“Sharing water and benefits in transboundary river basins” by D. Arjoon et al.

The authors would like to thank the editor for his helpful comments. Our responses and the proposed changes/corrections are detailed below.

Editor's comments:

There are 6 technical corrections that in my view need to be made and that were not mentioned by the reviewers.

1. When mentioning the Atbara (p. 8, line 6; p. 14 line 33; p. 16 line 9), it is in my view better to give it the more appropriate name of Tekeze-Atbara or Tekezze-Atbara, in recognition of the name of the same river in Ethiopia from where it originates.

   Each mention of the Atbara has been changed to Tekeze-Atbara.

2. In Figure 3, the water fluxes are given the dimension of volume (m3); this should be volume per time unit.

   In Figures 1, 2, 3 and 7 (which has been added as part of the modifications to the manuscript) we have changed the description of each figure to include the phrase “for a time period”. For example, the description of Figure 1 now reads “*Demand curve. D = quantity of water demanded for a time period, x*= quantity of water allocated for a time period. P = price of water.*” In general, it is implicit in the demand curve that there is a time component. We chose to address this in this way because we did not want to frame the methodology in a particular time period because we want the methodology to stay general. Depending on the technique used to allocate water (for instance) the time period could be a week, a month, a year, or a growing season (in the case of irrigation).

3. Actually the water demand D, as well as the quantity allocated x, are also fluxes, and should be expressed in volume per time units, so Figures 1 and 2 should also be amended (both horizontal axes).

   Please see our response to comment #2.

4. The same for the payments and transactions, these are quantities of money per time unit. So ENB, GB and E and FNB have as the correct unit money per time; so the correct unit for the amount $3 million mentioned on p. 12 lines 8, 10 and 23 is $3 million per year. The same for the amounts mentioned on p. 14 lines 22-24.

   We agree that the 3 million USD is a yearly operating cost and the manuscript has been updated to reflect this.

5. It would be advisable to use one symbol for US dollar (now the ms uses both $ and USD).

   Thank you for this observation. We have changed the symbol for US dollar to read USD in the document.

6. In Figures 5, 6, 7 and 10, the border between Sudan and South Sudan is missing. This must be rectified.

We have updated the figures to include the border between Sudan and South Sudan.

“Sharing water and benefits in transboundary river basins” by D. Arjoon et al.

The authors would like to thank the reviewer for his/her interesting and constructive comments. Our responses and the proposed changes/corrections are detailed below.

Referee #1

General Comments:

1.1 The paper considers an institutional arrangement to distribute welfare in a river basin by maximizing the economic benefits of water use and then sharing these benefits using a (game theoretic?) method developed through stakeholder involvement. The methodology was applied to the Eastern Nile River basin.

RESPONSE: In Section 2.4, we describe a method of sharing the economic benefits which “should be determined in collaboration with the water users. Properties that define fairness, as determined through negotiations with the water users, are then translated into a sharing rule using an axiomatic approach.” This description of the sharing method is left intentionally very general, since this will be different for each river basin. How the benefits will be shared depends entirely on the definition of fairness that results from negotiations with the water users. Benefits could be shared proportionally or using an egalitarian method or some other form of sharing could be used.

In our case study, using the Eastern Nile River Basin (Section 3), the method used is not game theoretic; we abstract from any stability/equilibrium analysis. We do not investigate the possibility that one or more of the water users could be better off on their own. Instead, we propose a mechanism whereby overall benefits would be maximized as a result of full cooperation and then shared according to a key perceived as fair by the different water users. In other words, the proposed institutional arrangement makes sure that (1) the size of the pie is the largest and (2) the pie is shared in an equitable manner between the participants.

CHANGES TO MANUSCRIPT: Pg. 7 Ln. 31-33 to Pg. 8 Ln. 1-2

The following statement has been added: “*How the benefits are shared depends entirely on this definition as agreed to by water users. For example, a simple proportional sharing method may satisfy the properties of equity defined by the users, or an egalitarian method, or some other form of sharing may be required.*”

1.2 The paper makes an interesting contribution to the body of knowledge surrounding calculating the benefits of transboundary water sharing. However, there are several shortcomings that should be addressed before the paper can be published in the journal. First the Methodology section of the paper is incomplete and needs to be improved as suggested in the specific comments below, mainly that the axiomatic process that implements the bankruptcy game should be introduced and explained in the methodology section. Otherwise, the main potential contribution of the paper is without a methodological basis and is completely ad hoc depending on the site being studied. Second, the method was not actually applied using real stakeholders but it is applied to the widely studied Eastern Nile Basin. The authors need to acknowledge the history of water use in this basin and how the benefits sharing indicated in the results of the paper differ from recent or projected use of water in the basin.

RESPONSE:

1. We agree that the last part of the methodology section might look ad hoc. This is because the benefit sharing mechanism is meant to be flexible since it will depend on the specific conditions of the basin being studied.

   CHANGES TO MANUSCRIPT: Pg. 7 Ln. 25-33 to Pg. 8 Ln. 1-2

   The section (2.4) has been updated to make this clearer. It now states: "*At this point in the methodology, the RBA has collected an amount of money, referred to as the estate (E), that can be shared among the water use agents. Using an axiomatic approach, a method of sharing this estate should be determined. The aim of the axiomatic approach is to find and capture the notion of fairness that water users could agree upon. The approach then sets out axioms (properties) that fairness should or should not satisfy. Finally, these properties are translated into a sharing rule that quantifies the particular definition of fairness. How the benefits are shared depends entirely on this definition as agreed to by water users. For example, a simple proportional sharing method may satisfy the properties of equity defined by the users, or an egalitarian method, or some other form of sharing may be required. Since each river basin will have a different definition of fairness (depending on conditions in the basin and the outcome of negotiations with the water users), each river basin will likely have its own unique sharing rule.*"

2. A brief history of water sharing agreements in the Nile River Basin is given in Section 3.1 of the paper. The purpose of the presented methodology is an alternative to these types of agreements on international river basins, which are often perceived as zero-sum games and can lead to distrust and tension between riparian countries, as is the case in the Nile River Basin. What we present is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements. For example, with respect to the Nile Basin, the current agreement driving water allocation legally constrains Sudan to 18.5 bcm of water use. Sudan has land resources to expand irrigation and use much more water than this (Allan et al 2013), but is limited due to the agreement. As well, uncertainty with respect to changing climate and the possibility of increased evaporation, uncertain hydrology and sea level rise could create an imbalance in water demand and supply in the basin (Whittington, 2014). A rise in sea level would result in the loss of agricultural land in the Nile Delta and, subsequently, a large portion of Egypt's historic water use would no longer be required (Whittington, 2014).

   CHANGES TO MANUSCRIPT: Pg. 4 Ln. 4-7

   We have added a paragraph in the introduction (Section 1) which states "*The institutional arrangement described in this paper should encourage full cooperation between water users because it is intended as a replacement for traditional types of agreements on international river basins, which can lead to distrust and tension between riparian countries. What we present is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements.*"

   It is difficult to compare the results of the case study with current water use in the basin. The presented case study is highly hypothetical and is not consistent with the actual, current allocation scheme. In the case study, we assume complete cooperation, there is expanded irrigation in the basin and the Grand Ethiopian Renaissance Dam is online. This represents a possible long-term future scenario in the basin and the results reflect this.

CHANGES TO MANUSCRIPT: Pg. 21 Ln. 10-14

We have added a paragraph to the end of the results (Section 4) to clarify this: "*Finally, it should be noted that we make no attempt to compare the results of the case study with current water use in the basin. While the presented case study is hypothetical and is not consistent with the actual, current situation, it represents a possible long-term future scenario in the basin and the results reflect these assumptions. In the case study, we assume complete cooperation, there is expanded irrigation in the basin and the Grand Ethiopian Renaissance Dam is online.*"

Specific Comments:

1.3 P.1-L.20: "There is a consensus among water professionals that the cooperative management of shared river basins should provide opportunities to increase the scope and scale of benefits" The authors have provided a single reference to justify this assertion. A broader consensus needs to be demonstrated before this statement can be accepted.

RESPONSE: More references have been added.

CHANGES TO MANUSCRIPT: Pg. 2 Ln. 1-2

Two additional references have been included: "*There is a consensus among water professionals that the cooperative management of shared river basins should provide opportunities to increase the scope and scale of benefits (Phillips et al., 2006; Grey and Sadoff, 2007; Leb, 2015), stepping beyond the volumetric allocation of water that reduces negotiations between riparians to a zero-sum game.*"

1.4 P.2-L.10: "water is allocated to maximize the net benefits from water use over the whole basin (economically efficient allocation)." Not all of these papers take the economist's position that one can simply maximize the benefits of water use in a basin and many of them recognize the political and administrative boundaries present in their case study basins and how those boundaries affect (restrict) the allocation of water in the basins.

RESPONSE: We agree that not all of these papers take the position that the benefits of water use can simply be maximized without recognizing the various constraints within the cases studied.

CHANGES TO MANUSCRIPT: Pg. 2 Ln. 13-17

We have changed the wording in the 3rd paragraph of the introduction to make this clearer. The sentence now reads "*The traditional approach to estimating the economic benefits of cooperation relies on hydro-economic modelling (Arjoon et al., 2014; Jeuland et al., 2014; Tilmant and Kinzelbach, 2012; Teasley and McKinney, 2011; Whittington et al., 2005). These studies present various implementation strategies representing various levels of cooperation, but all show that there are significant economic benefits to be had through basin-wide cooperation.*"

1.5 P.3-L.30: "pseudo-market approach, a river basin authority (RBA) plays the role of water system operator, identifying economically efficient allocation policies which are then imposed on the agents (water users). The agents are charged for water, payments are redistributed to ensure equitability among the users." "the RBA collects information that is required to assess the demand curves, or at least the productivity of all users in the system, once at the beginning of each year." How realistic is this? In many parts of the world, this information is considered confidential. ". . .based on the bid information, the demand curve can be inferred using the residual imputation method. . ." This seems much more realistic that requiring users to give up their business information.

RESPONSE: The authors believe that in the future, it will be realistic to get some of this information. Currently, market prices, either national or international, can be observed and transportation costs can be estimated, allowing for an approximation of the mark-up that may accrue to farmers, for example. We stress that this paper describes a system in which it is assumed that there is cooperation over the whole basin. This means that water users have agreed to bid for water and to supply the information that is necessary to make the methodology work. It is up to the RBA to check that the information is reliable. Increasingly, river basins are being monitored and the information required is becoming available (for example, current hydromet projects in the Senegal River Basin). The system may not seem realistic at this point, but, in the long-term, exchange of information will increase the availability of data over river basins. This increase in information exchange is in keeping with the obligation to cooperate and exchange information that is outlined in the UN Convention on the Law of the Non-navigational Uses of International Watercourses.

CHANGES TO MANUSCRIPT: Pg. 22 Ln. 34-35 to Pg. 23 Ln. 1-4

We have added a paragraph to the conclusions Section 5 (second to last paragraph) to discuss the constraint of available/reliable data. This paragraph reads: "*Another constraint is the availability of reliable data. Some information such as market prices, either national or international, can be observed and transportation costs can be estimated, allowing for an approximation of the mark-up that may accrue to farmers, for example. This paper describes a system in which it is assumed that there is cooperation over the whole basin and that water users have agreed to bid for water and to supply the information that is necessary to make the methodology work. Increasingly, the information required is becoming available through the use of remote sensing and monitoring of river basins.*"

1.6 P.4-L. 15: "techniques such as remote sensing can be applied to validate land classification and cropping areas" Do the authors utilize these methods in this paper?

