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Key Points:

- Cooperative game theory and social justice approaches are compared for the allocation of the cost of adaptation measures at the river basin scale
- Insights are provided to overcome the common assumption of perfect cooperation among the stakeholders of an optimized water resources system
- The comparison is performed in a Mediterranean river basin, to consider equity issues in the allocation of the cost of the adaptation measures

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Sharing the cost of river basin adaptation portfolios to climate change: Insights from social justice and cooperative game theory

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Abstract The adaptation of water resource systems to the potential impacts of climate change requires mixed portfolios of supply and demand adaptation measures. The issue is not only to select efficient, robust, and flexible adaptation portfolios but also to find equitable strategies of cost allocation among the stakeholders. Our work addresses such cost allocation problems by applying two different theoretical approaches: social justice and cooperative game theory in a real case study. First of all, a cost-effective portfolio of adaptation measures at the basin scale is selected using a least-cost optimization model. Cost allocation solutions are then defined based on economic rationality concepts from cooperative game theory (the Core). Second, interviews are conducted to characterize stakeholders' perceptions of social justice principles associated with the definition of alternatives cost allocation rules. The comparison of the cost allocation scenarios leads to contrasted insights in order to inform the decision-making process at the river basin scale and potentially reap the efficiency gains from cooperation in the design of river basin adaptation portfolios.

1. Introduction

Reducing the potential impacts of climate change on water resource systems requires mixed portfolios of supply and demand adaptation measures. So far the debate on adaptation at the local level has mainly focused on the definition of efficient, robust, and flexible adaptation portfolios of measures to tackle the uncertainty associated with future climate and demand scenarios [*Lempert and Groves*, 2010; *Halegatte*, 2009; *Walker et al.*, 2013; *Kwakkel et al.*, 2015; *Girard et al.*, 2015b]. Although these are crucial criteria, insufficient attention has been paid as yet to the equity issues associated with the sharing of adaptation costs among stakeholders. In a river basin, the implementation of an adaptation portfolio requires the effective support of the concerned stakeholders. This support (or lack of) will mainly be determined by their perception of how fair the allocation of costs and benefits of adaptation is likely to be.

Indeed, until now, previous studies have mainly looked at adaptation in river basins from a public economics perspective, using hydroeconomic modeling tools to find optimal basin wide strategy that aim at optimizing social welfare, economic productivity of water or minimizing management costs within the field of hydroeconomic modeling [*Tanaka et al.*, 2006; *Heinz et al.*, 2007; *Harou et al.*, 2009]. These approaches often adopt a social-planner perspective and share the assumption of perfect cooperation between the different stakeholders involved in the operational implementation of adaptation measures [*Madani*, 2010]. However, in practice, stakeholders may refuse to implement the adaptation measures optimal at the basin scale, but not necessarily in their own interest, creating difficulties to agree on how to share the cost among them. One of the key factors that determines stakeholders' willingness to contribute to the implementation of a plan is the perception of how equitably its cost will be shared among them [*Young et al.*, 1982; *Heaney*, 1997]. In order to implement a basin-wide optimal adaptation portfolio, we have to come up with a cost allocation strategy perceived as fair by the different stakeholders.

Equity issues in water planning research have generally been addressed in the allocation of the cost of the projects and infrastructure developed among various stakeholders [*Young et al.*, 1982], such as multipurpose reservoirs or in allocation issue [*Ward and Pulido-Velazquez*, 2008, 2009]. Equitable cost allocation has long been seen as the best way to ensure the agreement or cooperation of those who have to bear the costs of large water infrastructure projects [*Young et al*., 1982]. Various sets of principles have been established and recommended as guidelines to ensure an equitable cost allocation in water resource projects [*Ransmeier*, 1942; *Heaney*, 1997; *James and Lee*, 1971; *Loehman et al*., 1979*; Straffin and Heaney*, 1981; *Heaney and Dickinson*, 1982; *Driessen and Tijs*, 1985]. Those guidelines highlight the fact that every cost allocation strategy has its unique history and set of arguments as to what constitutes a "fair" division of costs [*Heaney*, 1997]. Equity is strongly shaped by cultural factors, by historical precedent, and by the type of goods and burdens being distributed [*Young*, 1994]. Therefore, the definition of a cost allocation can be seen rather as a way of ensuring the successful resolution of a conflict of interests, than as a quest for a theoretical universal equity definition.

Most of the climate change adaptation literature addresses the issue of equity associated with the spatial impacts on welfare at the global level, or with temporal intergenerational equity concerns [*Paavola and Adger*, 2006; *Paavola*, 2008]. Equity in adaptation at a more local level is an emerging issue [*Thomas and Twyman*, 2005; *Hughes*, 2013; *Graham et al*., 2015; *Benzie*, 2014; *Benzie et al*., 2011]. We should consider that adaptation decisions are framed by previous decisions and existing institutional frameworks that determine the distribution of power and resources [*Adger and Nelson*, 2010]. However, adaptation is already required, and decisions need to be taken now at the local level. Thus, equity needs to be addressed so that the impact of climate change and the process of adaptation do not contribute to reinforcing existing inequity in society [*Thomas and Twyman*, 2005]. Specifically at the local level (catchment), equity is an issue that also deals with the time and spatial dimensions of a river basin. Spatially, the adaptation of some stakeholders located at different places in a river basin (upstream for instance) can benefit or damage some others (downstream). Temporally, the current need for adaptation of some stakeholders can stem from previous development and/or challenge the future of others. Therefore, an effective adaptation might not take place if equity issues are not addressed in the analysis.

This paper presents a method that integrates efficiency and equity considerations in the definition of a portfolio of adaptation measures at the river basin level. It contributes to bridging the gap between the literature on optimizing adaptation portfolios and that dealing with equity in water management. Based on a real case study conducted in southern France, we conceive the problem as a two-step decision-making approach: we first use an optimization model to design a least-cost and robust portfolio of adaptation measures at the basin scale; we then investigate the acceptability of alternative cost allocation scenarios, using two different theoretical approaches—cooperative game theory and social justice theory.

After a brief presentation of the least-cost river basin optimization model used in the first step of the analysis to define the cost-effective and robust adaptation plan (section 2.1), the two approaches dealing with the equity issue (second step) are presented in sections 2.2 and 2.3, respectively. The case study area, where the methods have been implemented, is introduced in section 3.1. The least-cost river basin optimization model developed in this area is described in more details in section 3.2. Sections 3.3 and 3.4 present the implementation of cooperative game theory and social justice approaches in the real case study and the associated calculation. The results of both approaches are analyzed and compared in section 4. Finally, the differences between the results of these different approaches are discussed in the light of the understanding of the local context (section 5).

2. Material and Methods

2.1. Least-Cost River Basin Optimization Model

The general method developed in this study comprises two main stages. An interdisciplinary modeling framework was first developed for combining demand and water resources modeling into a least-cost river basin optimization model [*Girard et al*., 2015a]. This LCRBO model was developed and run to select the set of measures that minimizes the total annualized cost of the adaptation plan C for all the n stakeholders of the basin (assuming full cooperation in this first stage), while meeting the demands and minimum in-stream flow constraints at the subriver basin level. The in-stream environmental flow requirements were defined as minimum flow constraints at selected nodes of the river basin represented as a network flow. The target deliveries to the different water users were introduced as constraints for a given level of reliability. The adaptation measures (decision variables) include irrigation and urban water supply network efficiency improvement, as well as the possibility to implement infrastructure development projects such as desalination plant or groundwater projects. Climate change uncertainty is then considered to assess a least-regret portfolio, e.g., likely to perform reasonably under a range of possible future climate change scenarios [*Girard et al*., 2015b]. The objective function of the optimization problem for the n stakeholders can be formulated as:

$$\text{Minimise } C(\mathrm{N})=\sum_{i=1}^{\mathrm{n}} C(i) \tag{1}$$

where,

$$C\ (\mathrm{i})=\sum_{\mathrm{m,i}} \mathrm{Act}_{m,i}\times \mathrm{FC}_{m,i}+\sum_{\mathrm{t}}\sum_{\mathrm{m,i}} \mathrm{V}_{m,i,t}\times \mathrm{VC}_{m,i,t}/\mathrm{T} \tag{2}$$

N is the group made of n stakeholders of the river basin, {1, 2, . . .,i, . . ., n} = N; i is the index of the stakeholder from 1 to n; m is an index of the measures of urban or agricultural demand, groundwater or desalination project;t is the time step index (monthly);

Act(*m,i*) are binary decision variables about implementing (value 1) or not implementing (value 0) each measure m;

FC*(m,i)* is the fixed equivalent annual cost (€) of the measures, m;

V*(m,i,t)* is the volume of water in Mm^3/month coming from a measure with variable cost;

VC(*m,i*) is the variable cost of the measures in €/Mm^3/month;

T is the total number of years of optimization.

