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Keywords: Water Reallocation, Sequential Sharing Rule, Water Scarcity, Axiomatic Approach, Cyprus

JEL Classification: D63, D71, Q25

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Reallocating water:
An application of sequential sharing rules to Cyprus*

Erik Ansink[†] and Carmen Marchiori[‡]

Abstract

We present an axiomatic approach to the reallocation of water rights among economic sectors. Reallocation may be appropriate when the current schedule of water allocation is considered unfair. Our proposed approach is based on the combination of initial water rights, sectors' claims to water, and an exogenous ordering of these sectors. We apply sharing rules, based on bankruptcy rules, to reallocate water, which complements other approaches to the reallocation of water rights, including those based on water markets. Our approach is illustrated using an application to water reallocation in Cyprus, where reallocation of water rights has been recognised as an essential step towards good water governance and one of the main challenges for current water policies.

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1 Introduction

It is now widely recognised that water resources are becoming increasingly scarce worldwide, due to both the impacts of climate change and increasing demand from various sectors, including agriculture, industry, domestic use, and the environment. Overall water consumption has almost doubled in the last 40 years and—unless consumption patterns are significantly altered—by 2050 at least one in four people will live in countries affected by chronic or recurrent shortage of freshwater (Gardner-Outlow and Engelman, 1997). The situation is particularly critical in arid and semi-arid regions, such as the Middle East and North Africa, where water withdrawals have already exceeded total renewable supplies (MEA, 2005).

On the supply side, in many parts of the world water resource development has by now reached its limits and marginal additional sources provide only very costly alternatives. Increasing water supply continuously, which has been the main policy in the past, is not a viable option in the long run (Molle and Berkoff, 2009).

In the face of the above constraints, the focus of current thinking in water resource management is on the allocation of scarce water between competing demands. Groom et al. (2003) rightfully observe that: "...the combination of the arbitrariness of the prevailing property rights structure for water resources in most jurisdictions and the failure of markets to capture the value of many watershed services implies that the prevailing distribution of water within most societies is not likely to be the most desirable one". This calls for a reappraisal of sectoral water allocations and the development of new criteria and methodologies that can assist decision-makers in this effort.

In this paper we present an axiomatic approach to the reallocation of water resources among economic sectors. This approach is illustrated using an application to water reallocation in Cyprus. Reallocation of water among sectors is a delicate intervention that poses two fundamental questions: (i) on the basis of which criteria should water be reallocated?; and (ii) through which mechanisms? With regard to the first question, optimization of sectoral allocation is widely seen as a fundamental pillar of water demand management. Many believe that water is too often devoted to economically inefficient, low return (usually agricultural) uses and that reallocation to more efficient, high return (usually urban) sectors would substantially increase total economic welfare (Molden, 2007; Gleick, 2003). As stated by Gleick (2001): "the largest single consumer of water is agriculture—and this use is largely inefficient ... as much as half of all water diverted for agriculture never yields any food. Thus, even modest improvements in agricultural efficiency could free up huge quantities of water that could be reallocated to higher value uses". However, as pointed out by Molle and Berkoff (2009), assessing the allocation gap between agricultural and non-agricultural uses may not be so straightforward, due to complexities in the legal, social, and political aspects of water reallocation, that limit the benefits of reallocation.

In general, determining the desirable allocation of water among sectors is a complex process, which is likely to depend not only upon economic efficiency, but also upon other aspects, such as the sustainable use of water and the fairness of its distribution (Groom et al., 2003). This, in turn, implies emphasis on environmental water demand and on such aspects as water demands, pre-existing customary (or other) rights, water uses etc. The axiomatic approach to water reallocation used in this paper offers the possibility to take into account a multiplicity of relevant aspects—including pre-existing water rights and sectoral water demands—and to apply different fairness criteria that jointly characterize a solution to the reallocation problem at hand.

Our approach is based on the class of sequential sharing rules proposed by Ansink and Weikard (2009).[1] These sharing rules, based on bankruptcy rules (Thomson, 2003), allow the redistribution of a resource when the resource is insufficient to meet all claims or demands. The particular class of sequential sharing rules is relevant for situations where agents are ordered and have endowments of the resource that may be redistributed. In the setting of this paper, the agents are sectors that are endowed with an initial amount of water rights. Given water scarcity, however, they claim a larger amount of water. The reallocation is based on an exogenous ordering of the sectors. The order of sectors determines the direction of reallocation (i.e. from sector A to B to C). Sectors can be ordered according to different criteria, such as the historical chronology of sectors' allocations or their water use efficiency. In the application discussed in this paper, we will use a chronological order. As we will see later, in the context of Cyprus this ordering also implies a redistribution of water from low-value to high value uses, thus ensuring a more efficient allocation of the resource. While the order of sectors determines the direction of reallocation, the selected sharing rule determines the magnitude of the reallocation. The resulting reallocation is based on the combination of endowments (initial water rights), claims, the ordering of sectors, and the particular sharing rule used.