RESPONSE: It is up to the RBA to check that the information given by water users is reliable. Remote sensing is one of the techniques available to validate information such as land classification and cropping areas. We do not use these methods in the present case study.

CHANGES TO MANUSCRIPT: Pg. 4 Ln. 29-31

We have updated paragraph 2 in Section 2.1 to more clearly state this. This paragraph now states: *"In order to control the declarations of agents in the agricultural sector, the RBA can use techniques such as remote sensing to validate land classification and cropping areas (Gallego et al., 2014; El-Kawy et al., 2011; Rozenstein and Karnieli, 2011)."*

1.7 P.4-L.30: "allocation decisions are identified by matching demand with supply in a cost effective way, i.e. by giving priority of access to users with the highest productivity" It is not clear what the authors mean by "cost effective" way and this should be more clearly defined.

Giving water to its highest valued use may be cost effective, but that depends on how you define "cost effective". Please clarify. As mentioned previously, this allocation method depends on the benevolent water manager having the authority to allocate the water is such a manner and in the real world this ignores any water rights or transboundary agreements that may exist in the basin. I think the authors should point out this limitation and discuss its implications in detail later in the paper.

RESPONSE:

1. The authors have changed the term "cost-effective" to "cost-efficient" implying least cost, or maximum productivity.

   CHANGES TO MANUSCRIPT: Pg. 5 Ln. 14

   cost-effective* has been changed to *cost-efficient

2. The allocation method departs from traditional (physical) allocation mechanisms based on water rights and relies instead on a bidding process whereby all water users are granted equal access to the resource. Productive use and allocation decisions are separated. The benevolent water manager is a non-profit, regulated organization that acts as a third party operator of the water resources system. In other words, it does not directly put water to productive use for its own benefit. Instead, it coordinates allocation decisions throughout the system based on the offers provided by eligible water users, and tries to achieve allocative efficiency by ensuring that the good or service is consumed by those who value it most highly. The benevolent water manager, then, is the operator of an auction-based market. We agree that this is a highly hypothetical scenario but technological changes (e.g. availability of massive remote sensing data) combined with the need to achieve greater efficiency due to external pressures (population growth, climate change) might trigger major regulatory reforms in the water sector. This was seen in the energy sector in the late XXth century where, before 1970, energy generation was widely believed to be part of a natural monopoly. Technological developments such as cheap gas-fired power plants, combined with costly and inefficient investments made by the monopolies, suggested that competition was needed and lead to the introduction of deregulated electricity markets. This manuscript must be seen as a prospective analysis. We are concerned with a future situation that does not currently exist and we look at how the institutional arrangement would perform under these conditions.

1.8 P.4-L.30: "...power companies are considered non-rival water users since a unit of water released through one dam can be used downstream by another dam. . ." This may or may not be the case. In the case of the Syr Darya basin in Central Asia, this is certainly NOT the case since electricity production is in high demand in the winter when there is no irrigation water demand and hydropower releases in winter are lost to summer irrigation use. In the Eastern Nile, where the authors apply their model, the Grand Ethiopian Renaissance DamÂă may or may not be operated in a manner that allows the non-rival use of the water for power. The authors need to make this clear and explain the limitations of their assumptions.

RESPONSE: Thank you for this insight. We are in agreement.

CHANGES TO MANUSCRIPT: Pg. 5 Ln. 16-17 to Pg. 6 Ln. 1-3

We have changed the text to read: "*For example, water flowing through a dam may be*

***considered a non-rival water use since a unit of water released through one dam can be used downstream by another dam. In rival water use, units are consumed and are no longer available to other water users (for example, water lost to irrigation or water held in a reservoir during a period when it is required downstream for irrigation).*"**

1.9 P.6-L.5: ". . .Non-consumptive users buy inflow from the RBA, at the marginal value at the user site, and then sells the outflow downstream, back to the RBA, at the marginal value of water at the downstream site. . ." Why not just say that the users pay the difference between marginal value at the user site and the marginal value of water at the downstream site?

CHANGES TO MANUSCRIPT: Pg. 7 Ln. 7-9

This sentence now reads "*Non-consumptive users buy inflow from the RBA at a price equal to the difference between the marginal value of water at the user site and the marginal value of water at the downstream site (Fig. 3).*"

1.10 P.7-L.5: The Methodology section of the paper is incomplete since it does not indicate any method of determining the "transfer payments". The idea is stated that the "fairness" of the payments will be determined through an "axiomatic process" involving the stakeholders, but no methodology is mentioned for how this procedure is carried out. Some description of a method should be given here, since this is the main contribution of the paper (the other components are well known and reported in the literature previously). Otherwise, the main potential contribution of the paper is without a methodological basis and is completely ad hoc depending on the site being studied. Section 3.5 presents much of the methodology (bankruptcy game theory) and should be moved back to Section 2 and the main aspects presented as general methodology.

RESPONSE: Please see the response to comments 1.1 and 1.2 for further details.

CHANGES TO MANUSCRIPT: Pg. 7 Ln. 31-33 to Pg. 8 Ln.

We have updated the first paragraph in Section 2.4 to further describe the method of transfer payments. We have added the following: "*How the benefits are shared depends entirely on this definition as agreed to by water users. For example, a simple proportional sharing method may satisfy the properties of equity defined by the users, or an egalitarian method, or some other form of sharing may be required.*"

1.11 P.13-L.5: ". . .for this study, the properties for this rule were not developed with stakeholder input as this was beyond the scope of this research project" So the method was not actually applied using real stakeholders. This fact needs to be pointed out in the abstract as it substantially weakens the impact of the paper. In addition, the authors do not acknowledge the history of water use in this river basin and the massive efforts that have been made to develop lasting and fair transboundary water sharing agreements in the basin. How do these historic efforts differ form the water allocation and benefits sharing indicated in the results of the authors' model? This should be explained and discussed in some detail, since this could be a major contribution of the paper to understanding water sharing in the Nile basin.

RESPONSE:

1. While it is true that the method for determining transfer payments was not developed using

stakeholder input, we do not believe that this weakens the impact of the methodology. We have an objective point of view and our analysis is a benchmark or reference point.

CHANGES TO MANUSCRIPT: Pg. 12 Ln. 4-7

A paragraph has been added to Section 3.5 which reads "*It should be noted that, for this study, the properties for this rule were not developed with stakeholder input as this was beyond the scope of this research project. Although stakeholder involvement is imperative in this institutional arrangement, in this case study, we are giving an objective viewpoint and this analysis serves as a benchmark or reference point.*"

2. Please see the response to comment 1.2.2 for a detailed response to the question of water sharing agreements in the basin.

Allan, J. A., Keulertz, M., Sojamo, S. & Warner, J. eds. (2013). Handbook of Land and Water Grabs in Africa: Foreign Direct Investment and Food and Water Security. Routledge International Handbook. Routledge, Abingdon.

Whittington, D, J. Waterbury, and M. Jeuland (2014), The Grand Renaissance Dam and prospects for cooperation on the Eastern Nile, *Water Policy*, 16, 595–608.

<u>"Sharing water and benefits in transboundary river basins" by D. Arjoon et al.</u>

The authors would like to thank the reviewer for his/her interesting and constructive comments. Our responses and the proposed changes/corrections are detailed below.

Referee #2

<u>Summary</u>

This paper describes an approach to equitable sharing of benefits among multiple stakeholders in transboundary river basin systems. The basic idea is to maximize efficiency by allocating water where its value is highest, and then to collect payments from users using an axiomatic rule based on the marginal value of water at each site.

<u>General comments</u>

I like the paper and think it proposes an interesting approach. I see four main shortcomings that are not at all discussed, however. Ignoring them diminishes the credibility of the work.

2.1 The first problem is that the issue of property rights is never discussed. Given how water rights are usually assigned in real world systems (and given their existence in the authors' application of interest, the Nile), this is a major problem.

RESPONSE: A brief history of water sharing agreements in the Nile River Basin is given in Section 3.1 of the paper. The purpose of the presented methodology is as an alternative to these types of agreements on international river basins, which can lead to distrust and tension between riparian countries, as is the case in the Nile River Basin. What we present is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements. For example, with respect to the Nile Basin, the current agreement driving water allocation legally constrains Sudan to 18.5 bcm of water use. Sudan has land resources to expand irrigation and use much more water than this (Allan et al 2013), but is limited due to the agreement. As well, uncertainty with respect to changing climate and the possibility of increased evaporation, uncertain hydrology and sea level rise could create an imbalance in water demand and supply in the basin (Whittington, 2014). A rise in sea level would result in the loss of agricultural land in the Nile Delta, and, subsequently, a large portion of Egypt's historic water use would no longer be required (Whittington, 2014).

<u>CHANGES TO MANUSCRIPT: Pg. 4 Ln. 4-7</u>

We have added a sentence to the last paragraph in the introduction (Section 1) which states "*The institutional arrangement described in this paper should encourage full cooperation between water users because it is intended as a replacement for traditional types of agreements on international river basins, which can lead to distrust and tension between riparian countries. What we present is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements.*"

2.2 The second concern I have is about transaction costs. The need for a river basin authority to implement the allocation and sharing rule is taken for granted, and the cost of setting it up is totally ignored.

RESPONSE: As stated in P21-L9 "One obvious constraint of this method is its dependance on the existence of a strong basin-wide authority...". The assumption is made that the RBA exists. This is not unrealistic given that there are a number of river basins that already have an RBA in place (OMVS on the Senegal, MRC on the Mekong, ZAMCOM on the Zambezi, NBA on the Niger River, etc.) and others that are working toward this goal (Volta Basin Authority, for example). As well, in this methodology, we assume that the countries cooperate through the RBA and we agree that this involves transaction costs. If countries agree to the kind of institutional arrangement described, they do so because these transaction costs are less than the cost of cooperation. As well, the transaction cost is not proportional to water allocation or use and, hence, could be introduced as a fixed cost, as we have done in the case study. A fixed cost would diminish the estate available to share and, ultimately, the final benefits of the water users, but it would not alter the proportion.

2.3 The third concern is about perfect information (for the RBA). In a way, the authors fall directly into this trap with their rather simple assumptions about irrigation and hydropower values, by assuming that these are uniform across space and time in the Nile. It is almost certainly true that costs and productivity varies across sites, however. In general, this will greatly complicate the ability to establish an effective RBA for achieving the efficient and equitable allocation. Private information will also pose a problem, given that users at different locations in the basin have differing incentives to reveal their true valuations. The authors spend some time discussing preference revelation, but do not fully acknowledge the challenge.

RESPONSE: We agree that simple assumptions about irrigation and hydropower values in the case study were made. These assumptions have been made by other researchers (Whittington, 2005) and are generally consistent with international experience in well-run irrigation schemes and power systems. However, it is obvious that the quality of the results are dependent on the quality and availability of data to run the models, and on the assumptions made. This is a challenge in all studies of this type.

The authors believe that, in the future, it will be realistic to get some of this data. Currently, market prices, either national or international ones, can be observed and transportation costs can be estimated, allowing for an approximation of the mark-up that may accrue to farmers, for example. We stress that this paper describes a system in which it is assumed that there is cooperation over the whole basin. This means that water users have agreed to bid for water and to supply the information that is necessary to make the methodology work. It is up to the RBA to check that the information is reliable. Increasingly, river basins are being monitored and the information required is becoming available (for example, current hydromet projects in the Senegal River Basin). The system may not seem realistic at this point but, in the long-term, exchange of information will increase the availability of data over river basins. This increase in information exchange is in keeping with the obligation to cooperate and exchange information that is outlined in the UNConvention on the Law of the Non-navigational Uses of International Watercourses.