More details on the formulation of the constraints of the model can be found in Appendix A and in *Girard et al*. [2015a].

2.2. Cooperative Game Theory

In the second step, to deal with equity issues in the cost allocation of the adaptation plan, this first approach assumes that an equitable cost allocation can be identified by stakeholders through a negotiation process where they will form coalitions and come up with a certain cost allocation scenario. The outcome of the negotiation can be predicted using cooperative game theory, the branch of game theory dealing with the formation of coalitions and the allocation of cooperation benefits under binding agreements [*Montet and Serra*, 2003]. Benefits can also be cost savings, and include the possibility of side payments defined as monetary transfers [*Leyton-Brown*, 2008]. The application of cooperative game theory to water resources management problems dates back to the 1930s, when engineers and economists of the Tennessee Valley Authority (TVA) investigated ways of allocating the cost of multipurpose water resource development projects among multiple users [*Ransmeier*, 1942; *Straffin and Heaney*, 1981]. Since then, cooperative game theory has been applied to the management of water resources as a theoretical framework to analyze the possibility and stability of long-term agreements on the allocation of water resources or on cost-sharing agreements at the basin scale [*Young et al*., 1982; *Parrachino et al*., 2005; *Sechi et al*., 2013; *Lejano and Davos*, 1995; *Dinar and Howitt*, 1997].

Cooperative game theory (CGT) relies on a transferable utility assumption, considering that the total utility may be redistributed (transferred) among coalition players indifferently [*Leyton-Brown*, 2008]. In our case, we consider payoffs as an amount of money (cost or cost saving) and we assume that players derive the same utility from the same amount of money, then each coalition can be assigned a single monetary value as its payoff. Under the CGT approach, we consider that players' decisions to form coalitions are guided by the following economic principles: rationality, marginality, and efficiency.

The rationality principle implies that no player will join a coalition if this implies paying more than would have to be paid by staying on their own (equation (3)). It means that the sum of the individual cost y(i) allocated to the players i included in S must be lower than cost C(S) associated to a project of the subgroup of players S on their own for them to agree on the cost allocation of the total project. Otherwise they will not join the coalition, as they would pay a lower cost by staying among subgroup S and implementing a project for themselves.

$$\sum_{i \in S} y_i \le C(S) \;\; \forall \; S \;\; \in N \tag{3}$$

where

N is the group made of i players, {1,2,. . .,n}=N;i is an index representing a single player of the total of the group of n players (N);

S is any subgroup of players i included in N;

$Y=(y_1, y_2, \ldots, y_n)$ is a vector representing a given cost allocation associated to n player;

C(S) is the cost associated to subgroup S obtained from the equation (1).

The marginality principle (marginal individual cost coverage) assumes that a coalition will only accept a new player if this player pays at least the marginal cost of including them in the project (equation (4)).

$$\sum_{S} y_i \ge C(N) - C(N - S) \;\; \forall \; S \;\; \in N \tag{4}$$

Finally, the principle of efficiency states that all costs have to be met by the players of the grand coalition (the grand coalition is when all players join) (equation (5)).

$$\sum_{N} \mathrm{y_i} \ge C(N) \tag{5}$$

The Core of the game is the set of vectors Y (y_i) satisfying the previous set of constraints. The Core is a solution space, implying that there are multiple cost allocation vectors within that space that can be chosen by the players of the grand coalition.

The LCRBOM model developed in the first step (section 2.1) is used to assess the characteristic function of the game, defined as the set of all possible coalitions S included in N = {1, 2, . . ., n} and their associated costs C(S). The objective function is defined for each of the players individually or in coalition in a similar way so as to run multiple optimizations with different constraints. The players in a coalition are minimizing the sum of their costs C(S). A player outside of a coalition follows their stand-alone strategy optimizing their own cost without the possibility of activating measures from other players. Their stand-alone strategy defined thus imposes constraints on the measures available for the other players. Consequently, equations (3–5) are used to estimate the boundaries of the Core of the Game.

2.3. Social Justice Approach

The second approach adopts a different perspective. It assumes that the definition of an equitable cost allocation has to be constructed though social dialog, by considering the prevailing social, ethical, and philosophical values of stakeholders in their specific context. Such an approach corresponds to the perspective adopted in the social justice literature, following which, agent decisions related to the environment are strongly influenced by social justice principles [*Wenz*, 1988; *Neal et al*., 2014; *Syme*, 2012; *Zwarteveen and Boelens*, 2014].

Theories of social justice, grounded in economic sociology and economic psychology, adopt a different standpoint to define what an equitable cost allocation is. Instead of assuming that stakeholders can reach an agreement based on an optimization of individual monetary payoff, they assume that agreement is based on social, ethical, and philosophical values that shape the notion of distributive justice [*Wenz*, 1988; *Tyler and Blader*, 2000; *Neal et al*., 2014; *Syme*, 2012; *Zwarteveen and Boelens*, 2014]. Individuals may be willing to give up some monetary payoff for motives relating to altruism, solidarity, reciprocity, etc. This implies that stakeholders could agree on a cost allocation solution that would not match with what the CGT predicts.

The notion of distributive justice can refer to very different interpretations and philosophical principles [*Lamont and Favor*, 2013; *Syme and Nancarrow*, 1997; *Gross*, 2008; *Rinaudo et al*., 2016b] such as strict egalitarianism [*Nielsen*, 1979], the difference principle and equality of opportunity [*Rawls*, 1971], the

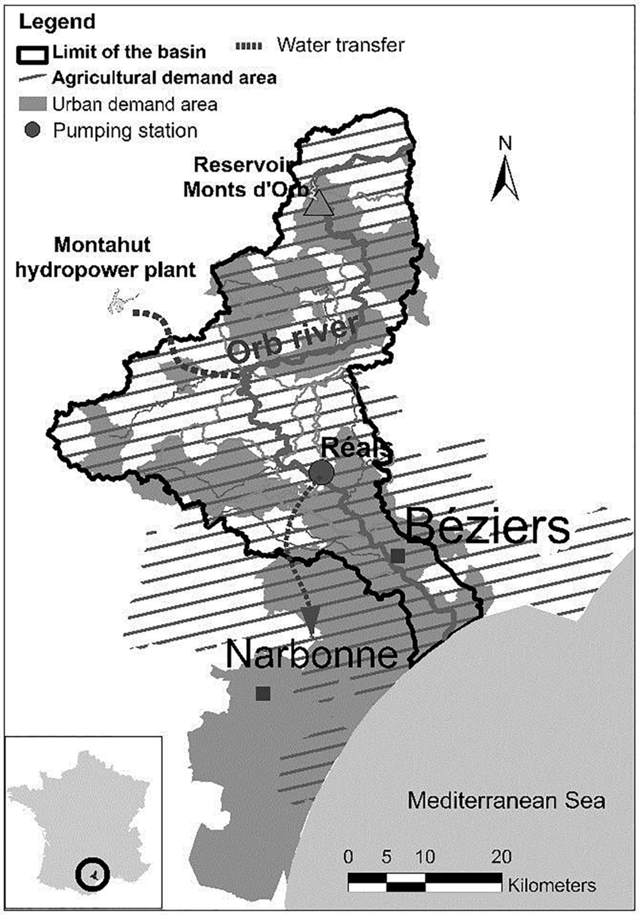

Figure 1. General map of the Orb River basin.