The advantage of sequential sharing rules over alternative axiomatic approaches is that our approach takes explicitly into account both the current allocation of water

[1] The only alternative axiomatic approach to reallocation that we are aware of comes from the literature on allocation with single-peaked preferences (Sprumont, 1991). Klaus et al. (1997) extended this literature to cover reallocation problems and proposed a "uniform reallocation rule". This rule is, however, powerless in situations where all agents claim more than their initial endowment, which is a relevant situation in case of water reallocation under scarcity.

rights and the chronology of sectors' allocations. As it will emerge more clearly from the analysis, the joint consideration of these two aspects is extremely important. On the one hand, any reallocation that aims to be acceptable to all relevant stakeholders should take into account that we are not allocating water as if there are no *de facto* property rights. On the other hand, in many real-world situations, water resource expansion has essentially followed the 'rule of capture'; that is, the current allocation of water rights is the result of the order of arriving of sectors rather than long term planning on the part of governmental authorities. By incorporating the chronological order of sectoral allocations, our approach is, therefore, able to 'correct' for the potential arbitrariness of the current schedule of water rights, without neglecting the importance of customary uses.

An application to the case of water reallocation in Cyprus demonstrates the merits of our axiomatic approach. In recent years, reductions in precipitation and over-pumping of groundwater resources have led to reductions in water availability. As a result, competition over scarce water among agriculture, domestic use, industry, tourism, and the environment has intensified, and sectors are rationed on their water demand. The government of Cyprus does not have many options left to increase supply. Reallocation may therefore be a sensible alternative. In our analysis, we show how the selection of a specific sequential sharing rule affects this reallocation and discuss how to select among alternative rules.

Our approach is also of relevance for the mechanisms to implement inter-sectoral water reallocation. As previously mentioned, this constitutes a second fundamental issue of any reallocation policy. Inter-sectoral water redistributions can be implemented in different ways—for example, through water markets, buy-back schemes and formal administrative decisions with or without compensation (Dinar et al., 1997; Marchiori, 2008). The proposed approach does not impose the adoption of a specific implementation mechanism; instead, it can be used to support or complement alternative instruments. For example, as pointed out by Molle and Berkoff (2009), water markets often do not take account of third party effects and trade of water rights is generally only permitted in a regulated market, with the terms of the trade set and enforced by a public agency. The sequential sharing rule approach discussed in this paper can help policy makers to set out the terms on which transfers are to be made, for example by establishing overall sectoral allocation targets.

In many real-life contexts, inter-sectoral water reallocations have been implemented through formal administrative decisions, taken by a national, provincial or basin entity. Whether a formal administrative decision occurs with or without compensation, the support of the interested parties is a critical condition for its long-term success. Stakeholders' support typically translates into easier implementation, less litigation and improved 'stability' of the the resulting solution (Caldart and Ashford, 1999). For this reason, formal administrative decisions generally involve consultation with the interested parties, even where the parties do not hold formal water rights (Molle and Berkoff, 2009). The fairness properties embedded in the sequential sharing rule approach makes the proposed framework particularly useful to policy-makers—especially in the phase of stakeholders' consultation—in that it can help to achieve a solution which is perceived as legitimate and fair.

To conclude, this paper contributes to the literature on implementability (Stratton et al., 2008) and fairness (Ambec and Ehlers, 2008) of water rights allocation, a topic that will only grow in relevance given increasing worldwide water demand, and the projected impacts of climate change on water resources. The paper is organised as follows. In section 2 the situation of water scarcity in Cyprus is presented. In section 3 we introduce the class of sequential sharing rules. In section 4 we apply sequential sharing rules to the Cyprus case. In section 5 we discuss the results and their applicability, and we provide some conclusions.

2 The case of Cyprus

2.1 Physical context and water supply

Cyprus is a semi-arid island located in the north-eastern part of the Mediterranean Sea and has always been confronted with limited water availability. The hydrological cycle of Cyprus is characterized by temporal and spatial water scarcity. Precipitation is highly concentrated during the winter period and varies from 300 mm/year in the eastern plains to 1100 mm/year at the top of the Troodos mountains where most of surface runoff is generated (Klohn, 2002).

