from upstream countries, $E'_1 = e'_1$ and $\sum_{j \in P^0 1} t_j = 0$. Thus the sustainability constraint for country 1 simplifies to $b_1(x'_1) + t_1 \geq b_1(e'_1)$. In the next proposition, we show that it is violated under the downstream incremental RSA (x^*, t^d) as long as water flow controlled by 1 is reduced.

Proposition 3 *The downstream incremental RSA is not sustainable for any reduced flow $e'_1 < e_1$.*

[11] We assume that countries release water only when they are paid: a country cannot receive the water released without paying upstream countries.

[12] Otherwise defection is not a choice but an obligation.

[13] The budget balance constraint implies that $t_n = -\sum_{j \in P^0 n} t_j$ combined to $E'_n = x'_n$, leads to the same value both sides of the inequality in Definition 3.

The downstream incremental RSA is not sustainable to a drought of water controlled by country 1. Under mean flow e_1, country 1 obtains its stand-alone welfare $b_1(e_1)$ by releasing water and consuming x_1^*. More precisely, it receives a compensation $b_1(e_1) - b_1(x_1^*)$ in exchange of $e_1 - x_1^*$ units of water. Under reduced flow $e_1' < e_1$, the RSA allows country 1 to consume $x_1' = e_1' - (e_1 - x^*) < x_1^*$ in exchange for the same transfer $b_1(e_1) - b_1(x_1^*)$. If it defects, it obtains its reduced stand-alone welfare $b_1(e_1')$. However, since the marginal benefit from water consumption is decreasing (b_1 is concave), its marginal loss from water released $b_1(e_1') - b_1(x_1')$ is higher than the compensation it receives $b_1(e_1) - b_1(x_1^*)$. Having higher-value water with reduced flow, country 1 prefers to keep it rather than to release what it is committed to in exchange for the same transfer of compensation.

We are able now to establish our main result.

Theorem 1 *The constrained upstream (resp. downstream) incremental RSA is the most (resp. less) sustainable RSA in the sense that it is (resp. is not) sustainable to more severe droughts than any other core and fair RSA.*

By maximizing lexicographically the welfare of the most upstream countries, the constrained upstream incremental RSA assigns the highest compensations for water released to country 1, 2,..., n. It thus sets the "price" $\sum_{j\in Pi} t_j$ paid by a country $i+1$ to country i for the $\sum_{j\in Pi}(e_j - x_j^*)$ units of water released from upstream at the highest possible level. Doing so it minimizes the incentive for i to defect by not releasing water, making defection not profitable for some levels of droughts. On the other hand, by maximizing lexicographically the welfare of the most downstream countries, the downstream incremental RSA assigns the lowest compensations to country 1, 2,...,n. Doing so it minimizes the price paid for the same volume of water released $\sum_{j\in Pi}(e_j - x_j^*)$. In particular, the price t_1^d paid for $e_1 - x_1^*$ released by 1 to 2 is so low that country 1 prefers to defect as long as water flow is lower than the mean. The following example shows that with a compensation t_1^{cu}, country 1 still transfers $e_1 - x_1^*$ for some levels of reduced flow. That is, the constrained upstream incremental RSA is sustainable to some drought at the source while the downstream incremental RSA is not.

Example 1 Let assume $n = 2$, $b_1 = b_2 = b$, $e_2 < e_1 < \hat{x}_1 = \hat{x}_2$ and, therefore, $x_1^* = x_2^* = \dfrac{e_1 + e_2}{2}$ and the total welfare to be shared is $v(N, e) = v(1, 2, e) = 2b(\dfrac{e_1 + e_2}{2})$. Under the constraint upstream incremental RSA with mean flow, country 1 obtains $b_1(x_1^*) + t_1^{cu} =$