desert-based principle [*Sadurski*, 1985], welfare-based principles [*Mill*, 1861] and libertarian principles [*Nozic*, 1974]:

1. According to the "prior appropriation" principle, people who first use the resource are entitled to keep it (entitlements) provided they do not violate the rights of others. Applied to cost allocation problems, this principle means that the cost of managing water scarcity should be attributed to the most recent water users, who contributed to creating the water scarcity problem.
2. "Strict egalitarianism" assumes that people are morally equal, and that equality in material goods and services is the best way to give effect to this moral ideal. Applied to a cost allocation problem, this can be used as each water user in a basin bears an equal share of management cost, proportional to the quantity of water delivered to each user.
3. The "difference principle" assumes that inequalities in the distribution of resources and costs are acceptable if they improve the situation of the worst-off in a society, whereas the "equality of opportunity" principle aims at attenuating inherited sources of inequalities (gender, race, etc.). This could support the idea that users located in poor remote rural areas should bear a smaller share of the cost than better-off users of urban areas, for example.
4. The "desert principle" assumes that resources should be allocated considering the socially valuable efforts (i.e., leading to the production of goods and services desired by others) made by each group or individual. In the case of water management, this would support the idea that efficient users (e.g., municipalities where losses in distribution networks are small) should be advantaged in the cost allocation process in comparison with less efficient municipalities.
5. Welfare-based principles of justice assume that the allocation of cost and resources should maximize social welfare, defined as the sum of individual satisfied preferences, and frequently interpreted in terms of economic wealth (utilitarian approach).

Social justice approaches have been barely applied to water resources management, mainly for addressing the problem of water resources allocation [*Syme and Nancarrow*, 1997; *Gross*, 2008; *Moreau et al.* 2015; *Rinaudo et al.*, 2016b]. The operational approach implemented in this paper consisted in defining a limited number of cost allocation scenarios, each being based on one of the social justice definitions given above. The scenarios were then presented and discussed with the main stakeholders of the basin, and ranked in terms of acceptability. The design of the scenarios was inspired by previous research on groundwater allocation [*Rinaudo et al.*, 2016b]. Scenarios were adapted to the cost allocation issue and presented as short narratives integrating elements from the local context. Stakeholders' perception was collected through face-to-face semistructured interviews. Interviewees were asked if they considered the different scenarios as leading to a fair and equitable distribution of the cost, as well as to identifying their preferred option.

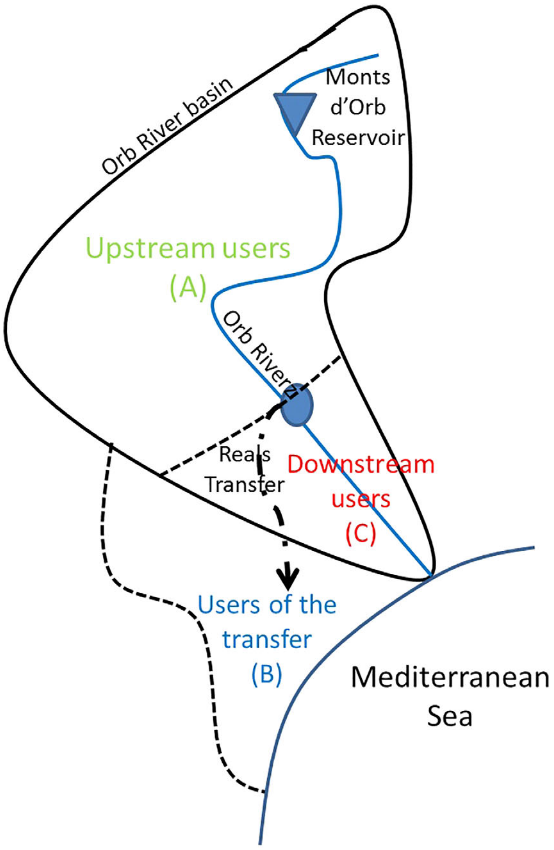

Figure 2. Schematic representation of the Orb River basin for addressing cost allocation.

In parallel to this survey, we estimated the actual cost that would be borne by each actor within each of these scenarios. These quantitative results are then compared with those obtained from the cooperative game theory approach presented in the previous section.

3. Case Study and Implementation

3.1. The Orb River Basin (France)

The two stages methodological approach presented above was implemented in the Orb River basin. This is a Mediterranean basin located in southern France, where global change is expected to exacerbate the existing imbalance between available water resources and increasing water demands [*Girard et al.*, 2015c]. Water scarcity is an emerging issue in the basin. The projections for the near-future (2020–2049) over the French Mediterranean rim, predict a warmer climate compared to the present (+1.5°C) [*Taylor et al.*, 2012; *Terray and Boé*, 2013]. In the Orb River basin, a +10 to −55% variation in average interannual flow is forecasted for a midterm horizon (2050–2070) [*Chazot et al.*, 2012].

The Orb River basin is relatively small in extension (1580 km^2, Figure 1), but is at the heart of local and regional water management issues, since water resources are also transferred to the neighboring coastal area (around Narbonne city). The region experiences the highest population growth rate in the country (1.6% per year), associated with important seasonal variation due to the tourist population in the summer. The demand to irrigate the vineyards is increasing fast in order to secure constant production and quality levels to meet the requirements of the market. Supplying urban water demand means competing in space and time with agricultural and environmental water demand.

River flows are regulated by a 30 Mm^3 reservoir (Mont d'Orb), which is operated to offset the effects of a large interbasin transfer diversion in the lower part of the basin (Réals transfer). In the last two decades, the Orb River basin stakeholders have teamed up in a single stakeholder platform, the Orb River Basin Management Board. It is composed of representatives of water users (including associations for environmental protection and recreational activities), government agencies, and elected members of local authorities. The board develops the local water management plan and identifies specific management actions to be supported by public funds. Those actions are then implemented by local water users owning, managing, and developing their own infrastructure. No single water manager has the possibility of implementing measures at the river basin level, so management must be agreed collaboratively among stakeholders.

3.2. Least-Cost Adaptation Portfolio

The LCRBO model defines a least-cost adaptation portfolio to adapt to global change at the river basin scale [*Girard et al.*, 2015a, *Girard*, 2015]. The optimization spans over a multiannual monthly flow series integrating successions of wet and dry periods for the future midterm climate scenario (2046–2065) and agricultural and urban demand estimates for the planning horizon. This LCRBO model has been developed using GAMS (General Algebraic Modeling System), applying Mixed Integer Linear Programming based on the Cplex solver (www.gams.com). We determined the least-cost adaptation portfolio that ensures that the environmental flow requirements are met at 11 nodes, and 64 urban and 19 agricultural demand units are supplied with the required reliability. The LCRBO model selects the least-cost portfolio of measures out of the 462 possible

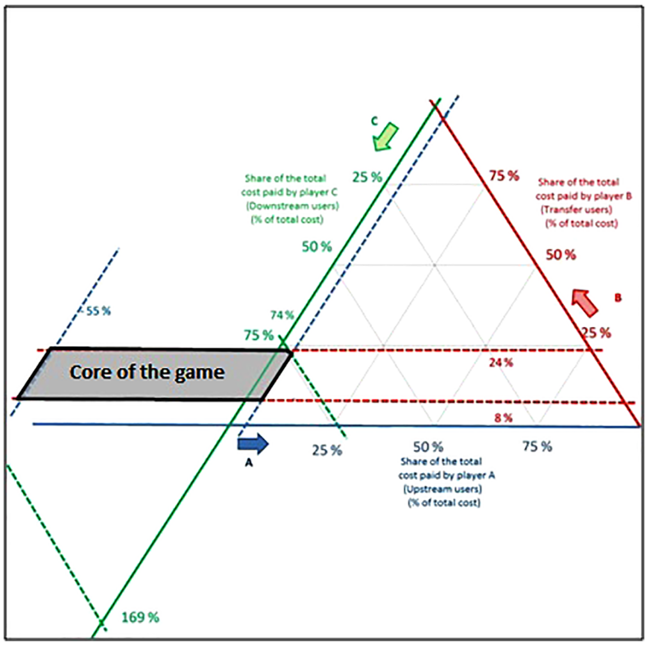

Figure 3. Cost allocations following cooperative game theory approach. (a–c) The triangle plot represents the three users of the cost allocation problems as the three sides of a triangle. Each cost allocation scenario can be represented as a point with three coordinates corresponding to the share allocated to each user, the sum of the three contributions being always equal to 100%.