Since the independence of Cyprus in 1960, its government embarked on a number of impressive water-supply investments and interventions to increase water supply. Under the motto *"not a drop of water to the sea"*, numerous dams and conveyance infrastructures of different size and importance were built, which led to an increase of the freshwater storage capacity from 6 MCM in 1960 to 300 MCM today.[2]

[2] One of the most significant infrastructure investment project was the Southern Conveyor Project, which allows the transfer of water resources throughout the southern part of the island, and to and from the capital Nicosia. This project has proved effective in expanding the required water infrastructure and enabling wide area water management. At the same time, its implementation transformed the commanded land radically and induced a change in cropping patterns towards high water demanding

During the last thirty years, Cyprus has experienced a significant reduction of rainfall and an increase in the frequency and intensity of droughts. Statistical analyses of the precipitation records available over the hydrological years 1916–2000 show that the precipitation time series displays a step change around 1970 and can be divided into two separate stationary periods. The mean annual precipitation of the more recent period (1970–2000) is about 25% lower than the mean annual precipitation of the older period (1916–1970). This decrease in precipitation has resulted in a reduction of the mean annual inflow to dams of about 40%. Thus, the actually available surface water on the island is substantially less than what had been assumed as a basis for the early water development works (Rossell, 2001).

Due to limited supply of surface runoff, groundwater has traditionally represented a crucial source of supply for domestic use and irrigation. Throughout the years, groundwater resources have been heavily over-pumped, especially during periods of drought. This has caused serious problems of saline water intrusion, with consequent quality deterioration of coastal aquifers and depletion of inland aquifers. The possibilities for additional exploitation of surface and groundwater resources have been largely exhausted and this has necessitated the consideration and use of costly unconventional sources of supply, such as desalination, waste-water reuse and evaporation suppression (Groom et al., 2003).

Despite these efforts, the country still faces water shortage and scarcity problems, which have been aggravated by the severe droughts of the 1990s. These conditions have recently led the government to revise its general water policy and place more emphasis on water demand management.

2.2 Water demands and shortage

The total annual water demand in Cyprus amounts to approximately 265.9 MCM (year 2000) and its distribution among sectors is shown in figure 1.

Agriculture accounts for 69% of total water demand—corresponding to 182.4 MCM—which is mainly due to irrigation water demand.[3] In 1960, when Cyprus became independent, it was mainly an agricultural country, with more than 40% of the economically active population being employed in agriculture. Today, the agricultural sector contributes only a minor part to GDP (about 4%) and accounts for less than 7% of total employment. Despite its decreasing importance for the economy of the island, agricul-

crops, thus creating a water demand that did not exist before (Groom et al., 2003).

[3]Irrigation demand accounts for 96% of total agricultural demand and is distributed between permanent crops (59%) and annual crops (41%).

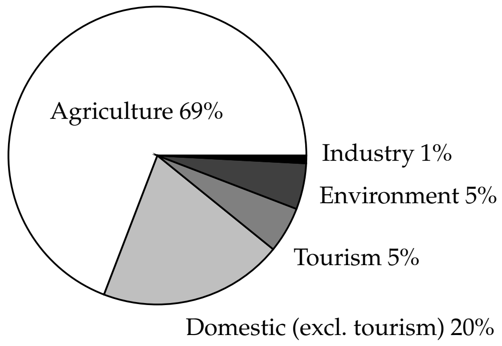

Figure 1: Distribution of water demand from various sectors—year 2000 (Savvides et al., 2001).

ture remains the main water-consuming sector (Iacovides, 2007).[4]

The annual water demand for the domestic sector is estimated at 67.4 MCM. Of this amount, approximately 80% refers to the demand of permanent population, while the remaining 20% refers to tourism demand. From an economic point of view, tourism is one of the most dynamic sectors and one of the main sources of income in Cyprus. According to current estimates, tourism alone contributes to more than 21% of GDP and exhibits an upward trend, which is expected to continue over the next years.

The industrial sector in Cyprus mainly consists of light manufacturing, mining and electricity, gas and water distribution and has so far exhibited a stable course both in terms of output and in terms of employment. Industry uses the lowest volume of water compared to the agricultural and domestic sectors. The annual demand of water for industrial purposes is estimated at 3.5 MCM, corresponding to 1% of the total water demand. Shortages during periods of drought have been insignificant and it could be said that the actual use and demand of water for the industrial sector are at the same level.