CHANGES TO MANUSCRIPT: Pg. 22 Ln. 34-35 to Pg. 23 Ln. 1-4

We have added a paragraph to the conclusions Section 5 (second to last paragraph) to discuss the constraint of available/reliable data. This paragraph reads: "*Another constraint is the availability of reliable data. Some information such as market prices, either national or international ones, can be observed and transportation costs can be estimated,*

***allowing for an approximation of the mark-up that may accrue to farmers, for example. This paper describes a system in which it is assumed that there is cooperation over the whole basin and that water users have agreed to bid for water and to supply the information that is necessary to make the methodology work. Increasingly, the information required is becoming available through the use of remote sensing and monitoring of river basins.*"**

2.4 Finally, the approach depends on allowing all stakeholders a place at the table, but this seems unlikely. In the specific application, urban and environmental uses are imposed as constraints, which is one example of asymmetric bargaining position. There are likely other users that would be ignored as well.

RESPONSE: Allowing all stakeholders a place at the table is indeed challenging, especially for large systems with diversified water use activities. In the irrigation sector, for instance, farmers could send a representative, e.g. a member of the water user association. For uses of water as a public good (e.g. environmental flows), the representative could be the Ministry of Environment of the country of interest. For municipal uses, the system could be designed in such a way that a minimum amount of allocated water is guaranteed (a fixed constraint in the allocation system) while quantities beyond that minimum would be part of the pool for which municipalities would have to bid. Industrial and power companies are easier to handle. All users that can be rationed (mainly private water users) are allowed a place at the table for the purpose of defining fairness with respect to transfer payments.

Another possibility is that the government (or at least a high level representative of the stakeholders) has the ultimate negotiation power, akin to negotiations on trade liberalizations. Clearly, different lobbies exist that would try to influence the government, implying, ultimately, some form of compensation (the analysis of which would lie outside the scope of this paper).

<u>CHANGES TO MANUSCRIPT: Pg. 23 Ln. 5-15</u>

We have added the following paragraph to the conclusions to discuss this: "*One obvious constraint of this method is its dependance on the existence of a strong basin-wide authority to impose fees and that can enable negotiations between stakeholders for the development of a sharing rule. Allowing all stakeholders a place at the table might prove challenging, especially for large systems with diversified water use activities. In the irrigation sector, for instance, farmers could be represented by a water user association. For uses of water as a public good, such as for environmental flows, the representative could be the Ministry of Environment of the country of interest. For municipal uses, the system could be designed in such a way that a minimum amount of allocated water is guaranteed (a fixed constraint in the allocation system) while quantities beyond that minimum would be part of the pool for which municipalities would have to bid. Industrial and power companies are easier to handle. All users that can be rationed (mainly private water users) are allowed a place at the table for the purpose of defining fairness with respect to transfer payments. Another possibility is that the government (or at least a high level representative of the stakeholders) has the ultimate negotiation power, akin to negotiations on trade liberalizations. Clearly, different lobbies exist that would try to influence the government, implying, ultimately, some form of compensation (the analysis of which would lie outside the scope of this paper).*"

Specific comments

Besides these three main comments, I have a few specific comments.

2.5 The abstract makes it seem like there is no efficiency-equity tradeoff, but in general there is, except when a fully efficient compensation mechanism exists. The main paper acknowledges this more clearly.

RESPONSE: With the physical allocation of water, policy makers face an efficiency-equity trade-off. With the proposed benefit-sharing mechanism, the trade-off still exists but the extent of the imbalance between the two is reduced because benefits are maximized and redistributed according to a key that has been collectively agreed on by the participants.

CHANGES TO MANUSCRIPT: Pg. 1 Ln. 13-15

We have added the following sentence to the abstract: "*With the proposed benefit-sharing mechanism, the efficiency-equity trade-off still exists but the extent of the imbalance is reduced because benefits are maximized and redistributed according to a key that has been collectively agreed upon by the participants.*"

2.6 Introduction: Unidirectional flow is not what imposes externalities. Rephrase.

CHANGES TO MANUSCRIPT: Pg. 1 Ln. 23-26

This sentence in the introduction (Section 1) has been rephrased to read: "*This is particularly evident in the case of transboundary river basins in which unidirectional, negative externalities, caused by the upstream regulation of the natural flow, often place some parties at a disadvantage and results in asymmetric relationships that add to the challenge of coordinating resource use (van der Zaag, 2007).*"

2.7 Introduction: Is there really consensus that cooperative management increases benefits? Can you provide more than one citation to back this up? What about transaction costs?

CHANGES TO MANUSCRIPT: Pg. 1 Ln. 26 to Pg. 2 Ln. 1-3

Additional citations have been added. The statement now reads: "*There is a consensus among water professionals that the cooperative management of shared river basins should provide opportunities to increase the scope and scale of benefits (Phillips et al., 2006; Grey and Sadoff, 2007; Leb, 2015), stepping beyond the volumetric allocation of water that reduces negotiations between riparians to a zero-sum game.*"

2.8 Can you discuss the implications of assuming constant marginal product of water in irrigation?

RESPONSE: In our case study there are 3 (upstream) irrigation schemes that do not (on average) get the amount of water demanded. This is because the productivity of water that is used over the entire basin (0.05 USD/m3) is less than the marginal value of water at these nodes in the system. This productivity value is used because there is currently a lack of data for irrigation in the basin. The availability of economic/agricultural data in each irrigation scheme over the basin, as well as details of cropping patterns in each scheme, would allow us to develop a non-horizontal demand curve. If this were the case, high value crops in the upstream schemes may be irrigated and the low value crops in downstream schemes may not be irrigated. This means that the irrigation water users that are rationed may change and may be spread out over the basin.

CHANGES TO MANUSCRIPT: Pg. 15 Ln. 16-20

The first paragraph in the results section (Section 4) has been updated to the following statement: "*The rationing of water for upstream irrigation users is a result of the horizontal demand curve used for irrigation. If more detailed economic/agricultural data were available, a non-horizontal demand curve could be produced. This may result in irrigation schemes with high value crops having priority to water and those areas with low value crops not being irrigated. This means that the irrigation water users that are rationed may change and they may be more spread out over the basin.*"

<u>"Sharing water and benefits in transboundary river basins" by D. Arjoon et al.</u>

The authors would like to thank the reviewer for his/her interesting and insightful comments. Our responses and the proposed changes/corrections are detailed below.

Referee #3

3.1 P3 L 14–17. You implicitly state that axiomatic approaches ignore economic welfare. This is not exactly true. You may not be aware of some recent work in this area, e.g.: - Ambec, S., A. Dinar, and D. McKinney (2013). Water sharing agreements sustainable to reduced flows. Journal of Environmental Economics and Management 66(3), 639– 655. - Van den Brink, R., G. van der Laan, and N. Moes (2012). Fair agreements for sharing international rivers with multiple springs and externalities. Journal of Environ- mental Economics and Management 63(3), 388–403. These papers apply axioms on the welfare distribution resulting from the physical allocation of water. Actually, most axiomatic papers in the river sharing literature do so.

RESPONSE: We do not agree that we implicitly abstract from economic welfare. The text in question reads: "As discussed previously, the economically efficient allocation of water is not necessarily equitable. Conversely, axiomatic approaches may be considered equitable but do not necessarily maximize the total economic welfare over the basin and may be considered deficient as a result. Institutional arrangements that ensure maximum economic welfare, as well as the equitable sharing of these benefits over the basin, are required."

We use the word "deficient" to mean that the axiomatic approaches may result in less than optimal water allocations from an economic perspective. For example, Madani et. al. (2014) uses bankruptcy rules to determine the allocation of water within the Qezelozan-Sefidrud river system in Iran. The resulting allocations are defined by the notion of fairness that are inherent in each rule, but these rules do not necessarily maximize the economic welfare over the basin.

<u>CHANGES TO MANUSCRIPT: Pg. 3 Ln. 23-27</u>

In order to clarify this, we have changed the paragraph to read "*As discussed previously, the economically efficient allocation of water is not necessarily equitable. Axiomatic approaches, on the other hand, allow the characterization of an equitable distribution of welfare, but do not necessarily maximize the aggregated economic welfare over the basin. Institutional arrangements that ensure maximum economic welfare, as well as the equitable sharing of these benefits over the basin, are required.*"

3.2 You introduce, in Sections 2.1-2.3 a social planner that collects all information and derives an appropriate social cost of water and its related price. A tremendous task I would say, especially since water is not a regular good and this price will vary by quality, location, time, and possibly other aspects. What is more problematic is that the planner relies on all water users for its collection of information, a crucial step in the analysis. In Section 2.1 this process is described but this section ignores the problem posed by incentive compatibility: why would users truthfully reveal their demand curves (or make truthful bids) if they could benefit by pretending a higher demand curve (i.e. a higher bid)? Sure, the section mentions some methods to check the reliability of information, like remote sensing, but this does not eliminate the incentives to "cheat".

RESPONSE: We agree that the incentives to cheat will remain even if the river basin authority is able to audit the bids. For industrial uses, including hydropower generation, cheating might be more difficult because the market prices and production functions are often well characterized. In our opinion, the main challenge is to be found in the agricultural sector because (a) it is often the largest water use (and hence cheating might have serious basin-wide consequences), and (b) the heterogeneity in terms of cropping patterns and irrigation efficiency requires that significant data be collected and analyzed to audit the demands. However, due to river basin closure, there is a strong incentive to strengthen the monitoring of river basins, either directly (on-site measurement stations) or indirectly (remote sensing). Various initiatives, at different levels, demonstrate that significant effort and financial resources are being devoted to observations of water resources. For example, the Surface Water and Ocean Topography (SWOT) satellite mission (anticipated launch date 2020), The Sentinel-3 satellite mission, the Hydromet project in the Senegal River basin, etc. We argue that the incentives to cheat might not be eliminated but they can be suppressed, or at least kept within limits, through a robust monitoring system and a strong RBA to negotiate disputes. An example of how this has worked, with good success, is the Indus River basin. Zawahri (2009), in discussing the Permanent Indus Commission, states "The commission's ability to monitor development of the shared river system has permitted it to ease member states' fear of cheating and confirm the accuracy of all exchanged data. Finally, its conflict resolution mechanisms have permitted the commission to negotiate settlements to disputes and prevent defection from cooperation."

CHANGES TO MANUSCRIPT: Pg. 22 Ln. 23-33

The following paragraph has been added: ""*Incentives for water users to cheat, with respect to the data they provide, will remain even if the river basin authority is able to audit the bids. For industrial uses, including hydropower generation, cheating might be more difficult because the market prices and production functions are often well characterized. The main challenge is to be found in the agricultural sector because (a) it is often the largest water use in a basin (and, hence, cheating might have serious basin-wide consequences), and (b) the heterogeneity in terms of cropping patterns and irrigation efficiency requires that significant data be collected and analyzed to audit the demands. We argue that the incentives to cheat might not be eliminated but they can be suppressed, or at least kept within limits, through a robust monitoring system and a strong RBA to negotiate disputes. An example of how this has worked, with good success, is the Indus River basin. Zawahri (2009), in discussing the Permanent Indus Commission, states "The commission's ability to monitor development of the shared river system has permitted it to ease member states' fear of cheating and confirm the accuracy of all exchanged data. Finally, its conflict resolution mechanisms have permitted the commission to negotiate settlements to disputes and prevent defection from cooperation.*"

3.3 In general, it is not clear what the status quo / baseline situation is w.r.t. property rights over water, which makes it hard to interpret the model. I see three candidates for the status quo: - First, on P4 L26 an exogenous water price P_D is introduced. This suggests that there is a planner or a market active in the status quo, where users can buy their water. Second, expected net benefits (ENB) are derived assuming that a user can abstract any water unhampered by other (upstream) users' water use. This suggests that you take the principle of Unlimited Territorial Integrity as your status quo. - Third, the sharing of the RBA money seems to ignore any historical water use rights. This suggests that the status quo is one without any water use or where the RBA owns all water (since apparently water prices are paid to the RBA).