measures by running the optimization over a 20 year monthly time flow series for the midterm climate scenario (2046–2065) [*Girard et al.*, 2015a]. The optimization is repeated for nine different climate change scenarios and a least-regret portfolio is selected balancing the cost of the portfolio with the level of agricultural deficit [*Girard*, 2015]. The cost of the corresponding portfolio is 3.05 M€/yr (investment, operation, and maintenance costs). Measures aiming at improving water use efficiency in agriculture (changing to drip or sprinkler irrigation) and the drinking water sector (leakages reductions) all over the river basin should be implemented with priority. However, if these improvements are not undertaken by some of the players, then infrastructure development measures are needed such as desalination plants (downstream) or groundwater projects in different locations of the basin (*Girard, et al.*, 2015a). It could be considered unfair to ask a player to implement and pay a measure on their own because this measure is considered as cost-effective or robust at the river basin scale. The issue is now how to allocate the cost of such an adaptation plan at the river basin scale among the different users and to define a compensation scheme with monetary transfers to ensure that the plan is considered acceptable, based on a cost allocation perceived as equitable.

3.3. Implementing the CGT Approach

For the implementation of game theory concepts, we propose a simplified representation of the Orb River basin and the stakeholders involved in the implementation of the adaptation portfolio [*Girard*, 2015]. We assume that the basin comprises three main players: A, B, and C. Player A (Figure 2) corresponds to all users in upstream rural areas with low-density population and gravity irrigation systems. Player B represents users supplied by the interbasin transfer. Player (C) corresponds to the downstream subbasin with densely populated urban areas and an intensively irrigated agriculture. In order to simplify the formulation of the problem, we also consider each player as taking management decisions for agriculture and urban areas together in each area. One of the main features of the game is that the upstream reservoir is operated by player B since the reservoir was constructed to offset water diverted from the basin by this player.

In a noncooperative situation, players take decisions independently from each other: each one would design their own program of measure at the subbasin level to ensure that the water demands of the users in their area are satisfied while meeting the environmental flow requirements at the outlet of their subbasin. Player B can optimize the use of the reservoir operation to meet their demand and minimum flow constraints, without considering the other two players. Player B thus has to pay the cost of operating and managing the reservoir alone (€690,000/yr), and to implement additional measures if necessary. Players A and C also implement measures independently from each other (water conservation or capacity development) without being able to influence the management of the reservoir. We will name the Program of Measures (PoM) corresponding to these noncooperative situations as PoM_A, PoM_B, and PoM_C (stand-alone solutions of players A, B and C) and their costs as C_A, C_A, and C_C.

Alternatively, the three players can also decide to cooperate to reach the objectives in the three subbasins at the lowest cost for A, B and C together. In this case, cooperation means: (1) that the management of the reservoir is optimized for meeting the three environmental flow constraints in subbasin A, B, and C; (2)

Table 1. Description of the Characteristic Functions of the Three-Player Game

Coalition	Optimization Problems		
	A	B	C
A, B, C stand-alone	Min C(A)	Min C(B)	Min C(C)
AB, C	Min C(A + B)		Min C(C)
AC, B	Min C(A + C)	Min C(B)	Min C(A + C)
A, BC	Min C(A)	Min C(B + C)	
ABC (grand coalition)	Min C(A + B + C)		

additional measures are implemented for minimizing their total cost for the coalition. Let us call PoM_{ABC} the PoM corresponding to the cooperative case and C_{ABC} its cost. The measures of the least-cost PoM_{ABC} will only be implemented by A, B, and C if they agree on how to share their cost. We can expect each player A, B, and C to compare the cost of the stand-alone solution (C(A), C(B), and C(C)) with the share of the cost C_{ABC} they would have to pay (called Y_A, Y_B, and Y_C) if they cooperate. Intermediary solutions also exist, where only two players would cooperate while the other would decide to stand-alone.

Identifying the CGT solution requires estimating the cost associated with each possible coalition, to construct the characteristic function of the game (the set of all the coalitions and associated costs; Table 1). The LCRBO model presented previously (sections 2.1 and 3.2) is used to assess the characteristic function of the game defined as the cost of the PoM for A, B, and C in the different coalitions by modifying the objective function to fit the players of the coalition and by defining the measures implemented by others as constraints.

The first row corresponds to the case where all players follow a stand-alone strategy, selecting independently the measures they need to implement and supporting the related cost alone. It corresponds to a sequential optimization from the upstream to the downstream player: the upstream player A optimizes the management of their subbasin, then player B optimizes a program of measures bearing in mind the measures implemented by A but without any possibility of modifying them, and C comes at the end, assuming the measures applied by A and B as given. It corresponds to the optimization of the objective function defined in equation (1) for $N = \{A\},\{B\},\{C\}$ successively, adding the measures previously selected as constraints.

The bottom row corresponds to the grand coalition, where the three players jointly implement the least-cost solution and share its cost after agreeing on compensatory payments within the coalition if needed. It corresponds to the optimization of the objective function defined in equation (1) for $N = \{A, B, C\}$. The grand coalition combines the three player actions, to minimize the deficit at the full river basin scale, corresponding to the solution described in section 3.2. The priorities in the management of infrastructure (reservoir) are taken into account in the optimization to supply the users. For instance, if B has a priority on the management of the reservoir, the reservoir is optimized first to supply B, then C and A.

3.4. Implementing the Social Justice Approach

3.4.1. Cost Allocation Scenario

The general conceptions of social justice previously defined (section 2.2) were used to formulate cost allocation scenarios specifically applied to the Orb River basin case study. The formulation of these scenarios was adapted based on discussions with local key informants. They are briefly presented below.

S1: Allocation proportional to water withdrawals. Each water user pays a share of the cost of the adaptation plan proportional to the volume withdrawn (as a percent of total abstraction in 2030). An upstream or downstream user that withdraws 10% of the total volume of water withdrawn would pay 10% of the total cost of the plan.

S2: Allocation proportional to the increase in water abstraction from 2008 to 2030. Each user pays in proportion to its increase in water abstraction from 2008 to 2030 as a percentage of the total increase at river basin level. This allocation relies on the assumption that no adaptation would be needed if there was no increase in demand (the effect of climate change alone is not enough). The cost of the adaptation plan is therefore allocated among the users responsible for this increase, rewarding those that have controlled their increase in demand (desert principle).

S3: Allocation proportional to saving efforts. An abstraction quota is allocated to each water user, calculated by the river basin authority based on technical criteria [*Rinaudo et al.*, 2016b]. In urban water supply, this quota takes into account: the type of water supply service (urban or rural), the presence of economic and industrial activities, and the efficiency of the water supply networks. In the agricultural sector, the quota accounts for the irrigated area and the type of crops and the efficiency of irrigation. Users pay proportionally to what they withdraw in excess of their quota. This scenario rewards the efforts already undertaken by each user to improve their water use efficiency (desert principle).

S4: Allocation proportional to deficits. Costs are allocated to the users of subbasins that would experience a deficit in 2030 without any action plan. Those subbasins without water deficits are not required to contribute even if measures are applied in their area to avoid deficits elsewhere. This scenario takes into account that some subbasins are water rich and their water savings will mainly benefit other water-poor subbasins (prior appropriation principle).

S5: Allocation taking into account the initial function of the Monts d'Orb reservoir. The upstream Monts d'Orb reservoir was initially built to offset the impact of the water transfers. Therefore, the cost of the adaptation plan is allocated between the users not benefitting from this transfer (A and C), considering that the users of the water transfer (B) implicitly have a right to the water stored in the reservoir (prior appropriation principle).