Finally, there exists an estimated environmental demand of approximately 12.5 MCM a year. This comprises demand for landscape irrigation (7.5 MCM) and ecological areas (5.0 MCM). Groundwater is the main source of supply for landscape irrigation. Subsidized drilling within the main towns has helped in meeting part of the landscape irrigation demand—approximately 60% (Iacovides, 2007). Over the past years, environmental considerations and objectives have become progressively more important in water policies, especially after Cyprus' accession to the European Union in May 2004.

[4]The magnitude and distribution of irrigation demand are not expected to change significantly up to 2020 (WDD, 2004).

Table 1: Water demand and consumption by sector—year 2000.

Sector	Water demand (MCM)	Actual water consumption (MCM)
Agriculture	182.4	100.4
Domestic	53.4	42.7
Tourism	14.1	10.7
Industry	3.5	3.5
Environment	12.5	4.5

In the light of climate change, the environmental demand is expected to play an even more significant role that needs to be taken into consideration both in the assessment of the available water resources of the country and in the design of any future policy interventions.

The data summarized in figure 1 refers to the amount of water *demanded* by the economic sectors.[5] Over the past decades, however, the actual water consumption has been typically lower due to shortage of supply (Savvides et al., 2001; WDD, 2004). The period 1997–2000 in particular was characterized by a series of intense droughts which significantly reduced the availability of water especially in major dams. In periods of low rainfall and limited water supply, priority is given to domestic demand. During the year 2000, water supply was rationed in all irrigation projects, with priority given to permanent crops over annual crops at an average water shortage of 38% of the normal demand. In the domestic sector, water restrictions reached 20% of the domestic demand. More recently, water shortage has been less severe thank to a series of relatively wet years that has helped alleviate some restrictions. Domestic water demand, however, is expected to increase from 67.4 MCM in 2000 to 104.3 MCM in 2020 (Savvides et al., 2001). At the same time, the options for supply enhancement are diminishing due to the intensive amount of water resource developments which has already occurred in Cyprus. Water restrictions at 2000 levels seem, therefore, to constitute a good benchmark for the underlying water shortage and scarcity problems of the island.

Table 1 summarizes the sectoral water demands and consumption at 2000 levels.

2.3 Water reallocation

Until recently, water demand management in Cyprus has been largely overlooked by the government, and still faces some difficulties due to the existing legal and institutional framework. Most of these difficulties arise from the fragmentation of jurisdiction in the planning, design, implementation and control of water resource management. In addi-

[5]In the next section, we will interpret these demands as *claims*.

tion, the expansion of surface water and groundwater use has not been accompanied by a simultaneous evolution of the property rights regime. Despite government ownership of *de juro* water rights, both surface and groundwater resources are largely subject to open access, determining *de facto* water rights. This property rights regime is partially based on the riparian principle and the 'rule of capture'. As a result, the pattern of water rights tends to be uncoordinated (Groom et al., 2003).

As mentioned in section 2.1, the reduction of rainfall, the frequent occurrence of droughts and the increasing competition over water among economic sectors have recently led the government to revise its general water policy and place more attention to water demand management. Within this context, the reallocation of water among sectors has been recognised as an essential step towards good water governance and one of the main challenges for current water policies. As pointed out by Iacovides (2007), any potential reallocation of water must deal fairly with farmers, domestic users, industry, tourism, and the environment, allowing each group to contribute to the economy, while ensuring the sustainable use of water resources. This calls for the development of new criteria and methodologies that can assist in this effort. The sequential sharing rule approach, introduced in section 3 and applied in section 4, can provide a useful tool for policy makers. As we will see shortly, this approach offers the possibility to apply different fairness criteria that jointly characterise a solution to the reallocation problem at hand, while taking into account both the initial system of water rights and the claims of all relevant sectors.

3 Sequential sharing rules

The characterisation of sequential sharing rules in this section is largely based on Ansink and Weikard (2009). Consider an ordered set N of $n \geq 2$ sectors, where $i \in N$ reflects the sector's position in the historical order of sectors. Sector j arrived later than sector i whenever $i < j$. Denote by $B_i = \{j \in N : j < i\}$ the set of sectors that arrived before i, and denote by $L_i = \{j \in N : j > i\}$ the set of sectors that arrived later than i. Current water consumption of sector i is considered its endowment $e_i \geq 0$; $e = (e_1, \ldots, e_n)$. In addition to its endowment, each sector is characterised by having a claim $c_i \geq 0$; $c = (c_1, \ldots, c_n)$ to total available water. This claim reflects the total volume of water that is demanded by the sector, and which it would use absent scarcity (see table 1).