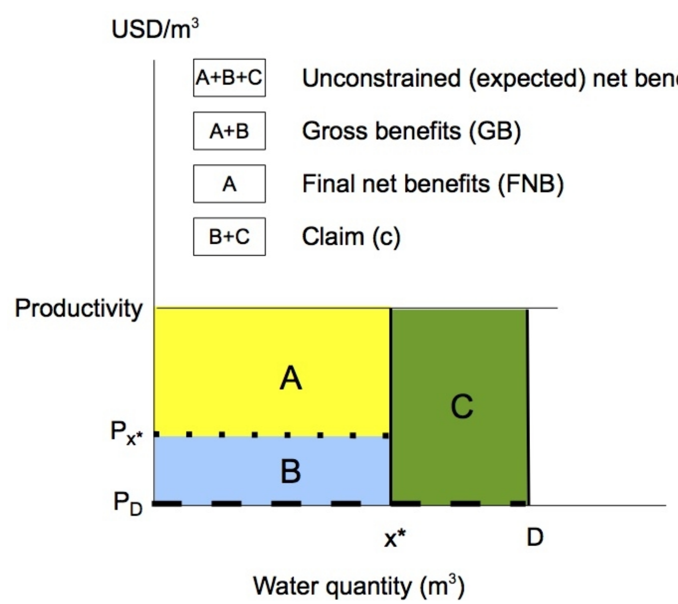
RESPONSE: The purpose of the presented methodology is to provide an alternative to the types of agreements on international river basins which attempt to define the rights to water. These agreements are often perceived as zero-sum games and can lead to distrust and tension between riparian countries, as is the case in the Nile River Basin. What we present is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements based on physical allocation. For example, with respect to the Nile Basin, the current agreement driving water allocation legally constrains Sudan to 18.5 bcm of water use. Sudan has available land resources to expand irrigation and use much more water than this (Allan et al 2013), but is limited due to the agreement. As well, uncertainty with respect to changing climate and the possibility of increased evaporation, uncertain hydrology and sea level rise could create an imbalance in water demand and supply in the basin (Whittington, 2014). For instance, a rise in sea level would result in the loss of agricultural land in the Nile Delta, and, subsequently, a large portion of Egypt's historic water use would no longer be required (Whittington, 2014). Therefore, as part of the application of this methodology to a river basin, the historical water use rights are disregarded.

The institutional arrangement that we describe departs from traditional (physical) allocation mechanisms that are based on water rights and relies instead on a bidding process whereby all water users are granted equal access to the resource. Productive use and allocation decisions are separated. The benevolent water manager (RBA) is a non-profit, regulated organization that acts as a third party operator of the water resources system. It does not directly put water to productive use for its own benefit. Instead, it coordinates allocation decisions throughout the system based on the offers provided by water users, and tries to achieve allocative efficiency by ensuring that the water is consumed by those who value it most highly. The benevolent water manager is, in this case, the operator of an auction-based market. So, as part of the institutional arrangement, the RBA may be considered as the owner of bulk (raw) water in the basin. Since the RBA is a supranational institution, the riparian countries own the water. However, once the allocated water is diverted to the user, the water belongs to the user (who has paid for it). Note that price (P_D) is not exogenous; it is derived from the aggregate demand curve for water that results from the market operated by the RBA as part of the methodology.

As mentioned earlier, water users are invited to communicate basic economic information required to estimate their demand curve and to derive the expected net benefit (ENB), i.e. the benefit they would get without rationing. At this stage, we do assume that a user's benefits are maximized unhampered by other upstream users' water use or by the historical claims of downstream users. In a sense, the status quo, in this case, is a balance between two extreme principles: the principle of Unlimited Territorial Integrity and the principle of Absolute Territorial Sovereignty.

3.4 In Section 2.1, ENB was calculated as consumer surplus. In Section 3.2, however, ENB is calculated as unconstrained water use (Dj) multiplied by productivity (Pj). This seems to be a completely different measure. Where consumer surplus equals willing- ness to pay minus the water price for all consumed units of water and is measured in money terms, this new measure is a production measure: productivity of water times consumed units of water, probably measured in terms of physical output. This is very confusing (it is also confusing that P is used to denote both productivity and price). In section 3.3, Eq (2), again the production measure is used to calculate gross benefits. Gross benefits cannot be the product of water use and productivity.

RESPONSE: In section 2.1 of the paper, in Figure 1, we show the ENB as being the consumer surplus. Figure 1 is the demand function for conditional factors needed to produce a certain level of output. In our case, this is the demand for water needed to produce a certain amount of crop and there is unconstrained output. We disregard the fact that the WTP is, in fact, constrained by the final output level that one wishes to produce. In our case study (section 3), we implicitly assume that the input demand is horizontal (perfectly elastic) with the price (P) = marginal productivity. Underlying this assumption we suppose that the productivity remains the same for the producer and that the output can always be sold on the market. The gross consumer valuation is equal to the rectangle under the horizontal demand curve (or marginal productivity (USD/m3) x water quantity (m3)). For the ENB this is the whole area under the horizontal curve where the water quantity is equal to the water demand. For the gross benefits (GB), this is the area under the horizontal curve given the amount of water they are allocated. The final net benefits (FNB) are the GB minus the area under the horizontal curve representing the cost of water. Please see the figure below which we will incorporate into the paper in section 3.



CHANGES TO MANUSCRIPT: Pg. 13 Ln. 5-8

Figure 7 has been added and the following description has been inserted into the text: "*Fig. 7 shows the annual demand curve for an irrigation agent in this case study. In this study, we implicitly assume that the input demand is horizontal (perfectly elastic) with the price (P) = marginal productivity. The area to the left of line D*

***(comprising areas A, B and C) is the expected net benefits (ENB) (we see that the agent does not pay for water) resulting from unconstrained water use. When water is constrained, area A is the final net benefits (FNB).*"**

3.5 The innovative part of the paper is where you distribute the rents using the axiomatic approach. This method is postponed to Section 3.5. My main comment here is that there is no clear motivation for distributing E such that each user obtains an equal proportion of benefits (FNB+tp) to claims (ENB). There are many axiomatic solutions that are similar in spirit to yours, but I do not see a compelling motivation why this particular new rule is introduced and applied here. It seems standard to motivate a new solution in terms of its characterizing properties, but such a characterization is not provided here. There are some statements in the text that claim this rule satisfies the properties "solidarity" and "security of minimum benefits", but these properties are not clearly defined. Note that I am not saying that a full characterization should be provided here, as that is perhaps less relevant for the HESS audience, but I would expect a convincing motivation for introducing this new solution over any other (existing) solutions. Two additional minor comments: - By taking account of FNB in your bankruptcy rule, you have a problem that is more general than a standard bankruptcy problem (see e.g. work by Hougaard). - Your proposed solution does not take into account historical water use or any other property rights regime? (see my comment on the status quo).

RESPONSE: Please note our response to comment 3.3 regarding water rights.

As previously mentioned, section 2 describes the methodology while section 3 is an example of how this methodology can be applied using the Eastern Nile River Basin as the case study. In section 2.4 we describe the last step – transfer payments.

CHANGES TO MANUSCRIPT: Pg. 7 Ln. 25-34 to Pg. 8 Ln. 1-2

We have added to this section, which should read: "*At this point in the methodology, the RBA has collected an amount of money, referred to as the estate (E), that can be shared among the water use agents. Using an axiomatic approach, a method of sharing this estate should be determined. The aim of the axiomatic approach is to find and capture the notion of fairness that water users could agree upon. The approach then sets out axioms (properties) that fairness should or should not satisfy. Finally, these properties are translated into a sharing rule that quantifies the particular definition of fairness. How the benefits are shared depends entirely on the definition of fairness as agreed to by water users. For example, a simple proportional sharing method may satisfy the properties of equity defined by the users, or an egalitarian method, or some other form of sharing may be required. Since each river basin will have a different definition of fairness (depending on conditions in the basin and the outcome of negotiations with the water users), each river basin will likely have its own unique sharing rule."*

In section 3.5 we describe a possible solution to transfer payments, assuming that the agents have all agreed on the properties underlying this rule. It is important to note that there were no negotiations done to develop this rule (this was beyond the scope of the project), however, we do not believe that this weakens the impact of the methodology. We present an objective viewpoint and consider our analysis to be a benchmark or reference point.

CHANGES TO MANUSCRIPT: Pg. 14 Ln. 4-7

A paragraph has been added to section 3.5 which reads "*It should be noted that, for this study, the properties for this rule were not developed with stakeholder input as this was beyond the scope of this research project. Although stakeholder involvement is imperative in this institutional arrangement, in this case study, we are giving an objective viewpoint and this analysis serves as a benchmark or reference point.*"

The motivation for using this rule is that the cost of cooperation is divided equally among the agents. Again, we are certainly not saying that this solution is better than another, or even that this would be the solution to sharing the benefits for the Eastern Nile River Basin. Rather, we are giving an example of how the overall methodology could work when applied to a river basin. The rule or method used for the transfer payments would be based on the definition and properties of fairness that are developed through negotiations with the water users.

Allan, J. A., Keulertz, M., Sojamo, S. & Warner, J. eds. (2013). Handbook of Land and Water Grabs in Africa: Foreign Direct Investment and Food and Water Security. Routledge International Handbook. Routledge, Abingdon.

K. Madani, M. Zarezadeh, and S. Morid. A new framework for resolving conflicts over transboundary rivers us- ing bankruptcy methods. Hydrol. Earth Syst. Sci., 18: 3055–3068, 2014.

D.J. Whittington, D, J. Waterbury, and M. Jeuland. The Grand Renaissance Dam and prospects for cooperation on the Eastern Nile, *Water Policy*, 16, 595–608, 2014

N. Zawahri. India, Pakistan and cooperation along the Indus River system. Water Policy 11: 1-20, 2009

Sharing water and benefits in transboundary river basins

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Abstract. The equitable sharing of benefits in transboundary river basins is necessary to solve disputes among riparian countries and to reach a consensus on basin-wide development and management activities. Benefit sharing arrangements must be collaboratively developed to be perceived not only as efficient, but also as equitable in order to be considered acceptable to all riparian countries. The current literature mainly describes what is meant by the term benefit sharing in the the context of transboundary river basins and discusses this from a conceptual point of view, but falls short of providing practical, institutional arrangements that ensure maximum economic welfare as well as collaboratively developed methods for encouraging the equitable sharing of benefits. In this study we define an institutional arrangement that distributes welfare in a river basin by maximizing the economic benefits of water use and then sharing these benefits in an equitable manner using a method developed through stakeholder involvement. We describe a methodology in which (i) a hydrological model is used to allocate scarce water resources, in an economically efficient manner, to water users in a transboundary basin, (ii) water users are obliged to pay for water, and (iii) the total of these water charges are equitably redistributed as monetary compensation to users in an amount determined through the application of a sharing method developed by stakeholder input, thus based on a stakeholder vision of fairness, using an axiomatic approach. With the proposed benefit-sharing mechanism, the efficiency-equity trade-off still exists but the extent of the imbalance is reduced because benefits are maximized and redistributed according to a key that has been collectively agreed upon by the participants.The whole system is overseen by a river basin authority. The methodology is applied to the Eastern Nile River basin as a case study. The described technique not only ensures economic efficiency, but may also lead to more equitable solutions in the sharing of benefits in transboundary river basins because the definition of the sharing rule is not in question, as would be the case if existing methods, such as game theory, were applied, with their inherent definitions of fairness.