S6: Allocation following the users' capacity to pay. This scenario assumes that payment must be proportional to the financial capacity of the users. It is considered fair to ask the urban and touristic users to pay more than the agricultural users. The cost is allocated proportionally to the abstractions and then weighted proportionally to the economic value of the water uses (difference principle).

S7: Allocation proportional to the wealth of the territories. The cost is allocated based on the wealth generated in each territory (subbasin). It is considered as fair that wealthier urban territories pay more than poorer rural ones (equal opportunity principle). Cost is allocated in proportion to the volume abstracted, weighted by a factor proportional to the wealth of each territory (subbasin).

S8: Allocation proportional to summer abstractions. The adaptation plan is mainly designed to supply the summer peak demand (from May to September). Thus, its cost could be allocated in proportion to the share of water abstractions during this period. This scenario increases the share paid by seasonal users, such as the agriculture and tourist sectors (desert principle).

S9: Allocation to water users located outside the basin. The cost is allocated only to the water users outside the Orb River basin (belonging to B). Indeed, no adaptation plan would be needed in the absence of this transfer. Cost is shared proportionally to their water withdrawals. In this scenario, fairness is considered as giving the priority of water allocation to the user within the river basin (prior appropriation principle).

3.4.2. Field Survey

In order to understand the perception that the local actors have of these different social justice principles, we conducted a survey. Fifteen key-informants from different areas located inside or outside the basin, upstream or downstream, and different sectors (urban/agricultural) were interviewed in semistructured face-to-face interviews (see list and map in Appendix B). First of all, the context of the adaptation to climate change was introduced, as well as the measures probably needed to ensure that water management objectives are met at the river basin scale. Then, the nine scenarios were presented and discussed with the key informants prior to asking them if they considered each scenario to be an equitable distribution of the cost of the adaptation measures (Figure 4).

3.4.3. Cost Allocation Scenarios for Each Scenario

The next step of the analysis consisted of quantifying the distribution of the cost among players for each scenario (we assumed the same three players A, B, and C as in the game theory setting to allow a comparison of the results). The data provided to estimate the cost allocation associated with each scenario have been collected from previous local studies in the area for: water withdrawals, the potential of saving efforts, and the allocation of water among the various users [*Vernier and Rinaudo*, 2012; *Rinaudo et al*., 2016b]. The territory wealth has been estimated based on statistical data provided on financial potential per inhabitant (*"potentiel financier par habitant,"* indicator of the wealth of a territory) of the local municipalities of the study area [*Direction Générale des Collectivités Locales (DGCL)*, 2013]. The relative ability of users to pay has been approximated as the current difference between the urban and agricultural water fees, as a first proxy [*Ministère de l'Energie et du Développement Durable (MEDDE)*, 2012] (more details in Appendix C).

4. Results

4.1. Results of the CGT

4.1.1. The Characteristic Function

Cooperation between the three users permits the reduction of the total cost by a factor of 2 (from 6 to 3 M€/yr) as compared to the stand-alone situation (Table 2), theoretically providing very significant incentives for cooperation. However, the contributions of the different users have to be considered in order to ensure

Table 2. Characteristic Function of the Three-Player Cost Allocation Game

Coalition	Cost (€M)			Total Cost
C_A, C_B, C_C (stand-alone)	0.12	0.69	5.15	5.96
C_{AB}, C_C	0.79		5.15	5.93
C_A, C_{BC}	0.12	4.74		4.86
C_B, C_{AC}	0.69	2.81		3.50
C_{ABC} (grand coalition)		3.05		3.05

that the three players will join the grand coalition. Indeed, the distribution of the cost of the stand-alone solutions is unbalanced. Whereas the upstream players (A) and (B) have a low-cost stand-alone strategy (respectively, €0.12M and €0.69M) that could be an incentive to stand-alone, the downstream player (C) bears the highest cost (€5.15M), and would therefore be the main beneficiary of cooperation. These differences must be considered in the definition of a fair allocation of the cost between the players of the grand coalition.

4.1.2. The Core of the Game

Applying cooperative game theory principles, a cost allocation must follow the principles of rationality, marginality, and efficiency (section 2.1, equations (3)–(5)) to ensure that the solution is acceptable among different players and fits within the boundaries of the Core of the game (Table 3 and triangular plot in Figure 3). The Core of this three player Game is represented in the triangular plot of Figure 3. Each axis represents a player and the percentage of the total cost they will have to pay for a given allocation. The sum of the three coordinates is always equal to 100%. The boundaries of the Core are represented through the minimum and maximum dotted line for each player. The boundaries of the Core calculated in the cost allocation problem in the Orb River basin indicate that downstream users (C) should pay the highest share of the total cost (more than 74%). In addition, downstream users could provide incentives, such as a monetary transfer within a compensation scheme to the other users, to ensure that they join the grand coalition (Y_C can be higher than 100% of the total cost, and Y_A can be negative). In this case the transfer received by player A has an upper limit fixed at €1.69M. In contrast, player C could pay a monetary transfer to A and B up to €2.10M ($=5.15-3.05$). As mentioned previously, C was the player with greatest interest in the coalition due to the elevated cost of employing a stand-alone solution. The cost allocation should consider this issue, allocating a higher share to C. Player C could even provide incentives to join the grand coalition by a redistribution of the cost saved in comparison with a stand-alone solution.

4.2. Results of the Social Justice Approach

Based on the results of the survey (Figure 4), the scenario perceived as the most equitable is the one acknowledging the efforts in water savings accomplished by the different users (S3). This scenario was chosen almost unanimously by the key informants interviewed, who agreed on the value of rewarding effort (desert principle). However, they also pointed out the difficulty of technically defining the saving objectives for each user and the high burden placed on users that could already experience difficulties in efficiently managing their water services. For example, rural municipalities with less resources and a less efficient network having limited technical and financial resources to improve the efficiency of their system than wealthier urban municipalities.

The S3 scenario is followed in the ranking by a set of five scenarios considered as fair by about two thirds of the key informants. They are all based on different types of proportionality to the volume withdrawn or economic criteria (S8, S1, S6, S7, and S2) and correspond to different social justice principles, from strict equality and desert principles for the first two, to equal opportunity and difference principles. The idea of volumetric proportionality is seen as fair as it provides some reward (the more you abstract, the more you pay) and is

Table 3. Boundaries of the Core of the Three-Player Cost Allocation Game

Principle	Player Cost Allocation	Value (Cost in €M)	% of ABC Cost
Efficiency (all costs are allocated)	$Y_A + Y_B + Y_C =$	3.05	100%
Rationality (maximum = player × cannot pay more than the stand-alone cost, $Y_X \leq$)	$Y_A \leq$	0.12	4%
	$Y_B \leq$	0.69	23%
	$Y_C \leq$	5.15	169%
Marginality (Minimum = Player X cannot pay less than the marginal entry cost in the coalition, $Y_X \geq$)	$Y_A \geq$	−1.69	−55%
	$Y_B \geq$	0.24	8%
	$Y_C \geq$	2.26	74%

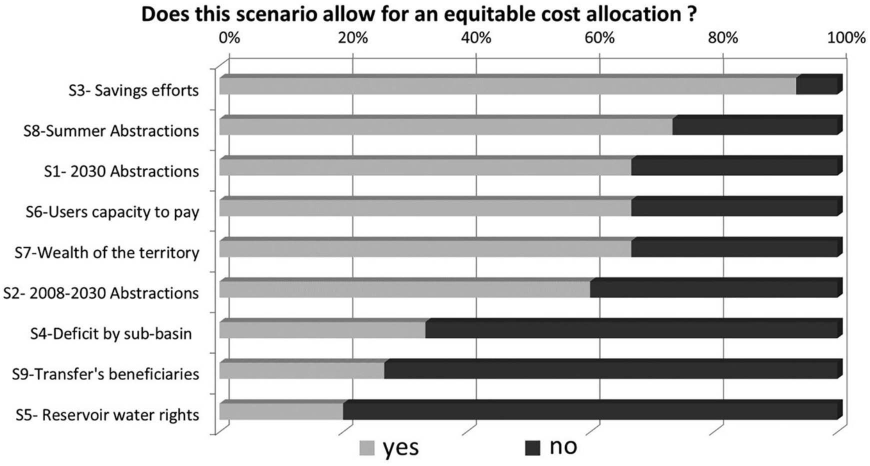

Figure 4. Equity of cost allocation scenarios (N = 15).

valued as well for its relative simplicity in terms of implementation. However, interviewees expressed as well that the various users need to be differentiated in accordance with additional characteristics to account for varying levels of development (history of water use) or for the economic characteristic of the users (capacity to pay and income level).