$v(1,2,e) - v(2,e) = 2b(\frac{e_1+e_2}{2}) - b(e_2)$. Country 1's welfare under (x^*, t^{cu}) with reduced water flow $e_1' < e_1$ is thus $b(x_1') + t_1^{cu} = b(e_1' - \epsilon) + b(x_2^*) - b(e_2)$ with $\epsilon = e_1 - x_1^*$. On the other hand, by not releasing water, country 1 obtains $b(e_i')$. The no-defection constraint holds for country 1 if $b(e_1' - \epsilon) + b(x_2^*) - b(e_2) \geq b(e_1')$, which, since $x_2^* = e_2 + e_1 - x_1^* = e_2 + \epsilon$ by the binding feasibility constraint (1), can be rewritten as

$$b(e_2 + \epsilon) - b(e_2) \geq b(e_1') - b(e_1' - \epsilon). \tag{8}$$

By concavity of b and $e_1' \geq \epsilon > 0$, a sufficient condition for (8) to hold is $e_2 \leq e_1' - \epsilon$, that is $\frac{e_1+e_2}{2} \leq e_1'$. Since $\frac{e_1+e_2}{2} < e_1$ by assumption, there exists a range of reduced water flows such that country 1 does not defect under (x^*, t^{cu}). For instance, if $e_2 = 0$, country 1 does not defect for any reduced control flow $e_1' \in [\frac{e_1}{2}, e_1]$. On the other hand, as shown in Proposition 3, country 1 defects under the downstream incremental RSA (x^*, t^d) for any reduced flow $e_1' < e_1$.

Theorem 1 sets lower bounds of reduced flow e_i' for which there exist a core RSA which is sustainable. Let us denote by $\underline{e}_i'$ the lowest water flow for which the constrained upstream incremental RSA is sustainable for every $i < n$. It is uniquely defined by the binding no-defection constraint:

$$b_i(\underline{E}_i') - b_i(\underline{e}_i') = \sum_{j \in P^0 i} t_j^{cu} = \sum_{j \in F^0 i} b_j(x_j^*) - v(F^0 i, e).$$

where $\underline{E}_i' \equiv \min\{\underline{e}_i + x^* - e_i, \hat{x}_i\}$.

Corollary 1 *A vector of reduced flows $e' \leq e$ can be sustained under an RSA based on mean flow e if and only if $e_i \geq \underline{e}_i$ for every $i > n$.*

We conclude the sustainability section with a last appealing property of the constrained upstream incremental RSA regarding efficiency. The defection of one country is efficient if the total welfare after defection can be higher than before defection. We show that the constrained upstream incremental RSA avoid inefficient defection in case of drought in one country only. Consider a drought $e' \leq e$ such that $e_i' < e_i$ for one $i < n$ and $e_j' = e_j$ for every $j \in N$. Under realized water flow e', country i controls less water than mean, whereas all other countries control mean flows. In the case of a river supplied only by the source located in country 1, country i is the last country to obtain some water under non-cooperative extraction. It experiences a reduction of the flow it controls in case of drought at the source.[14] In the case of a river with tributaries, the drought concerns only the tributary located in country i's territory. Suppose that country i defects, then $b_i(x_i') + t_i^{cu} < b_i(E_i') - \sum_{j\in P^0 i} t_j^{cu}$, which can be rewritten as

$$b_i(x_i') < b_i(E_i') - \sum_{j\in Pi} t_j^{cu}.$$

By definition of t^{cu}, $\sum_{j\in Pi}(b_j(x_j^*) + t_j^{cu}) = v(N,e) - v(F^0 i, e)$ which, substituted in the last inequality, yields:

$$b_i(x_i') < b_i(E_i') - v(N,e) + v(F^0 i, e) + \sum_{j\in Pi} b_j(x_j^*).$$

Since $v(N,e) = \sum_{j\in N} b_j(x_j^*)$, it simplifies to

$$b_i(x_i') + \sum_{j\in N\setminus i} b_j(x_j^*) < \sum_{j\in P^0 i} b_j(x_j^*) + b_i(E_i') + v(F^0 i, e). \tag{9}$$

The left side in (9) is the total welfare of river sharing with reduced water flow $e' < e$ if the RSA is still in order, while the right side in (9) is the highest total welfare if i defects by note releasing water and, therefore, countries downstream to i are on their own: they achieve at most $v(F^0 i, e)$. We therefore have established the following result.