1 Introduction

With growing water scarcity, as a result of expanding population demand, environmental concerns and climate change effects, there is increased international recognition of the importance of cooperation for the effective governance of water resources. This is particularly evident in the case of transboundary river basins in which ~~the unidirectionalflow of water through riparian countries creates negative externalitieswhich~~ unidirectional, negative externalities, caused by the upstream regulation of the natural flow, often place some parties at a disadvantage and results in asymmetric relationships that add to the challenge of coordinating resource use (van der Zaag, 2007).There is a consensus among water professionals that the cooperative management of shared river basins should provide opportunities to increase the scope and scale of benefits (Phillips et al., 2006; Grey and Sadoff, 2007; Leb, 2015), stepping beyond the volumetric allocation of water that reduces negotiations between riparians to a zero-sum game. In their seminal paper, Sadoff and Grey (2002) discussed the types of benefits that river basins can provide, assuming cooperation: *benefits to the river* can result from sustainable cooperative management of the ecosystem; efficient, cooperative management and development of river flow can yield *benefits from the river* in the form of increased water quality, quantity and productivity; policy shifts away from riparian disputes/conflicts toward cooperative development can reduce costs of non-cooperation arising *because of the river*; and cooperation between riparian states can lead to economic, political and institutional integration, resulting in *benefits beyond the river*.

A large proportion of past research has focused mainly on the economic benefits of cooperation (benefits from the river). Focussing on benefits in strictly economic terms does not lessen the importance of benefits from other spheres (Qaddumi, 2008). An economic perspective, however, may be an effective method for encouraging cooperation because it may help riparian countries to realize win-win situations (Dombrowsky, 2009).

The traditional approach to estimating the economic benefits of cooperation relies on hydro-economic modelling (Arjoon et al., 2014; Jeuland et al., 2014; Tilmant and Kinzelbach, 2012; Teasley and McKinney, 2011; Whittington et al., 2005)~~in which water is allocated to maximize the net benefits from water use over the whole basin (economically efficient allocation)~~. These studies present various implementation strategies representing various levels of cooperation, but all show that there are significant economic benefits to be had through basin-wide cooperation~~, however, ~~. However, economic efficiency is not necessarily compatible with equitability due to the different production abilities of water users (Wang et al., 2003). Analytical methods, including game theory solutions such as the Shapley value (Jafarzadegan et al., 2013; Abed-Elmdoust and Kerachian, 2012) and bankruptcy theory (Sechi and Zucca, 2015; Mianabadi et al., 2015; Madani et al., 2014; Mianabadi et al., 2014; Ansink and Weikard, 2012), have been examined for use in water allocation as equitable alternatives to the efficient economic allocation produced by hydro-economic models. Analytical methods were also used by van der Zaag et al. (2002) who looked at possible equitable criteria for sharing water and developed allocation algorithms to operationalize these, applying them to the Orange, Nile and Incomati rivers. It has been argued that the notion of equity, or fairness, involves a cultural component that should be incorporated into any type of water policy and, therefore, stakeholder involvement in decision-making is a significant determinant in the judgement of fairness (Syme et al., 1999; Asmamaw, 2015). The explicit provision of benefit sharing arrangements that are collaboratively developed and, thus, perceived as fair, are therefore necessary to help solve disputes and to reach a consensus in transboundary river basin development and management activities (MRC Initiative on Sustainable Hydropower, 2011).

Increasingly, efforts are focussing on the sharing of benefits generated through cooperation in order to solve the problem of equitability. The rapidly growing body of literature on benefit sharing mainly describes what is meant by this in the context of transboundary river basins and discusses benefit sharing from a conceptual point of view (Suhardiman et al., 2014; Skinner et al., 2009; Qaddumi, 2008). This literature introduces and defines different approaches but falls short of providing practical institutional arrangements for the sharing of benefits. Recently, Ding et al. (2016) introduced a methodology to address the problem of water allocation in the Nile River through a revenue re-distribution mechanism that leads to a fairly allocated revenue for each water user based on the proportional of its contribution to the basin.

Analytical methods such as game theory and related bankruptcy methods may also be useful for determining ways to fairly allocate generated benefits. Game theory, which is the mathematical study of competition and cooperation, can provide a somewhat realistic simulation of the interest-based behaviour of stakeholders (Madani, 2010). The framework that relates the preferences of players to the observable features of a game is the hypothesis that players care about nothing except their own payoffs (Hausman, 1999). Fair outcomes are captured in solution concepts such as the *core*, which selects the payoff allocations that give each group of individuals no less than their collective worth and the *Shapley value* in which payoffs are related to the marginal contributions of individuals to a coalition (de Clippel and Rozen, 2013). The aim of bankruptcy methods is to distribute an estate or asset among a group of creditors, all having a claim to the asset, where the sum of the creditors claims is larger that the amount available to distribute (Herrero and Villar, 2001). An overview of bankruptcy rules has been presented by Thomson (2003, 2013). Each bankruptcy rule defines fairness based on the properties behind the rule. The three most well-known bankruptcy rules (the proportional rule, the constrained equal awards rule and the constrained equal losses rule) all define equity through the *equal treatment of equals* requirement in which agents with identical claims should be treated the same[1]. In other words, agents with the same claim should receive the same compensation. The analysis and formulation of properties and principles of distribution rules, such as those in cooperative game theory and bankruptcy theory, is the object of the axiomatic method (Thomson, 2001).

The axiomatic method allows desirable properties to be translated into a sharing rule. If a particular rule has been adopted to solve a problem involving a group of agents, it is assumed that all agents have agreed on the properties that such a rule fulfills. The concept of fairness, then, can be embedded into a rule. The axiomatic approach is easily incorporated into negotiations because the axioms can be interpreted quite naturally as describing characteristics of a negotiation procedure (Ansink and Houba, 2014).

As discussed previously, the economically efficient allocation of water is not necessarily equitable. ~~Conversely, axiomatic approachesmay be considered equitable~~ Axiomatic approaches, on the other hand, allow the characterization of an equitable distribution of welfare, but do not necessarily maximize the ~~total~~ aggregated economic welfare over the basin~~and may be considered deficient as a result~~. Institutional arrangements that ensure maximum economic welfare, as well as the equitable sharing of these benefits over the basin, are required.

In this study we define an institutional arrangement that distributes welfare in a river basin by maximizing the economic benefits of water use and then sharing these benefits in an equitable manner. The methodology relies on a pseudo-market arrangement in the form of a highly regulated market in which the behaviour of water users is restrained to control externalities associated with water transfers and to ensure basin-wide coordination and enhanced efficiency. The term pseudo-market indicates that bulk water users are not free to choose how much water will be moved in the system. Freedom of contract and private

[1]Equal treatment of equals is one of the properties upon which these bankruptcy rules are defined. For a complete discuss of all properties, refer to Thomson (2003, 2013).

property rights, which are necessary conditions for the existence of a market, are restrained, giving rise to a pseudo-market[2]. These restrictions are due to the flow characteristics of water and to the need to account for externalities and third-party effects, which can seldom be achieved within a traditional market.

The institutional arrangement described in this paper should encourage full cooperation between water users because it is intended as a replacement for traditional types of agreements on international river basins, which can lead to distrust and tension between riparian countries. What we present is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements.

In the following section, we describe this arrangement which uses a hydro-economic model to determine the economically efficient allocation of water and a collaboratively developed sharing method for the equitable allocation of monetary benefits. Section 3 presents the application of this framework to the Eastern Nile River basin. Section 4 presents and discusses the results and Sect. 5 concludes the paper.

2 Methodology

In the proposed pseudo-market approach, a river basin authority (RBA) plays the role of water system operator, identifying economically efficient allocation policies which are then imposed on the agents (water users). The agents are charged for water use and these payments are redistributed to ensure equitability among the users. In this particular system, the mandate of the RBA consists of (1) collecting information on water use and productivity, (2) efficiently allocating water between the different agents in the system based on the information collected in the first step, (3) preserving the hydrologic integrity of the river basin, and (4) coordinating the collection and redistribution of the benefits associated with the optimal allocation policies.

2.1 Information Collection

In this first step, the RBA collects information that is required to assess the demand curves, or at least the productivity (unit net benefit), of all users in the system, once at the beginning of each year. The information must be validated to ensure that it is complete and reasonable since the economically efficient allocation of water in the next step depends on it. The collection of information can be the basis of a bidding process in which agents offer to buy water at a given price. In the case of irrigation agents, information such as crop area, crop type, yield, crop price and crop water requirement over a period can be used to determine the bid for each agent and, based on the bid information, the demand curve can be inferred using the residual imputation method (Pulido-Velazquez et al., 2008; Riegels et al., 2013). This method assumes that all input costs, except for the cost of water, are known. The water value is then imputed as the residual of the observed gross benefits after all non-water costs are subtracted (Young, 2005).

In order to control the declarations of agents in the agricultural sector, the RBA can use techniques such as remote sensing ~~can be applied~~ to validate land classification and cropping areas (Gallego et al., 2014; El-Kawy et al., 2011; Rozenstein and Karnieli, 2011). As an example, the European Union uses an Integrated Administration and Control System (IACS), which

[2] One could also argue that a true market is created by assuming that every agent agrees with, and respects, having to pay for water.

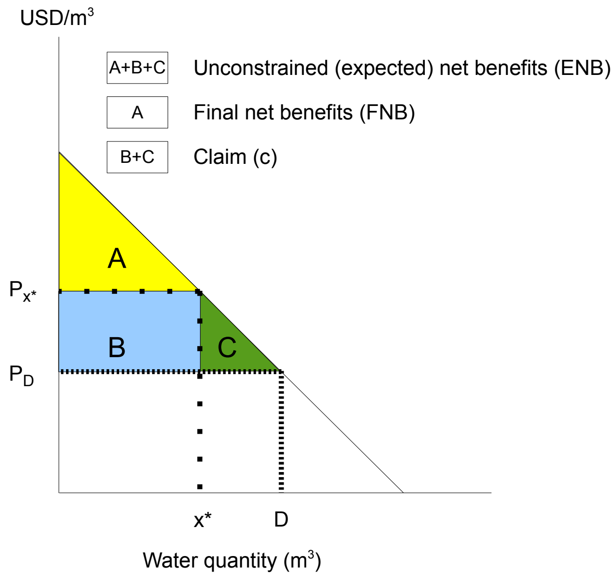

Figure 1. Demand curve. D=quantity of water demanded for a time period, x^*=quantity of water allocated for a time period, P=price of water.

includes a land-parcel identification system (LPIS), to control declarations from farmers for financial aid grants (Oesterle and Hahn, 2004). The LPIS uses orthophotos to monitor the evolution of the land cover and the management of crops and enables more accurate declarations by farmers.

In the case of hydropower, information regarding energy production and scheduling is important. For example, power plants might be off line for maintenance or might be obliged to generate a minimum amount of energy to meet its contractual commitments. As well, water use requirements such as environmental flow and minimum domestic use supply will also be required.