The last three scenarios (S4, S9, and S5) are considered inequitable by more than two thirds of the key informants. They reject the prior appropriation principle underlying those three scenarios, as some of the

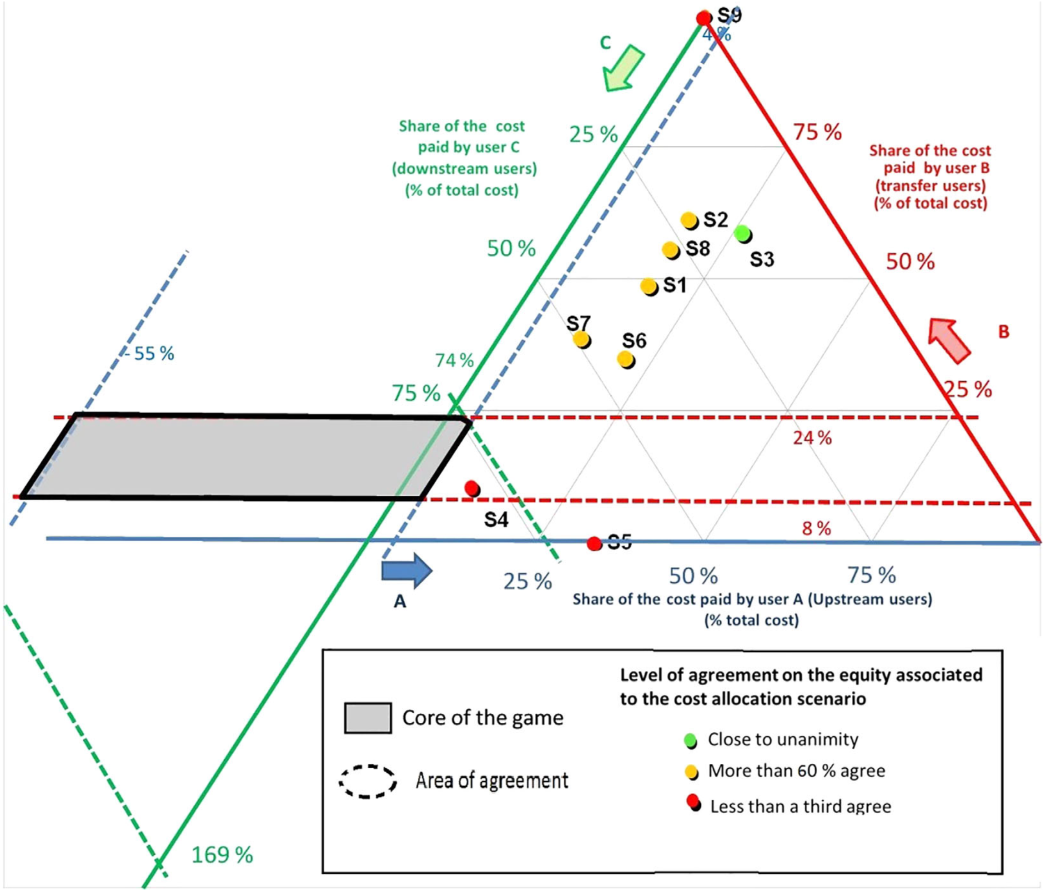

Figure 5. (a–c) Comparison of the cost allocation scenarios among the three players.

users would have bear the burden of the cost of the adaptation plan on their own. It is noticeable that for these three scenarios, the users favored under one scenario (no cost to be paid) did not systematically define this scenario as fair, arguing that the idea of not paying a share of the plan was unacceptable. This illustrates that stakeholders may defend options that do not necessarily coincide with their economic interest if they are in line with some of their philosophical, cultural, and social values. These results suggest that no single criterion can capture the complexity of the social justice issue associated with the cost allocation problem. A combination of different cost allocation rules (and their underlying principles of social justice) could be needed to ensure that the different values defended by stakeholders are considered while defining a socially acceptable cost allocation rule.

4.3. Comparing Cost Allocation Scenarios

In order to compare the cost allocation solutions from the different approaches, the cooperative game theory (CGT) and the social justice approach solutions are all plotted on a single triangle plot (Figure 5). The application of the principle of proportionality to water withdrawals (considering either the 2030 withdrawals (S1), the increase between 2008 and 2030 (S2), or the summer withdrawals in 2030 (S8)) leads to a similar cost allocation among the three players. The highest share is assigned to the users of the transfer (B from 58.8 to 61.2% of the total cost), and the lowest share is given to the upstream users (A around 17%). Two solutions (S5 and S9) are almost opposite depending on the definition of the priority over the use of the water resources. If we give the priority to the historical water right of the transfer, then the other sector will share the total cost (S5). On the other hand, if we consider that the users from the river basin have a priority, then the users benefitting from the transfer will bear the entire cost of the PoM (S9). The solution allocating cost proportionally to deficit (S4) leads to the highest share of the cost being allocated (80%) to the downstream users, considering that upstream users have a priority on the use of the resource.

The solutions following CGT principles (Core), recommending that a higher part of the cost be paid by the downstream users (C), are close to the cost allocation scenarios giving a priority to the users of the transfer from the Orb resources (S4). This scenario is the closest to those following CGT principles, given that it respects two of the three boundary conditions of the Core (for B and C, not for A). The remaining solutions following other social justice concepts are further from the CGT solutions. The furthest solution from the CGT is the one where all the costs are be paid by user B (S9), who benefits from the water transfer and manages the upstream reservoir. The area of agreement among social justice principles (dotted lines in Figure 5) lies outside the Core, and allocates almost half of the costs to user B.

The CGT approach informs us that the grand coalition is strategically attractive (the Core is nonempty—some solutions exist within its boundaries), but side payment in the form of monetary transfers may be required to ensure its stability (from C to A and B). The social justice approach brings in different results, especially the fact that a cost allocation including large side payments between users would not be perceived as fair. A cost allocation rule that recognized the efforts already implemented would probably be more widely accepted and form the basis of an agreement.

5. Discussion and Conclusions

The approach presented in this paper develops a two-stage decision-making approach in order to design cost-effective and equitable adaptation portfolios. First, it builds upon the previous results from a Least-Cost River Basin Optimization Model to define a least-cost and robust portfolio of adaptation measures at the river basin scale [*Girard et al.*, 2015a, 2015d]. Furthermore, to address the acceptability of the implementation of the plan, two different approaches were presented for sharing the cost of the plan: cooperative game theory and social justice. Contrasted insights were obtained from a survey identifying the social justice principles to be considered in the definition of a cost allocation rule, and from the assessment of the outcomes of a negotiation process over cost allocation and monetary transfer based on cooperative game theory.

In the French case study, the implementation of the cooperative game theory reveals the potential outcomes of a negotiation among the various users at the river basin scale. To ensure the formation of the grand coalition involving all the stakeholders, important side payments in the form of monetary transfers would be required from the downstream users to the users benefitting from the historical water rights of the water transfer, which was granted before climate change became an issue. However, such an agreement will be perceived as unfair by various stakeholders, highlighting the need to consider alternative principles of social justice to solve the cost allocation issue. The debate on the cost allocation involved in adaptation to climate change is influenced by the historical water resources allocation. Thus, an equitable cost allocation would need to be defined in the light of the historical water allocation, giving some more room for negotiation.