Proposition 4 *Consider a drought at i only, i.e. $e' \le e$ such that $e_i' < e_i$ and $e_j' = e_j$ for every $j \neq i$. Then (x^*, t^{cu}) is sustainable only if defection is inefficient in the sense that it reduces total welfare.*

5 Conclusion

Scientists agree that global warming is likely to reduce water flow. Yet they disagree on the magnitude of the future water shortage. This ambiguity is not embedded in international river sharing arrangements. Most international treaties assign average water flow based on historical data to countries that have poor predictive power under climate change. Even if the forecasted average water flow is corrected by the prospected climate change, the ambiguity

[14] Recall that with no tributaries, all countries upstream $j < i$ control their satiated level $e_j = \hat{x}_j$ whereas i controls what is left e_i and all countries downstream control no water flow. We consider a drought $e' \le e$ that allows countries upstream i to control their satiated consumption level $e_j = e_j' = \hat{x}_j$ for $j < i$ whereas i experiences reduced control flow $e_i' < e_i$. All countries downstream i still control no flow.

of its magnitude makes this prediction difficult to assess. It also increases the probability of predicted average flow to be false.

By signing international river sharing treaties voluntarily, countries have a self-interest in complying with them, as long as the average water flow is as expected. Even if an agreement specifies water supply to downstream countries, a country is better off by releasing what it had committed to, since the payment it receives from downstream countries offsets its welfare loss from releasing water. This is not always the case under water drought within its territory. To release the same amount of water, the country is obliged to consume less water than average. It prefers to defect if the payment does not compensate its welfare loss from releasing water.

In this paper, we analyze the above defection strategy by countries. We characterize the river sharing agreement that is robust to defection for the most severe droughts. The so-called constrained upstream incremental river sharing agreement maximizes lexicographically the welfare of the most upstream countries in the set of acceptable river sharing agreements (in the sense of being fair and in the core). It is opposite to the downstream incremental river sharing agreement that have been put forward by the literature on the river sharing problem.

An example computed in Appendix E shows that the two agreements might not coincide. It also illustrates how the design of a river sharing agreement impacts its sustainability to water shortage. Since drought events are likely to be more frequent in the future with global warming, the vulnerability of international water treaties is becoming an important issue. The paper suggests that, with more frequent and prolonged drought, financial transfers are required (in addition to a physical allocation of water) to preserve cooperation among countries. It provides some insights on how to design those transfers to avoid water conflicts as much as possible.

A Proof of Proposition 1

The following example shows that the upstream incremental RSA fails to satisfy the core lower bounds for $n = 3$. Let us consider a river shared among three countries with identical benefit functions $b_1(a) = b_2(a) = b_3(a) = a(12 - a) = b(a)$ for every $a \in [1, 10]$ but unequal controlled water flows $e = (e_1, e_2, e_3) = (4, 6, 2)$. The satiated consumption levels are $\hat{x}_i = 6$ for a maximal benefit of $b_i(\hat{x}_i) = 36$ for $i = 1, 2, 3$. The optimal water allocation prescribes to share equally the total flow of water $e_1 + e_2 + e_3 = 12$ which requires that country 2 supplies country 3 with 2 units of water. It leads to a total welfare $v(1, 2, 3, e) = 3b(4) = 96$. The coalition $\{2, 3\}$ can secure a welfare $v(2, 3, e) = 64$ by dividing equally $e_2 + e_3 = 8$ the same way. The upstream incremental RSA assigns $z_1^u = v(1, 2, 3, e) - v(2, 3, e) = 96 - 64 = 32$ and $z_3^u = v(3, e) = b(e_3) = 20$ to countries 1 and 3 respectively. On the other hand, both countries can secure a welfare of $v(1, 3, e) = 2b(3) = 54 > 52 = z_1^u + z_3^u$ if country 1 releases one unit of water to supply country 3.$\Box$