This setup allows us to define a water reallocation problem and its solution (a sharing rule) as follows.

Definition 1 (Water reallocation problem)**.** A water reallocation problem is a triple $\omega = \langle N, e, c\rangle$, with N an ordered and finite set of sectors, $e \in \mathbb{R}^n_+$ and $c \in \mathbb{R}^n_+$.

Definition 2 (Sharing rule)**.** A sharing rule $F(\omega)$ assigns to every water reallocation problem ω a water rights allocation vector $x = (x_1, \dots, x_n)$, $x \in \mathbb{R}^n_+$, such that (a) $\sum_{i\in N} x_i = \sum_{i\in N} e_i$, (b) $0 \leq x \leq c$, and (c) $x_i \leq e_i + \sum_{j\in B_i} e_j \; \forall i \in N$.

The allocation of water rights to sector i is $F_i(\omega) = x_i$. Requirement (a) of the sharing rule imposes efficiency: no water rights remain unallocated. Requirement (b) says that all sectors receive a non-negative allocation that is bounded by their claim. Requirement (c) is a feasibility constraint.

Ansink and Weikard (2009) characterise a class of sequential sharing rules that is constructed using the following two axioms.

Axiom 1 (Only n's Excess Claim Matters)**.** For each water reallocation problem $\omega = \langle N, e, c\rangle$, and each related problem $\omega' = \langle N, e', c'\rangle$ such that $e' = (e_1, \dots, e_{n-1}, e'_n)$ and $c' = (c_1, \dots, c_{n-1}, c'_n)$ with $e'_n = 0$ and $c'_n = c_n - e_n$, we have $F_i(\omega) = F_i(\omega') \; \forall i \in N$.

This property says that only n's excess claim $c_n - e_n$ matters; that is, the part of n's claim that n can satisfy with its own water endowment should not affect the allocation to the other sectors.

Axiom 2 (No Advantageous Merging)**.** For each water reallocation problem $\omega = \langle N, e, c\rangle$, and each related problem $\omega' = \langle N', e', c'\rangle$ such that $N' = N\backslash\{n\}$ and $e' = (e_1, \dots, e_{n-2}, e'_{n-1})$ and $c' = (c_1, \dots, c_{n-2}, c'_{n-1})$, with $e'_{n-1} = e_{n-1} + e_n$ and $c'_{n-1} = c_{n-1} + c_n$, we have $F_i(\omega) = F_i(\omega') \; \forall i < n - 1$.

This property says that consolidation of claims by sectors $n - 1$ and n should not affect the allocation to the other sectors.

Together, axiom 1 and recursive application of axiom 2 prescribe that endowments of sectors that arrived later are first used to (partly) satisfy their claims. Hence, only excess claims matter, which we denote c_{L_i}:

$$c_{L_i} \equiv \sum_{j\in L_i} (c_j - e_j). \tag{1}$$

Using (1), the two axioms lead to the representation of a water reallocation problem ω as a sequence $(\omega_1, \dots, \omega_n)$ of reduced water reallocation problems ω_i.

Definition 3 (Reduced water reallocation problem)**.** A reduced water reallocation problem is a triple $\omega_i = \langle N_i, E_i, C_i\rangle$, with two sectors $N_i = \{i, L_i\}$, who have claims $C_i = \{c_i, c_{L_i}\}$, to the resource E_i.

In each reduced problem ω_i, available water $E_i \equiv e_i + \sum_{j \in B_i}(e_j - x_j)$ is distributed between i and L_i.[6] Note that E_i is the total available water to sector i after sectors in B_i have taken their allocated share. A reduced water reallocation problem is mathematically equivalent to a bankruptcy problem. In a bankruptcy problem, a perfectly divisible resource is distributed over a set of agents who have overlapping claims. A solution to a bankruptcy problem is a bankruptcy rule, that is based on the agents' claims to the resource. Various axiomatic approaches to the construction of such bankruptcy rules have been analysed (cf. Thomson, 2003). We will provide examples of such rules in section 4. Because of the equivalence, bankruptcy rules can be applied to any reduced water reallocation problem.

In order to solve a water reallocation problem, the sequence $(\omega_1, \ldots, \omega_n)$ of its reduced problems is solved recursively in the linear order of sectors, using a bankruptcy rule. This is summarised in the following proposition (Ansink and Weikard, 2009).

Proposition 1. For each water reallocation problem $\omega = \langle N, e, c \rangle$ and its corresponding sequence of reduced water reallocation problems $(\omega_1, \ldots, \omega_n)$, we have $F_i(\omega) = F_i(\omega_i)$ $\forall i \in N$.