These results illustrate the large differences between a possible allocation defined according to an agreement grounded in social justice principles, and the economic and strategic position that some users could undertake in a negotiation process. Although all the cost allocation solutions seem to agree on attributing a low share of the costs to upstream user A, they differ significantly on the cost allocation between the two main users, B and C. Following economic rationality considerations, B should pay less than C and may claim monetary transfers to implement measures. However, following a social justice approach B should pay more than C. If the local authority lets the users agree on a cost allocation, users A and B would have more power of negotiation than player C, mainly due to their localization upstream of the river basin and to the historical water rights attributed to the users of the water transfer (B) that allow them to further develop and face climate change uncertainty on their own.

To some extent, this reflects the rising conflict between the water users located downstream of the transfer (player C) and the regional water company managing the reservoir and the users located outside of the river basin (player B). On the one hand, the downstream users demand more water from the reservoir to secure their development, considering that the water right allocated to the transfer was too generous at the time it was granted and needs to be reduced. On the other hand, the regional company, which manages the reservoir and supplies farmers and urban users, would agree on the possibility to release more water but in exchange for a monetary compensation.

The issue remains as to the definition of this monetary compensation. The previous results suggest that some issue linkage could be found between the monetary compensation for the allocation of the cost of the portfolio of measures and the reallocation of water withdrawal authorizations at the river basin scale. This could be a way to provide new substance for the on-going negotiation process on adaptation development, as highlighted in the literature [*Bruce and Madani*, 2015].

Different limitations can be pinpointed in relation with the approach adopted for the study of the cost allocation issue.

First, uncertainty linked to the long-term climate conditions are considered only in the first stage of the method during the definition of the least-regret adaptation portfolio under different climate projections [*Girard et al*., 2015b]. The consideration of this uncertainty during the definition of cost allocation solution (second step) could be improved by comparing results under different future climate projections to assess the impact of uncertainties on the stability of the coalition. The cost allocation scenarios could be reassessed under different climate projections, to finally identify a solution space considering climate uncertainties.

Our implementation of the CGT approach relies on a limited definition of the utility of each player restricted to the direct financial cost (equivalent annualized cost of investment, operation, and maintenance). A full economic analysis would include the estimation of indirect costs for each user in the implementation of measures in their area. It should also integrate the benefits for each user, bringing more elements in the analysis of an efficient and fair definition of the portfolio of measures. This could enable the Core of the game and the feasibility set to be extended. However, the assessment of these benefits could also be more controversial and probably exacerbate the difficulty in reaching an agreement between the different users discussing the evaluation methods or challenging the transferable utility assumption, given the complex nature of water resources.

An alternative approach would be to modify the optimization framework to enforce some additional constraints related to equity. For instance, defining equity criteria in order to assess the trade-offs between equity and the efficiency of an optimum program of measures. The spatial resolution of the analysis could be improved through the development of an agent-based model, or through the use of a decentralized optimization framework to perform the optimization at the subbasin level, or a finer spatial scale of analyses, which would reflect the interactions between stakeholders in more detail. The optimization framework could allow the different players to modify their strategies in response to the coalition made by other players, instead of considering that they will continue with their stand-alone solution, for instance, through a reinforcement learning approach [*Madani and Hooshyar*, 2014].

The implementation of the social justice approach relies on the definition of alternative scenarios based on theoretical social justice principles and translated into the real case study. These principles have been discussed with key informants of the case study. However, to ensure the consistency of this translation and to fully capture the principles at stake in the river basin, the scenario would benefit from a codevelopment of the cost-allocation scenarios through a participatory process involving the relevant stakeholders involved in the decision-making process. This would also allow the possibility of investigating the issue of social justice not only from an allocative justice perspective, but also from a procedural justice perspective, recognizing the importance of the way stakeholders take part in the decision-making process involved in defining the allocation of costs or benefits [*Lawrence et al.*, 1997]. Thus, considering these different aspects of the social justice approach would enable the achievement of the overall objective of a "just distribution justly achieved" [*Harvey*, 1973].

As a conclusion, the allocation of the cost of the least-cost portfolio adaptation measures has been addressed through two complementary approaches: one, representing the potential outcomes of stakeholder negotiation based on the principles of cooperative game theory; and the other, defining an equitable cost allocation rule based on social justice principles discussed with key informants through a field survey. This permits equity and acceptability issues to be considered when defining the adaptation strategies. This combined approach captures different rationales to be considered in the negotiation of cost allocation. Far from providing a ready-to-use cost allocation solution that would not be relevant, the comparison of approaches provides some elements to approach the problem from different perspectives. This allows the different representations of the problem to be quantified and represented on a common basis, providing food for thought during the necessary negotiation process, which can enable a consensus on the decision to be achieved. In the case study considered, addressing the cost allocation issue could require reconsidering the historical way of managing the reservoir, changing from its actual function of compensating water transfer considering the possibility of supporting water management and ensuring equity among the various stakeholders of the river basin.

Appendix A: Least-Cost River Basin Optimization Model

Objective function:

$$\text{Minimise } C(N)=\sum_{i=1}^{N} C(i) \tag{A1}$$

where

$$\mathrm{C}\ \ (\mathrm{i})=\sum_{\mathrm{m,i}} \mathrm{Act}_{m,i}\times \mathrm{FC}_{m,i}+\sum_{\mathrm{t}}\sum_{\mathrm{m,i}} \mathrm{V}_{m,i,t}\times \mathrm{VC}_{m,i,t}/\mathrm{T} \tag{A2}$$

N is the group made of i stakeholders or players of the river basin, {1, 2, . . ., n} = N;m is an index of the measures of urban or agricultural demand, groundwater or desalination project;t is the time step index (monthly);

Act(m,i) are binary decision variables about implementing (value 1) or not implementing (value 0) each measure m by a player i;

FC(m,i) is the fixed equivalent annual cost (€) of the measures, m;

V(m,i,t) is the volume of water in Mm^3/month coming from a measure with variable cost;

VC(m,i) is the variable cost of the measures in €/Mm^3/month;

T is the total number of years of optimization.

The equation below presents a detailed version of this equation

$$\begin{aligned}C\ (i)= & \sum_{ma,i} AA_{ma,i}\times CA_{ma,i}+\sum_{mu,i} AU_{mu,i}\times CU_{mu,i}+\sum_{mgw,i} AGW_{gw,i}\times CGW_{gw,i}+\sum_{mds,i} ADS_{mds,i}\times CDS_{mds,i}\\ & +\ \textstyle\sum_t \displaystyle\sum_{mgw,i} VGW_{gw,t}\times VCGW_{gw,i}/T+\sum_{t}\sum_{mds,i} VDS_{mds,i,t}\times VCDS_{mds,i}/T\ \ \forall i\end{aligned} \tag{A3}$$

where, for each stakeholder i of the basin mu, ma, mgw, and mds are indices of the measures of urban or agricultural demand, groundwater or desalination project respectively; t is time step (monthly) index; AA, AU, AGW, ADS are binary activation variables of the measures mu, ma, mgw, and mds; CU, CA, CGW, and CDS are fixed equivalent annual cost (€) of mu, ma, gw, and mds, respectively; VGW and VDS are the volume of water in Mm^3/month of the measure mgw and mds, respectively; VCGW and VCDS are the variable costs of the measures gw and mds in €/Mm^3/month divided by the total number of year T of the optimization.

Subject to:

Demand and supply side measures

$$\begin{aligned}SU_{t,u,i}= & \ DU_{t,u,i}-\sum_{mu,i} AU_{mu,i}\times VU_{mu,t,i}\times CM_{U_{MU}\,mu,u,i}-\sum_{mgw} VGW_{gw,t,i}\times CM_{GW_U\,mgw,u,i}\\ & -\sum_{mds} VDS_{mds,t,i}\times CM_D S_U mds,u,i\ \ \forall t,u,I\end{aligned} \tag{A4}$$

$$SA_{t,a,i}=DA_{t,a,i}-\sum_{ma,i} AA_{ma,i}\times VA_{ma,t,i}\times CM_A MA_{ma,a,i}\quad \forall t,a,I \tag{A5}$$

where SU and SA are the supply of u (a respectively) after the activation of the measures; DU and DA are the demand of the ADU "u" and ADA "a" at t, respectively; VU and VA are water saving (Mm^3/month) for mu or ma, respectively; CM_U_MU is a Connectivity Matrix between the "mu" and the demand "u" (respectively, CM_A_MA); CM_GW_U: Connectivity Matrix between the measures "mgw" and the demand "u", respectively, CM_DS_U.