B Proof of Proposition 2

Consider an arbitrary coalition $S \subset N$. If S is connected, the constrained upstream incremental RSA yields to coalition S a welfare

$$\sum_{i \in S} z_i^{cu} = \min \left\{ v(FS, e) - v(F^0 S, e) + r(minS - 1), \sum_{i \in S} b_i(\hat{x}_i) \right\}. \tag{10}$$

Since $FS = S \cup F^0 S$ for every S connected, by superadditivity of v, $v(FS, e) \geq v(S, e) + v(F^0 S, e)$. Moreover, $v(S, e) \leq \sum_{i \in S} b_i(\hat{x}_i)$. The last two inequalities combined with (10) and $r(j) \geq 0$ for any $j \in N$ establish $\sum_{i \in S} z_i^{cu} \geq v(S, e)$ for any connected coalition S.

Suppose now that S is not connected. Take the last country in S, which obtains some resource $l(S) = \max_i \{i \in S : x_i^S > 0\}$. If $l(S)$ does not exist, then $v(S, e) = 0 \leq \sum_{i \in S} z_i^{cu}$. Let $\bar{S} = Pl(S) \backslash P^0 \min S$ be the coalition composed by all countries from $minS$ to $l(S)$. Since $\bar{S}$ is connected then the welfare of $\bar{S}$ is

$$\sum_{i \in \bar{S}} z_i^{cu} = \min \left\{ v(F\bar{S}, e) - v(F^0 \bar{S}, e) + r(min\bar{S} - 1), \sum_{i \in \bar{S}} b_i(\hat{x}_i) \right\}$$

The last equation with $min\bar{S} = minS$ and $\sum_{i \in \bar{S}} z_i^{cu} = \sum_{i \in S} z_i^{cu} + \sum_{i \in \bar{S} \backslash S} z_i^{cu}$ implies,

$$\sum_{i \in S} z_i^{cu} = \min \left\{ v(F\bar{S}, e) - v(F^0 \bar{S}, e) + r(minS - 1), \sum_{i \in \bar{S}} b_i(\hat{x}_i) \right\} - \sum_{i \in \bar{S} \backslash S} z_i^{cu}. \tag{11}$$

Suppose first that $v(F\bar{S}, e) - v(F^0 \bar{S}, e) + r(minS - 1) \geq \sum_{i \in \bar{S}} b_i(\hat{x}_i)$. Then $\sum_{i \in S} z_i^{cu} = \sum_{i \in \bar{S}} b_i(\hat{x}_i)$. Since $z_i^{cu} \leq b_i(\hat{x}_i)$ for every $i \in \bar{S} \backslash S$, (11) implies

$$\sum_{i \in S} z_i^{cu} = \sum_{i \in \bar{S}} b_i(\hat{x}_i) - \sum_{i \in \bar{S} \backslash S} z_i^{cu} \geq \sum_{i \in \bar{S}} b_i(\hat{x}_i) - \sum_{i \in \bar{S} \backslash S} b_i(\hat{x}_i) = \sum_{i \in S} b_i(\hat{x}_i) \geq v(S, e).$$

Suppose now that $v(F\bar{S}, e) - v(F^0 \bar{S}, e) + r(minS - 1) < \sum_{i \in \bar{S}} b_i(\hat{x}_i)$. Then, since $F\bar{S} = \bar{S} \cup F^0 \bar{S}$, by superadditivity of v, $v(F\bar{S}, e) \geq v(\bar{S}, e) + v(F^0 \bar{S}, e)$ which, combined with (11) and $r(minS - 1) \geq 0$, implies

$$\sum_{i \in S} z_i^{cu} \geq v(\bar{S}, e) - \sum_{i \in \bar{S} \backslash S} z_i^{cu}. \tag{12}$$