Axioms 1 and 2 characterise a class of rules that we call sequential sharing rules. Sequential sharing rules are constructed by the recursive application of a bankruptcy rule to the sequence of reduced water reallocation problems.

4 Application

In this section, we apply sequential sharing rules to water reallocation in Cyprus using the data provided in section 2. Hence, we have a set of $n = 5$ sectors, ordered according to the chronology of their water demand (Savvides et al., 2001): 1. agriculture, 2. domestic, 3. tourism, 4. industry, and 5. environment. We interpret the data in table 1 as the sectors' claims (estimated water demand) and endowments (actual water consumption). Hence, the claims vector is $c = (182.4, 53.4, 14.1, 3.5, 12.5)$ and the endowments vector is $e = (100.4, 42.7, 10.7, 3.5, 4.5)$. Note that claims weakly dominate endowments, reflecting the situation of water scarcity. Both agriculture and environment have claims that go far beyond their current endowment. As discussed in section 2, only the industrial sector does not claim more than its current endowment.

The next step is to select relevant bankruptcy rules, based on their properties and results from experimental studies. We will limit ourselves here to three classi-

[6] We denote the second sector in the reduced water reallocation problem by L_i. This set of sectors is treated as a single claimant.

cal bankruptcy rules: the proportional rule, constrained equal awards, and constrained equal losses (cf. Herrero and Villar, 2001).

Proportional rule (PRO). For all $\omega_i = \langle N_i, E_i, C_i \rangle \in \Omega$, there exists $\lambda > 0$, such that $x_i^{\text{PRO}} = \lambda c_i$ and $x_{L_i}^{\text{PRO}} = \lambda c_{L_i}$.

PRO assigns each sector a share of the resource in proportion to their claims.

Constrained equal awards (CEA). For all $\omega_i = \langle N_i, E_i, C_i \rangle \in \Omega$, there exists $\lambda > 0$, such that $x_i^{\text{CEA}} = \min\{c_i, \lambda\}$ and $x_{L_i}^{\text{CEA}} = \min\{c_{L_i}, \lambda\}$.

CEA assigns each sector an equal share of the resource, subject to no sector receiving more than its claim.

Constrained equal losses (CEL). For all $\omega_i = \langle N_i, E_i, C_i \rangle \in \Omega$, there exists $\lambda > 0$, such that $x_i^{\text{CEL}} = \max\{0, c_i - \lambda\}$ and $x_{L_i}^{\text{CEL}} = \max\{0, c_{L_i} - \lambda\}$.

CEL assigns each sector a share of the resource such that their losses compared to their claim are equal, subject to no sector receiving a negative share.

PRO, CEA, and CEL satisfy a number of attractive properties such as *Claims Monotonicity*, *Resource Monotonicity*, *Equal Treatment of Equals*, *Consistency*, and *Scale Invariance* (see Thomson, 2003, for a detailed description of these properties). The reason for focusing on these three rules is that they have strong theoretical and empirical support. Theoretical support comes from Moulin (2000) and Herrero and Villar (2001) who show that these three bankruptcy rules are the only sensible rules that satisfy a.o. *Equal Treatment of Equals*, a property that is hard to dismiss. Empirical support comes from Gächter and Riedl (2006) and Herrero et al. (2009) who have conducted experiments on bargaining and coordination games, in both cases complemented by a survey. The experimental results show strong support for PRO, while survey results support PRO (see also Bosmans and Schokkaert, 2009), and to a lesser extent CEA or CEL. These results can be interpreted as saying that in non-cooperative situations, people tend to coordinate on PRO, while all three rules have moral support, depending on the type of situation, and framing of the problem. In addition to this theoretical and empirical support, PRO, CEA, and CEL have a long history of being used in practice. Examples of practical applications are manifold (e.g. cost allocation rules, inheritance rights, progressiveness of taxation schemes).[7]

Using these three bankruptcy rules, the reallocation of water among sectors in Cyprus is presented in tables 2–4. In the last column of these tables, $\delta_i \equiv x_i - e_i$ denotes

[7] See Young (1995) for an overview and discussion of these examples.

the difference between each sector' current water consumption and its allocation after reallocation according to the specific rule.