Supply and resources balance:

$$V_{t,n,i}=V_{t-1,n,i}+\ I_{t,n,i}+\ D_{t,n,i}-\ SU_{t,n,i}-\ SA_{t,n,i}+R_{t,n,i}-\ E_{t,n,i}\forall\ t,n,i \tag{A6}$$

where n is the number of indices of the node; I is the monthly inflow at node n; D is the discharge from n; Vis the volume of the reservoir; R is the volume released from the reservoir (in our case only reservoir at n1 else V = 0 and R = 0, at t = 0 with set $V = V_0 = 19.7\ Mm^3$).

Environmental flow constraints:

$$D_{t,n,i}\geq E_{t,n,i}\ \ \forall t,n,I \tag{A7}$$

where E is the level of the in-stream environmental flow requirements at n.

Reservoir constraint:

$$Vmax_t\ \ \geq\ \ V_{t,n1}\geq Vmin\ \ \forall\ t \tag{A8}$$

where Vmin and Vmax are the minimum and maximum volumes of the reservoir at n1.

Return:

$$R_{n,t,i}=\ \sum_u SU_{u,t,i}\times MC_R U\ _{u,n,i}+\ \sum_a SA_{a,t,i}\times MC_R A_{a,n,i}\ \ \forall\ t,n,i \tag{A9}$$

where MC_RU is the connectivity matrix connecting the return from a supply SU of an UDU to a node n (respectively ADU).

Evaporation from the reservoir

$$A_{t,n}=a\times V_{t,n}+b\ \ \forall t,n \tag{A10}$$

$$\mathrm{EV}_{t,n} = \frac{\mathrm{A}_{t,n} + \mathrm{A}_{t-1,n}}{2} \times \frac{\mathrm{ER}_{t,n}}{1000} \quad \forall \ \mathrm{t, n} \tag{A11}$$

where a and b are two parameters defined by linear regression; A is a positive variable presenting the area of the reservoir (in km^2) calculated from the Volume V of the reservoir; ER is the monthly Evaporation Rate defined in mm and therefore divided by 1000 to calculate the evaporation in Mm^3 directly.

Desalination measures:

Capacity and activation constraint: limits the capacity of the desalination plant and the availability of water to connectable UDUs.

$$\sum_{\mathrm{u}} \mathrm{VDS}_{mds,t,i} \times \mathrm{CM}_{\mathrm{D}}\mathrm{S}_{\mathrm{U}} mds, u, i \leq \mathrm{ADS}_{mds,i} \times \mathrm{CapDS}_{mds} \ \ \forall \mathrm{t, mds, I} \tag{A12}$$

where CapDS is the maximum capacity of a desalination plant mds

Groundwater measures:

Capacity and activation constraint: limits the capacity of the groundwater project and the availability of water to connectable UDUs.

$$\sum_{\mathrm{mgw}} \mathrm{VGW}_{mgw,t,i} \times \mathrm{CM}_{\mathrm{M}}\mathrm{GW}_{\mathrm{G}}\mathrm{W} \leq \ \mathrm{AGW}_{gw,i} \times \mathrm{CapGW}_{gw} \ \ \forall \ \mathrm{t, gw, I} \tag{A13}$$

where CapGW is the maximum capacity of a groundwater project gw.

Exclusivity constraint: ensures the mutual exclusivity of groundwater projects

$$\sum_{\mathrm{gw}} \mathrm{AGW}_{gw,i} \times \mathrm{MC}_{\mathrm{E}}\mathrm{xcl}_{\mathrm{G}}\mathrm{W}_{\mathrm{G}}\mathrm{W} \leq \ 1 \tag{A14}$$

where MC_Excl_GW_GW is a matrix ensuring the mutual exclusivity of groundwater projects.

Appendix B: List and Location of Key Informants Interviewed

Key Informant Function[a]	Key Informant Organization	Organization Type	Description and Relation With the Orb Basin	Coalition
Manager	Orb River water basin management association (SMVOL)	Local watershed council	Management of the Orb River basin	River basin perspective
Manager	Astien aquifer management association (SMETA)	Local watershed council	Management of Astien aquifer (neighboring the Orb basin)	River basin perspective
Head of the planning office	Bezier urban area Water supply utility (CABEM)	Users representative	Water supply of the main urban area in the Orb River basin	3
Farmer representative	Chamber of agriculture of the Hérault district (CA34)	Users representative	Representative of farmers in the area	3
Farmer representative	Chamber of agriculture of the Hérault district (CA34)	Users representative	Representative of farmers in the area	3
Manager	Aude river basin water management association (SMARR)	Local watershed council	Management of the Aude river basin (benefitting from transfer)	2
Mayor of the town	Vernazobre water utility (SAEP Vernazobre)	Users representative	Water supply utility of a Orb tributary (upstream)	1
Head of the office	Jaur Water utility (SAEP Jaur)	Users representative	Water supply utility of a Orb tributary (upstream)	1
Head of the office	5 valleys water utility (SIVOM 5 Vallées)	Users representative	Water supply utility (upstream area)	1
Head of the planning office	Regional water management company (BRL)	Users representative	Management of the reservoir and supply of farmers and urban users through regional network	2
Head of the technical office	Mare water utility (SAEP Vallée de la Mare)	Users representative	Water supply utility of a Orb tributary (upstream)	1
Head of the water and territories department	District authority (CG Aude)	Local government	Representative of the territory benefitting from the transfer outside the river basin	2
Deputy of the planning department	Water district river basin authority (AERMC)	Government agency	In charge of defining charges and allocating subsidies	River basin perspective
Head of the planning office	Narbonne water utility (Grand Narbonne)	Users representative	Water supply of the main urban supplied by a transfer from the Orb River basin	2
Deputy of the planning office	Narbonne water utility (Grand Narbonne)	Users representative	Water supply of the main urban supplied by a transfer from the Orb River basin	2

[a] Interviews have been made individually with key informants. Their points of view do not represent their organization rather we consider that we tried to capture their understanding of the cost allocation problem and the different rationales at stake, but we do not claim any official representativeness

Appendix C: Data for the Cost Allocation Scenarios for Each Scenario

Scenario	Description	Criteria Used	Data Source
S1	Allocation proportional to water abstractions	2030 water withdrawals estimation	*Vernier and Rinaudo*, 2012
S2	Allocation proportional to the increase in water abstraction between 2008 and 2030	2030 and 2008 water withdrawals estimation	*Vernier and Rinaudo*, 2012
S3	Allocation proportional to savings efforts	Water savings estimation	*Vernier and Rinaudo*, 2012
S4	Allocation proportional to deficit	Results from the Least-cost river basin optimization model	*Girard et al.* [2015a]
S5	Allocation taking into account the Monts d'Orb reservoir initial function (historical rights)	Minimum flow release below the intake of the transfer	*Chazot* [2011]
S6	Allocation following the users' capacity to pay	Ratio between the river basin authority volumetric fees between urban and agricultural sectors	*MEDDE* [2012]
S7	Allocation proportional to the wealth of the territories	Statistical data on financial potential per inhabitant of the local municipalities of the study area	*DGCL* [2013]
S4	Allocation proportional to deficit	Results from the Least-cost river basin optimization model	*Girard et al.* [2015a, 2015b, 2015c]
S8	Allocation proportional to summer abstractions	2030 water withdrawals estimation	*Vernier and Rinaudo*, 2012
S6	Allocation following the users' capacity to pay	Ratio between the river basin authority volumetric fees between urban and agricultural sectors	*MEDDE* [2012]
S7	Allocation proportional to the wealth of the territories	Statistical data on financial potential per inhabitant of the local municipalities of the study area	*DGCL* [2013]
S9	Allocation of the cost to water users located outside the basin	2030 water withdrawals estimation	*Vernier and Rinaudo* [2012]

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