Since countries in-between connected coalitions in S up to $l(S)$ divert $x_i^{ncS} = \hat{x}_i$ for every $i \in \bar{S} \backslash S$, the water allocation $((x_i^S)_{i \in S \cap \bar{S}}, (\hat{x}_i)_{i \in \bar{S} \backslash S})$ can be implemented in $\bar{S}$ and, therefore, $v(\bar{S}, e) \geq v(S \cap \bar{S}, e) + \sum_{i \in \bar{S} \backslash S} b_i(\hat{x}_i)$. Furthermore, since $x_i^S = 0$ downstream $l(S)$ in S for every $i \in S \backslash Pl(S)$, and, therefore $b_i(x_i^S) = 0$ for every $i \in S \backslash Pl(S)$, $v(S, e) = v(S \cap Pl(S), e) = v(S \cap \bar{S}, e)$. Thus we have:

$$v(\bar{S}, e) \geq v(S, e) + \sum_{i \in \bar{S} \backslash S} b_i(\hat{x}_i). \tag{13}$$

Since $z_i^{cu} \leq b_i(\hat{x}_i)$ for every $i \in \bar{S} \backslash S$ by definition, (12) and (13) imply $\sum_{i \in S} z_i^{cu} \geq v(S, e) + \sum_{i \in \bar{S} \backslash S} (b_i(\hat{x}_i) - z_i^{cu})$. Since by definition $z_i^{cu} \leq b_i(\hat{x}_i)$, it implies $\sum_{i \in S} z_i^{cu} \geq v(S, e)$ the desired conclusion.□

C Proof of Proposition 3

Suppose $e_1' < e_1$. By concavity of b_i, $0 < \epsilon \leq e_1'$ implies

$$b_1(e_1') - b_1(e_1' - \epsilon) \geq b_1(e_1) - b_1(e_1 - \epsilon). \tag{14}$$

Assuming $\epsilon = e_1 - x_1^* \leq e_1'$ where the last inequality is due to the assumption $x_1' = e_1' - e_1 + x_1^* \geq 0$, equation (14) becomes

$$b_1(e_1') > b_1(e_1) + b_1(x_1') - b_1(x_1^*).$$

Substituting $t_1^d = v(1, e) - b_1(x_1^*) = b_1(e_1) - b_1(x_1^*)$, it leads to the desired conclusion $b_1(e_1') > b_1(x_1') + t_1^d$, i.e. defection by country 1.□

D Proof of Theorem

Consider an acceptable RSA (x^*, t) and realized water flows $e' \leq e$ where the sign " $\leq$ " means $e_j' \leq e_j'$ for every $j \in N$ and $e_i' < e_i$ for one $i \in N$ at least. Suppose first that an acceptable RSA (x^*, t) is sustainable but not (x^*, t^{cu}) with $t \neq t^d$. Then $\exists i < n$ such that the no-defection constraint hold for i with (x^*, t) but not with (x^*, t^{cu}):

$$b_i(x_i') + t_i \geq b_i(E_i') - \sum_{j \in P^0 i} t_j,$$

$$b_i(x_i') + t_i^{cu} < b_i(E_i') - \sum_{j \in P^0 i} t_j^{cu}.$$

The two inequalities imply:

$$\sum_{j \in Pi} t_j > \sum_{j \in Pi} t_j^{cu}.$$

Adding $\sum_{j \in Pi} b_j(x_j^*)$ both sides of the last inequality leads to:

$$\sum_{j \in Pi} \left(t_j + b_j(x_j^*)\right) > \sum_{j \in Pi} \left(t_j^{cu} + b_j(x_j^*)\right). \tag{15}$$

Since (x^*, t) is a core RSA, it satisfies the core lower bound for coalition $F^0 i$:

$$\sum_{j \in F^0 i} \left(t_j + b_j(x_j^*)\right) \geq v(F^0 i, e).$$

By the core lower bound for N, we have

$$\sum_{j \in Pi} \left(t_j + b_j(x_j^*)\right) = v(N, e) - \sum_{j \in F^0 i} \left(t_j + b_j(x_j^*)\right).$$