The unconstrained or expected net benefits (ENB) for a water user is the consumer surplus (Fig. 1), which is the area under the demand curve above the price P_D. The surplus is the private user cost of water and corresponds to the willingness to pay for the last unit of water demanded in a situation where allocation is unconstrained. This area is made up of three regions (A, B and C) which will be discussed later.

2.2 Water Allocation

Once water user information has been collected, allocation decisions are identified by matching demand with supply in a ~~cost-effective~~ cost-efficient way, i.e. by giving priority of access to users with the highest productivity. In order to do this, an aggregation of the demand curve is carried out, which means that a distinction must be made between rival and non-rival water uses. When water users are not in competition for the same unit of water, non-rivalness is observed. For example, ~~power companies are considered~~ water flowing through a dam may be considered a non-rival water ~~users~~ use since a unit of water

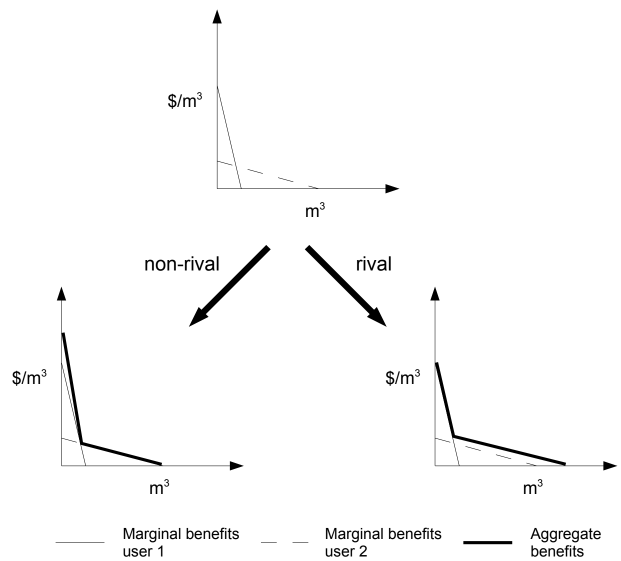

Figure 2. Aggregation of demand curves for rival and non-rival water uses for a given time period.

released through one dam can be used downstream by another dam. In rival water use, units are consumed and are no longer available to other water users (for example, water lost to irrigation or water held in a reservoir during a period when it is required downstream for irrigation). In this case, the demand curves are summed horizontally (see Fig. 2). Rival water uses need to be coordinated to prevent conflicts. The decision to divert one additional unit of water to any rival use depends on the at-source value[3] of water for that use. If this value is larger than the at-source value of all downstream marginal users, then it will be diverted to the rival use. See Tilmant and Kinzelbach (2012) for a detail description of rival and non-rival water uses. The value of the last unit of water at any site, then, is the sum of the marginal values of the non-rival users since the demand curves can be summed up vertically (see Fig. 2). This aggregation of the demand curve is done automatically in hydro-economic models. Hydro-economic models, then, can be used to determine the allocation of water between users at the same site and over a basin (comprising a number of sites) and to determine the marginal value of water and economic benefits at each site. A description of the mathematical formulation involved is given in the Appendix.

2.3 Collection of Bulk Water Charges

Based on the water allocation decisions and the corresponding water fluxes, pseudo-market transactions occur between the RBA and the water users. Users must pay the RBA for the water allocated to them. The cost of water is the marginal water value or shadow price (λ) calculated by the hydro-economic model at the site of water abstraction or use. Economic theory

[3]The at-source value of water is observed at the location where bulk water is diverted. The at-site value corresponds to the value of water delivered to the users (for example, a farm at the end of a conveyance and distribution system). At-site water values are generally larger than at-source values because they include losses in the system and conveyance costs. In the study of intersectoral allocation choices, at-source water values should be used (Young, 2005).

indicates that for efficient water allocation to occur, the price that users pay for the resource must be equal to the marginal value of still available opportunities of water use, which reflects the social cost of using water at a particular site. If the user pays less than this, the resource is over consumed or over utilized, as no efficient rationing occurs. Conversely, a user price higher than the marginal value would result in underconsumption/underutilization.

The RBA charges for the water entering the system in order to cover the costs associated with its mandates (conservation, coordination, compensation). In the case of consumptive users, water is purchased from the RBA at the marginal water value (the value of a marginal unit of water) at the site of abstraction. Non-consumptive users buy inflow from the RBA , at the marginal value at a price equal to the difference between the marginal value of water at the user site , and then sells the outflow downstream, back to the RBA, at the and the marginal value of water at the downstream site (Fig. 3). This bulk water charge system is based on a dynamic water accounting framework presented by Tilmant et al. (2014).

Payment for bulk water use has been addressed, recently, by the United Nations in their 2014 World Water Development Report (United Nations World Water Assessment Programme, 2014) in which they state that economic instruments such as markets for buying and selling a resource (such as water) or the imposition of water use tariffs could create incentives for more efficient use. And, in fact, payment for bulk water supply has been established in recent water laws in Zimbabwe, Tanzania and Mozambique (The World Bank, 2008).

Once transactions are collected by the RBA, water costs (CW) for each water user can be calculated along with the final net benefits (FNB) which is equivalent to the consumer surplus shown, on Fig. 1, as the area above the line P_{x^*} (area A). Line P_{x^*} is the social cost of water where x^* is the economically efficient water allocation.

The difference between the amount of benefits expected by each agent (ENB) and the final net benefits received (FNB) is the amount an agent will claim for compensation in the next step (c) and is equal to the value of the externalities (B+C on Fig. 1). These claims are composed of the difference in water costs between the unconstrained water demand (D) and the actual water allocation (x^*), which is area B on the figure, and the cost of cooperation (CC) which is the loss in benefits due to the allocation of less resource than what was demanded (area C in the figure).

2.4 Transfer Payments

At this point in the methodology, the RBA has collected an amount of money, referred to as the *estate* (E), that can be shared among the water use agents. The Using an axiomatic approach, a method of sharing this estate should be determinedin collaboration with the water users. Properties that define fairness , as determined through negotiations with the water users, are then . The aim of the axiomatic approach is to find and capture the notion of fairness that water users could agree upon. The approach then sets out axioms (properties) that fairness should or should not satisfy. Finally, these properties are translated into a sharing rule using an axiomatic approach. The incorporation of desirable properties into the sharing rule can lead to a final welfare division that is considered fair to allthat quantifies the particular definition of fairness. How the benefits are shared depends entirely on this definition as agreed to by water users. For example, a simple proportional sharing method may satisfy the properties of equity defined by the users, or an egalitarian method, or some other form of sharing may be required.

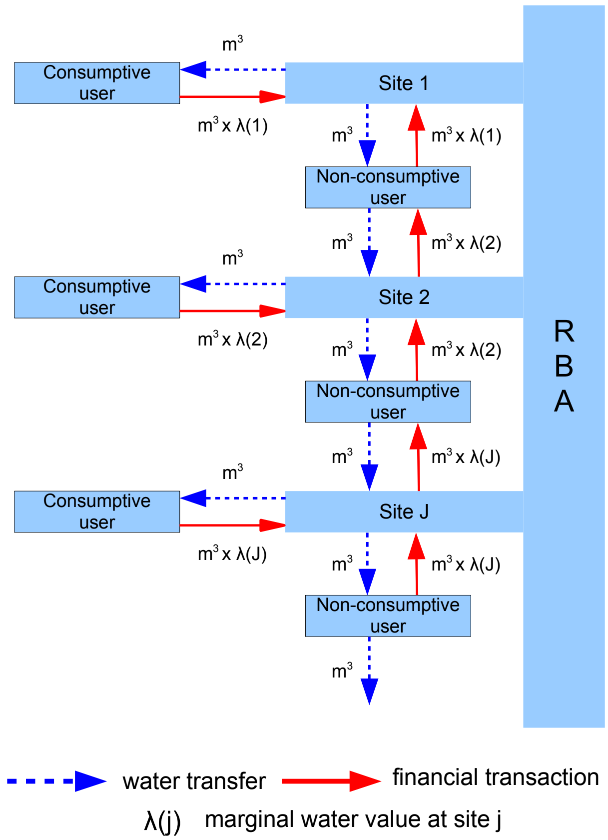

Figure 3. Collection of bulk water charges for a given time period.

Since each river basin will have a different definition of fairness (depending on conditions in the basin and the outcome of negotiations with the water users), each river basin will likely have its own unique sharing rule.

A flowchart of the complete methodology, including information obtained at each step, is shown in Fig. 4.

3 Case Study

3.1 Eastern Nile River Basin

The Eastern Nile River basin is used to illustrate the methodology described in the previous section. Covering an area of approximately 330,000 km^2 and with a length of 1529 km, the Blue Nile originates in the highlands of Ethiopia and flows into Sudan where it joins the White Nile at Khartoum to form the Main Nile. The Main Nile then flows out of Sudan, into Egypt and discharges into the Mediterranean Sea. The Eastern Nile River basin is composed of the Blue Nile, the ~~Atbara~~Tekeze-Atbara, the Baro-Aboko-Sobat, the White Nile downstream from Malakal and the Main Nile sub-basins (Fig. 5).

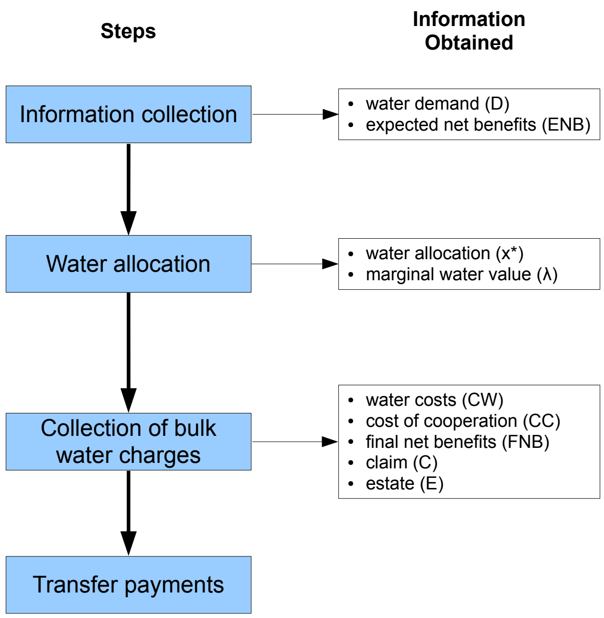

Figure 4. Flowchart of methodology including information obtained at each step.

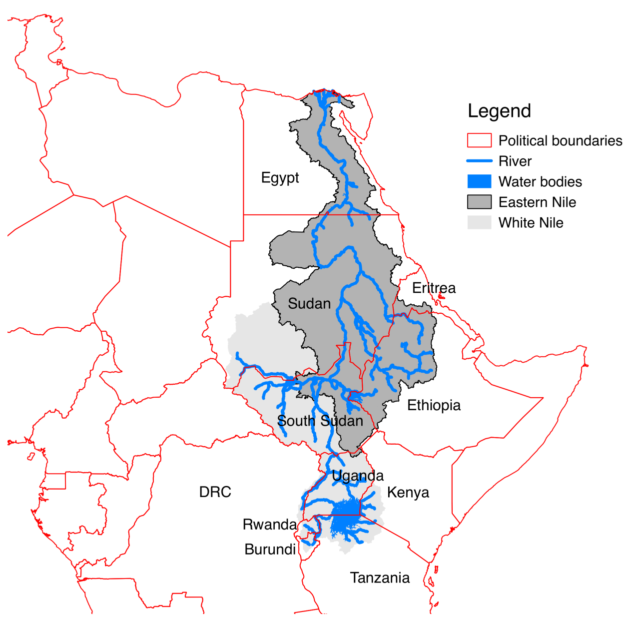

Figure 5. Eastern Nile River Basin

The dominant uses of water in the Eastern Nile River basin are irrigated agriculture and hydropower generation, mostly in Sudan and Egypt. This is, however, likely to change in the near future with the completion of the Grand Ethiopian Renaissance Dam on the border of Ethiopia and Sudan.