Table 2: Water reallocation using a sequential sharing rule based on PRO

i	e_i	c_i	$\Rightarrow$	E_i	c_{L_i}	$\Rightarrow$	x_i^{PRO}	$x_{L_i}^{PRO}$	$\Rightarrow$	δ_i^{PRO}
1 (agriculture)	100.4	182.4		100.4	22.1		89.5	10.9		-10.9
2 (domestic)	42.7	53.4		53.6	11.4		44.1	9.4		1.4
3 (tourism)	10.7	14.1		20.1	8.0		12.8	7.3		2.1
4 (industry)	3.5	3.5		10.8	8.0		3.3	7.5		-0.2
5 (environment)	4.5	12.5		12.0	-		12.0	-		7.5

Table 3: Water reallocation using a sequential sharing rule based on CEA

i	e_i	c_i	$\Rightarrow$	E_i	c_{L_i}	$\Rightarrow$	x_i^{CEA}	$x_{L_i}^{CEA}$	$\Rightarrow$	δ_i^{CEA}
1 (agriculture)	100.4	182.4		100.4	22.1		78.3	22.1		-22.1
2 (domestic)	42.7	53.4		64.8	11.4		53.4	11.4		10.7
3 (tourism)	10.7	14.1		22.1	8.0		14.1	8.0		3.4
4 (industry)	3.5	3.5		11.5	8.0		3.5	8.0		0.0
5 (environment)	4.5	12.5		12.5	-		12.5	-		8.0

Comparing tables 2–4, a number of results deserve some explanation and interpretation. Paying attention to the values of δ_i, a first result is that under PRO and CEA agriculture loses more than under CEL, while the opposite holds for the other sectors. Under PRO, the largest change in allocation is from agriculture to environment. Under CEA, this change in allocation is from agriculture to domestic and environment. Under CEL, the change is rather different as water is reallocated from tourism and industry to environment. A second result is that the only two features that all three rules have in common is that agriculture loses some if its allocation, while the environment gains. These features are induced by the construction of the sequential sharing rules, which does not allow a net transfer of water from a later-arriving sector to an earlier one. One other feature, which is not induced by the construction of the rules, is that industry weakly loses under all three rules. This is a result of the low claim of the industry sector, relative to its endowments.

The choice of a specific rule is not a straightforward issue. None of the reallocation

Table 4: Water reallocation using a sequential sharing rule based on CEL

i	e_i	c_i	$\Rightarrow$	E_i	c_{L_i}	$\Rightarrow$	x_i^{CEL}	$x_{L_i}^{CEL}$	$\Rightarrow$	δ_i^{CEL}
1 (agriculture)	100.4	182.4		100.4	22.1		100.4	0.0		0.0
2 (domestic)	42.7	53.4		42.7	11.4		42.4	0.4		-0.3
3 (tourism)	10.7	14.1		11.1	8.0		8.6	2.5		-2.1
4 (industry)	3.5	3.5		6.0	8.0		0.7	5.2		-2.8
5 (environment)	4.5	12.5		9.7	-		9.7	-		5.2

schemes resulting from the sharing rules analysed above can be said to be superior in absolute terms to the others. However, a number of aspects deserve to be discussed that could assist policy-makers in the choice of a rule that is most appropriate for the case of water reallocation at hand. Some aspects are context-specific; others relate to the characterising properties of PRO, CEA and CEL.

In general, CEA seems more appropriate for reallocation problems where the *sectors* themselves are considered the primary concern, leading to preferred treatment for sectors with small claims. CEL is more appropriate when the *claims* are the primary concern, leading to preferred treatment for sectors with large claims. PRO is somewhere in between the two, giving equal treatment to sectors and their claims (Herrero and Villar, 2001).[8]

As discussed in section 2, in the context of Cyprus a discrepancy has emerged between the relative water demand and economic importance of agriculture and tourism. Agriculture accounts for the largest share of total water demand (69%), while contributing only a minor part to the national wealth. By contrast, water demand for tourism—which is one of the most dynamic sectors—currently constitutes only 5% of total water demand. As stressed by recent studies, this calls for a reallocation of water resources that can take better into account the relative importance of each sector. Therefore, in the context of Cyprus CEA and PRO could be more appropriate than CEL.

A comparison of the properties that characterize PRO, CEA and CEL is also useful in order to assess which rule is most suitable for a specific reallocation problem. These properties, some of which were mentioned at the beginning of this section, are well-known and the selection of a few desirable properties may already single out one specific rule. For instance, the property *Exemption* could be considered indispensable:

[8]This is nicely reflected by its *Self-duality* property, discussed below.

Axiom 3 (Exemption)**.** For each water reallocation problem $\omega = \langle N, e, c\rangle$ and each $i \in N$, if $c_i \leq E_i/n$ then $F_i(\omega) = c_i$.