The two last equations imply:

$$\sum_{j \in Pi} \left(t_j + b_j(x_j^*)\right) \leq v(N, e) - v(F^0 i, e).$$

Combined with (15), it leads to

$$v(N, e) - v(F^0 i, e) > \sum_{j \in Pi} \left(t_j^{cu} + b_j(x_j^*)\right).$$

Therefore, by definition of (x^*, t^{cu}),

$$\sum_{j \in Pi} \left(t_j^{cu} + b_j(x_j^*)\right) = \sum_{j \in Pi} b_j(\hat{x}_j),$$

which combined with (15) contradicts that (x^*, t) is fair.

Suppose now that (x^*, t^d) is sustainable but not another acceptable RSA (x^*, t) $t \neq t^d$. Then $\exists i < n$ such that the no-defection constraint hold for i with (x^*, t^d) but not with (x^*, t):

$$b_i(x_i') + t_i^d \geq b_i(E_i') - \sum_{j \in P^0 i} t_j^d,$$

$$b_i(x_i') + t_i < b_i(E_i') - \sum_{j \in P^0 i} t_j.$$

The two inequalities imply:

$$\sum_{j \in Pi} t_j^d > \sum_{j \in Pi} t_j.$$

Adding $\sum_{j \in Pi} b_j(x_j^*)$ to both sides, it leads to:

$$\sum_{j \in Pi} (b_j(x_j^*) + t_j^d) > \sum_{j \in Pi} (b_j(x_j^*) + t_j).$$

Since $\sum_{j \in Pi} b_j(x_j^*) + t_j^d) = v(Pi, e)$ by definition of t^d, then the last inequality is equivalent to

$$v(Pi, e) > \sum_{j \in Pi} (b_j(x_j^*) + t_j),$$

Which contradicts that (x^*, t) is a core RSA, since it violates the core lower bound for $S = Pi$.□

E An illustrative example

We provide an example in which the downstream incremental RSA and the constraint upstream incremental RSA differ. Consider a river shared by $n = 3$ countries with identical benefit functions $b_1(x) = b_2(x) = b_3(x) = 100x - .5x^2$ for every $x \in (10, 120)$. Suppose that country 1 controls 80 units of water, country 2 controls 60 units and country 3 controls 40 units. Since the countries have identical benefits from water consumption, efficiency requires to share equally the 180 units of water, each of them consuming $x_i^* = 60$ units for $i = 1, 2, 3$. The transfers are $t^d = (600, 100, -700)$ for the downstream incremental RSA, and $t^{cu} = (800, 200, -1000)$ for the constrained upstream incremental RSA. Allocating mean flow efficiently requires that countries 1 and 2 release 20 units of water each. If the water flow in country 1 is 70 instead of 80, then country 1 consumes 50 units of water instead of 60 to supply country 2 with 20 units of water. Doing so, it obtains $b_1(50) + t_1^d = 3750 + 600 = 4350$ under the downstream incremental RSA and $b_1(50) + t_1^u = 3750 + 800 = 4550$ under the constrained upstream incremental RSA. On the other hand, country 1 can achieve $b_1(70) = 4550$ by defecting. Therefore country 1 defects under downstream incremental RSA (x^*, t^d) but not under the constrained upstream incremental (x^*, t^{cu}). If country 2 experiences the same reduction of 10 units of water which leads it to consume only 50 units of water, it obtains $b_2(50) + t_2^d = 3750 + 100 = 3850$ under (x^*, t^d) and $b_2(50) + t_2^{cu} = 3750 + 200 = 3950$ under (x^*, t^{cu}). Once country 1 has released 20 units of water, country 2 controls 50+20=70 units. By not releasing water, country 2 enjoys $b_2(70) - t_1^d = 4550 - 600 = 3950$ under (x^*, t^d) and $b_2(80) - t_1^{cu} = 4550 - 900 = 3250$ under (x^*, t^{cu}). Again, country 2 defects under (x^*, t^d) but not under (x^*, t^{cu}).$\square$

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