There is a long history of unsuccessful negotiations over water allocation and development of Nile water resources. Attempts at cooperation and benefit sharing within the Eastern Nile basin go back to the early part of the 20th century. The 1929 Nile Waters Agreement between Sudan and Egypt prioritized Egyptian water needs and reportedly gave Egypt the right to veto future hydroelectric projects along the Nile (Brunnée and Toope, 2003). Sudan and Egypt subsequently replaced the 1929 treaty, in 1959, with the Agreement for the Full Utilization of the Nile Waters, which essentially allocated the entire flow of the Nile at the Aswan Dam to Sudan and Egypt. Unsurprisingly, this has caused regional tension with the other riparians, who invoke the Nyerere Doctrine[4], and general principles of international water law, to contest the 1959 Agreement and claim a share of the Nile waters.

In 1999 the Nile Basin Initiative (NBI) was undertaken with the goal being to adopt a comprehensive, permanent, legal and institutional agreement over the Nile River basin. So far there has been little success in negotiations leading to an agreement. However, a Cooperative Framework Agreement (CFA) was signed by a number of the Nile basin countries with the notable exceptions of Egypt, Sudan and South Sudan.

Regional tensions have further complicated Nile cooperation efforts. For example, Ethiopia and Egypt have a long history of distrust and Egypt and Sudan, as well as Eritrea and Ethiopia, have long unresolved border disputes. Additionally, many Nile riparians have been broken by internal conflicts and instabilities that result in challenges to international relations.

In recent years, the construction of the Grand Ethiopian Renaissance Dam has been a source of concern and conflict among the three riparian countries. It should be noted, however, that in early 2015, Egypt, Sudan and Ethiopia signed an agreement on the declaration of principles with respect to the project.

It is pretty much agreed, at this point, that benefit sharing may offer a solution to the stalemate surrounding water use and allocation in the Eastern Nile River basin. While the concept of benefit sharing can be appreciated by most riparian countries, questions regarding methods of sharing benefits have emerged. The three Eastern Nile River basin countries need to, first and foremost, identify the bundle of benefits that can be generated, then agree on a mechanism for sharing these (Tafesse, 2009)).

3.2 Information Collection

Given the lack of accurate data with respect to irrigated agriculture in the Nile River basin, a net return of 0.05 USD/m^3 is chosen (as in Whittington et al. (2005)). For hydropower it is assumed that each MWh generated has an economic value averaging 80 USD/MWh for firm power and 50 USD/MWh for secondary power. These values are consistent with feasibility

[4]The Nyerere Doctrine of state succession, founded by the first President of Tanzania, states that a new nation should not be bound to international agreements dating back to colonial times and that these agreements should be re-negotiated when a state becomes independent.

studies of hydroelectric dams in Ethiopia. Using these values the unconstrained expected net benefits (ENB) are determined for each water use agent as:

$$ENB_j = D_j * P_j \tag{1}$$

where D_j is the unconstrained quantity of water demanded by agent j and P_j is its productivity. Note that the assumption is made that users do not currently pay for water.

The water demand for the irrigation agents is equal to the crop water demand. For the hydropower agents the water demand is equal to the amount that they are allocated in the next step. Since the allocation is economically efficient, the hydropower agents are assumed to be satisfied with the amount of water flowing through the turbines.

3.3 Water Allocation

The stochastic multistage decision-making problem (Eqs. (9) to (12) defined in the Appendix) was solved using stochastic dual dynamic programming (SDDP). Details of this algorithm can be found in Goor et al. (2010) and in Tilmant and Kinzelbach (2012). The hydro-economic model of the Eastern Nile basin is based on the schematization shown in Fig. 6. In this study the assumption is made that the Grand Ethiopian Renaissance Dam (located at H8 in Fig. 6) is online. Allocation decisions are chosen to maximize expected net economic returns from irrigated agriculture and hydropower generation over a planning horizon of 10 years and for 30 hydrologic sequences (see Arjoon et al. (2014) for a description of the model).

Once the allocation decisions are determined, the actual gross benefits (GB) can be calculated as:

$$GB_j = x_j^* * P_j \tag{2}$$

where x_j^* is the water allocation decision for agent j. The difference between the expected net benefits (ENB) and GB is the cost of cooperation (CC) to the agent due to the efficient allocation of water. In other words, it is the difference between the amount of benefits the agent is expecting to get if their unconstrained water demand is met and the actual benefits the agent receives given the allocation decision, excluding water costs.

3.4 Collection of Bulk Water Charges

The total of the transactions collected by the RBA (E), minus yearly operating expenses of 3 ~~million for operating expenses~~ million USD, will be used to compensate the agents for a percentage of the benefits lost either through efficient allocation (cost of cooperation) or water costs. Operating expenses of 3 million USD/yr is in line with those published by power pools (Southern African Power Pool, 2009) and river commissions (Mekong River Commission, 2013).

Final net benefits for each agent can be calculated as:

$$FNB_j = GB_j - CW_j \tag{3}$$

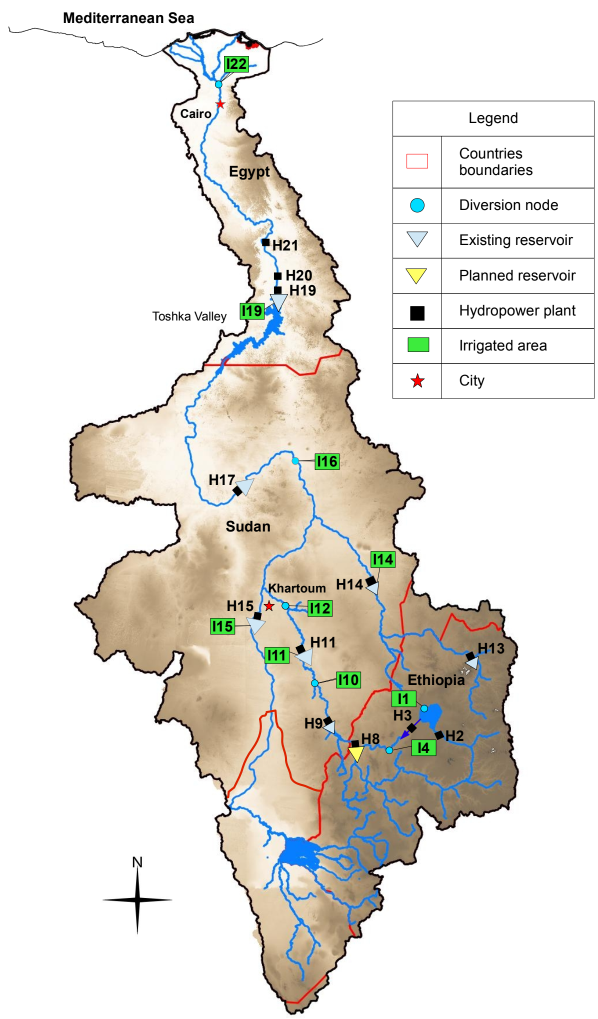

Figure 6. Model schematic of the Eastern Nile River basin. Irrigation agents (I) and hydropower agents (H) for this case study are shown. Note that the numbering is not consecutive because there are nodes that represent agents that are not part of the case study.

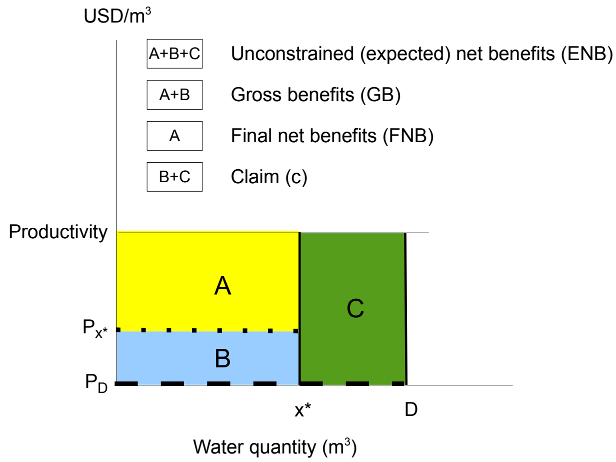

Figure 7. Demand curve for the case study. D=quantity of water demanded for a time period, x^*=quantity of water allocated for a time period, P=price of water.

where CW_j is the cost of water for agent j.

3.5 Transfer Payments

Once the final net benefits have been determined, transfer payments can be calculated for each agent. To do this, the total cost for each agent needs to be calculated, which will give the upper limit to the claim (c) of an agent to the estate.

~~From Fig. 1, we can~~ Fig. 7 shows the annual demand curve for an irrigation agent in this case study. In this study, we implicitly assume that the input demand is horizontal (perfectly elastic) with the price (P) = marginal productivity. The area to the left of line D (comprising areas A, B and C) is the expected net benefits (ENB) (we see that the agent does not pay for water) resulting from unconstrained water use. When water is constrained, area A is the final net benefits (FNB). The claims (c) are divided into two parts: area B is the cost of water (CW) to the agent and area C is the cost of cooperation (CC) due to the efficient allocation of water. Area B also represents the amount of money that the RBA collects from this agent. As previously mentioned, for hydropower agents the water demand and the water allocation are equal, therefore there is no cost of cooperation. The claim (c), then, for a hydropower agent, is the cost of water (CW). Over the whole basin the amount that the RBA collects (and is available for transfer payments) is enough to reimburse the agents for the actual cost of water, however, as mentioned, 3 million USD is held back for annual operating expenses. Therefore the shortfall between the amount the RBA has to share and the claims of the agents is the total cost of cooperation for irrigation agents ($\sum CC_j$) plus operating expenses.

The situation in which the amount available to share between agents is less than the total claims of the agents is, by definition, a bankruptcy problem.

In this case study, the collected benefits are shared among the water use agents following a rule that was developed based on a number of well defined properties in the bankruptcy literature (*feasibility, non-negativity, claims-boundedness*) as well as some that are specific to the problem (*solidarity, security of minimum benefits*).

It should be noted that, for this study, the properties for this rule were not developed with stakeholder input as this was beyond the scope of this research project. ~~However, in an~~ Although stakeholder involvement is imperative in this institutional arrangement, ~~this is imperative~~in this case study, we are giving an objective viewpoint and this analysis serves as a benchmark or reference point.

Benefits are shared in such a way as to ensure that each agent has the same proportion of final costs $(ENB_j - (FNB_j + tp_j))$ to benefits demanded (ENB_j) (where tp_j is the monetary transfer payment made to the agent) and that these are minimized. By extension, this rule also ensures that each agent receives an equal proportion of final benefits $(FNB_j + tp_j)$ to benefits demanded (ENB_j) and that these are maximized. This rule also applies a *solidarity* property in which all agents take equal responsibility for the shortfall in benefits at certain nodes due to the efficient economic allocation of water over the basin, and a property of *security of minimum benefits* in which the benefits obtained from the use of water (FNB_j) are uncontested.

The compensation rule is defined as follows :

$$tp_j = ENB_j - (FNB_j + \gamma ENB_j) \tag{4}$$

where γ is chosen such that :

$$\sum tp_j \leq E \tag{5}$$

Equation (5) ensures the property of *feasibility* which is the requirement that the sum of the transfer payments not exceed the amount available to share.