This property says that when E_i is sufficiently large relative to the claims, only those with large claims are to be rationed. CEA is the only of the three rules to satisfy this property (Herrero and Villar, 2001). Another example is the property *Self-duality*, for which we define $l \equiv c - e$ as losses relative to claims:

Axiom 4 (Self-duality)**.** For each water reallocation problem $\omega = \langle N, e, c\rangle$, and each related problem $\omega' = \langle N, l, c\rangle$, we have $F_i(\omega) = c_i - F_i(\omega')\ \forall i \in N$.

This property says that it does not matter for the reallocation whether resources ('what is there') or losses ('what is not there') are distributed. PRO is the only of the three rules to satisfy this property (Herrero and Villar, 2001). Similar arguments can be made to support CEL or any other bankruptcy rule, using one or more properties.

On the basis of the above considerations, the reallocations obtained under PRO and CEA may be more appropriate for the case of Cyprus than the reallocation resulting from the adoption of CEL. As previously mentioned, PRO is also the rule for which the experimental results show stronger support. In the context of Cyprus, a reallocation based on PRO would bring about a significant decrease in the volume of water allocated to the agricultural sector in favour of environment, tourism and domestic use, respectively.

Finally, another interesting issue is how the allocations under the three rules react to changes in the endowments or claims vectors. A decrease in endowments may occur due to the impacts of climate change on water supply, while an increase may occur due to for example the construction of new desalination plants. A change in claims may occur due to growth of one of the sectors. The sensitivity of the solutions under PRO, CEA, and CEL with respect to such changes differs slightly. Consider, for example, a doubling of the tourism claim from 14.1 MCM to 28.2 MCM. Under PRO, tourism would gain 10.4 MCM at the expense of mainly agriculture and domestic use. Under CEA, tourism would gain the full additional 14.1 MCM at the expense of agriculture. Under CEL, tourism would gain 9.5 MCM at the expense of all sectors except agriculture. These marginal effects reflect the properties of the rules discussed above; that is, CEA and CEL favour sectors with small and large claims respectively, while PRO lies somewhere in between those two.

5 Conclusion

Reallocation of water among sectors is a complex process which poses two fundamental questions: (i) on the basis of which criteria should water be reallocated?; and (ii) through which mechanisms? This paper has provided an approach to answer the first question, while also adding some useful insights to the second. More precisely, we present an axiomatic approach to the reallocation of water rights among economic sectors based on sequential sharing rules. The merits of this approach are illustrated using an application to inter-sectoral water reallocation in Cyprus and are briefly summarized below.

Our framework takes explicitly into account two distinct features of water reallocation problems, which are typically neglected by the theoretical literature. The first one is the importance of the schedule of current water rights (i.e. endowments). Any proposal for water reallocation that aims to be acceptable to all relevant stakeholders should take into account that we are not allocating water as if there are no *de facto* property rights. Instead, the term reallocation implies that existing water allocations are re-distributed from one sector to the other. This aspect is particularly important in the context of developing countries, where the institution of property rights is often not fully developed. A second distinct feature of many water reallocation problem is directly related to the chronological order of sectoral water demands. Historically, in many countries water resource expansion has been carried out with little management and planning on the part of governmental authorities and without being supported by a simultaneous evolution of the property rights regime (cf. Llamos and Martinez-Santos, 2005). As a consequence, the order of arriving is what has caused the current allocation of water and is the prime reason for its perceived arbitrariness (cf. Groom et al., 2003). Hence the calls for fair or more efficient reallocation. By including this ordering of sectors, our framework is able to fully capture its importance for inter-sectoral water reallocation.

An additional advantage of the sequential sharing rule method is that it can be easily adapted to changes in conditions, such as an increase in water availability due to, for example, the construction of new desalination plants, or climate change impacts. In addition, it can be further refined by considering allocation within sectors (for example permanent vs. annual crops within the agricultural sector) or by distinguishing between different sources of water supply (groundwater, surface water etc.).

Finally, as the mechanisms to implement inter-sectoral water reallocation are concerned, our framework can be used to support or complement existing instruments, such as water markets or formal administrative decisions. Trade of water rights, for example, is generally only permitted in a regulated market, with the terms of the trade set and enforced by a public agency. In such context, the sequential sharing rule approach can help policy makers to set out the terms on which transfers are to be made by establishing overall sectoral allocation targets. Where water reallocation is implemented through formal administrative decisions, the fairness properties embedded in the sequential sharing rule approach can help to achieve a solution which is perceived as legitimate and fair.

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