The following constraints also apply :

$$tp_j \geq 0 \tag{6}$$

$$tp_j \leq c_j \tag{7}$$

Equation (6) ensures *non-negativity*, which requires that each agent receive a non-negative amount, and Eq. (7) ensures *claims boundedness* which requires that each agent receive, at most, the amount of its claim.

Rewriting Eq. (4) to read

$$\gamma = (ENB_j - (FNB_j + tp_j))/ENB_j \tag{8}$$

shows that the property of *solidarity* is supported by ensuring that the final cost ($ENB_j - (FNB_j + tp_j)$) to expected benefit (ENB_j) ratio for all agents is the same.

In this final step, the transfer payments are calculated and the total final benefits ($FNB + tp$) for each agent are determined.

4 Results

The analysis of results was carried out on year 4 of the 10 year planning horizon. This ensures a steady-state condition that is not influenced by initial hydrological and storage conditions or by any end-effect distortion due to reservoir depletion that occurs as the end of the planning period approaches (Arjoon et al., 2014). As previously explained, the amount of water allocated to hydropower agents is equal to the amount demanded. This means that all hydropower agents receive 100% of the water demanded. The efficient allocation of water results in most irrigation agents also receiving their unconstrained demand. The exceptions are agents I1, I4 and I14 who receive, on average, 1%, 0% and 94% of their unconstrained demand, respectively (See Fig. 8) . This result is not unexpected because, from an economic standpoint, irrigation in the Eastern Nile River basin should take place downstream after water has been used for hydropower generation upstream (Whittington et al., 2005). These three irrigation agents have cooperation costs as well as, possibly, water costs. Looking at the cumulative distribution of the proportion of the allocated amount of water to the amount received for these agents (Fig. 9) we see that 95% of the time, agent I1 does not receive any water. Agent I14, on the other hand, receives its full demand about 75% of the time. Agent I4 (not shown in Fig. 9) always receives 0%. The rationing of water for upstream irrigation users is a result of the horizontal demand curve used for irrigation. If more detailed economic/agricultural data were available, a non-horizontal demand curve could be produced. This may result in irrigation schemes with high value crops having priority to water and those areas with low value crops not being irrigated. This means that the irrigation water users that are rationed may change and they may be more spread out over the basin.

Overall, the agents with the smallest claims are all hydropower agents in Sudan (H9, H11, H14, H15) with marginal values that are almost equal to marginal values at the downstream sites (see Fig. 10). This means that they sell water downstream at about the same price that they paid for it, resulting in lower water costs. Figure 11 gives a basin-wide view of the percentage of the unconstrained benefits claimed by each agent, by agent type, on average. The irrigation agents upstream claim a larger percentage of their expected benefits because, first, they pay more for water and, second, they also have cooperation costs. With respect to hydropower agents, H8 and H19 (Grand Renaissance and High Aswan, respectively) claim the largest percentage of their expected benefits. In both cases, the cost of water at these sites are much greater than the cost of water at the respective downstream sites.

From the collection of bulk water charges for the period analyzed (year 4), the RBA ends up with 3894 million USD to allocate between the agents (after removing 3 million USD for operating costs). The total claims for all agents, for the year, is 4266 million USD which means that there is a shortfall of 372 million USD between the amount available to share and the claims, or about 9% of the the total claims.

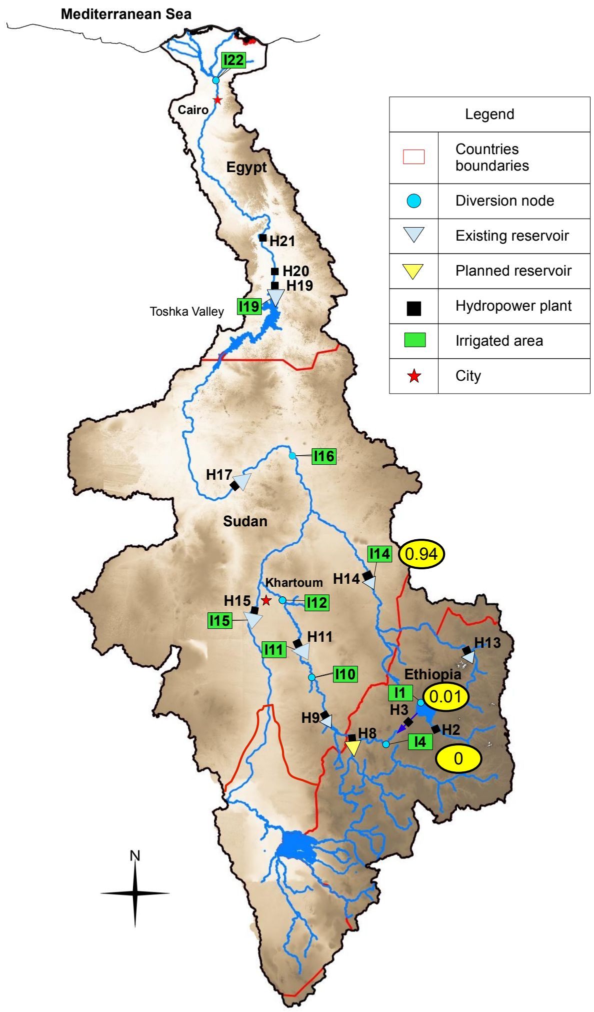

Figure 8. Average proportion of water allocation to unconstrained demand for all agents. Only the values for those agents in which the proportion is less than 1 are shown.

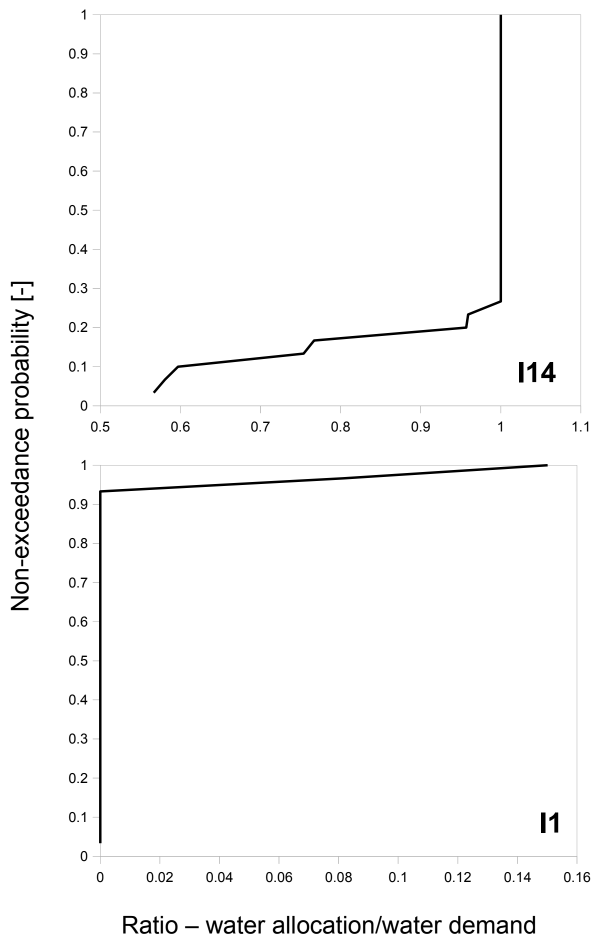

Figure 9. Cumulative distribution function for the proportion of water allocation to unconstrained demand for agents I1 and I14.

Using the bankruptcy rule developed for this example, the average amount of transfer payment is calculated for each agent. The ratio of final net benefits (FNB) to expected net benefits (ENB), referred to as the *initial ratio*, and final net benefits plus transfer payments (FNB+tp) to expected net benefits (ENB), referred to as the *final ratio* are determined and analyzed. These results were analyzed over the 30 different hydrologic sequences to assess how this rule performs under varying hydrologic conditions.

Figure 12 shows the mean values for initial ratios (shown as large filled squares) and final ratios (shown as large filled diamonds) for irrigation agents as well as the values for each of the hydrologic sequences. Agents I1 and I4 receive little or no irrigation water, on average, as discussed previously. Agent I14 initially receives about 23% of its expected net benefits, on average. This agent is located at the Kashm El Girba dam, on the ~~Atbara~~ Tekeze-Atbara River. The flow of this river is highly seasonal with annual flows entering Sudan from Ethiopia restricted to the flood period of July to October. The design storage

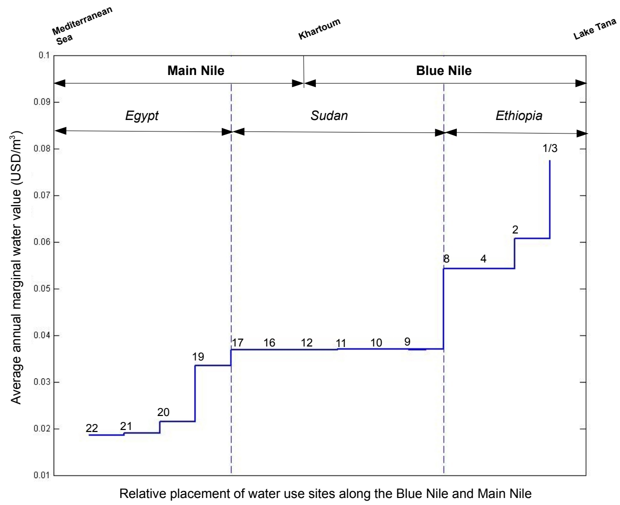

Figure 10. Marginal Water Value - Blue Nile and Main Nile

capacity of the reservoir at this site is about 10% of the inflow, however, high sedimentation in the reservoir dropped the storage capacity by 50% as of 1977. This loss of storage capacity has resulted in severe water shortages during drought years and an associated decline of the crop area cultivated. As a result, the restriction of water for this irrigation agent is more probably due to the hydrology as opposed to being economic in nature. Due to flow variation, the marginal water values are highly variable at this site, resulting in a wide spread of initial ratios over the hydrologic sequences (as indicated by a large vertical spread of data points on the graph for this agent). All other agents always receive their full unconstrained demand. Variability in the initial ratios of these agents are due to variability in the marginal water values over the hydrologic sequences.

Results for hydropower agents are shown in Fig. 13. Here we see more variation in the initial ratio than for the irrigation agents. The upstream hydropower agents (H2, H3), and those on the ~~Atbara~~ Tekeze-Atbara River (H13, H14) have large variations in initial ratios as a result of large inter- as well as intra-year variations in flow (and subsequently in marginal water values) which occurs because these sites are all upstream of flow regulating infrastructure. The agents with the smallest claims are the four smallest hydropower agents in Sudan (H9, H11, H14, H15). These agents have the largest initial ratios and, therefore, often do not receive monetary transfers. This also results in the final ratios for hydropower agents not being equal because the property of non-negativity, which is used to define the sharing rule, allows an agent to keep its initial benefits from water use even if this results in its final ratio being larger than those of the other agents.

Overall, the average final ratios for all agents (irrigation and hydropower) are equal, with the exception of agents H9, H11, H14 and H15 as mentioned above. There is also very little variation in final ratio values with respect to hydrologic sequence. The final ratio for irrigation agents varies from 93.5% to 95% of their uncontested benefits. For hydropower agents the statistical distribution of final benefit ratios is shown in Fig. 14. We see that these final ratios also vary between 93.5% and 95% with the exception, again, of agents H9, H11, H14 and H15 which have high initial ratios that vary with inter- and intra-annual

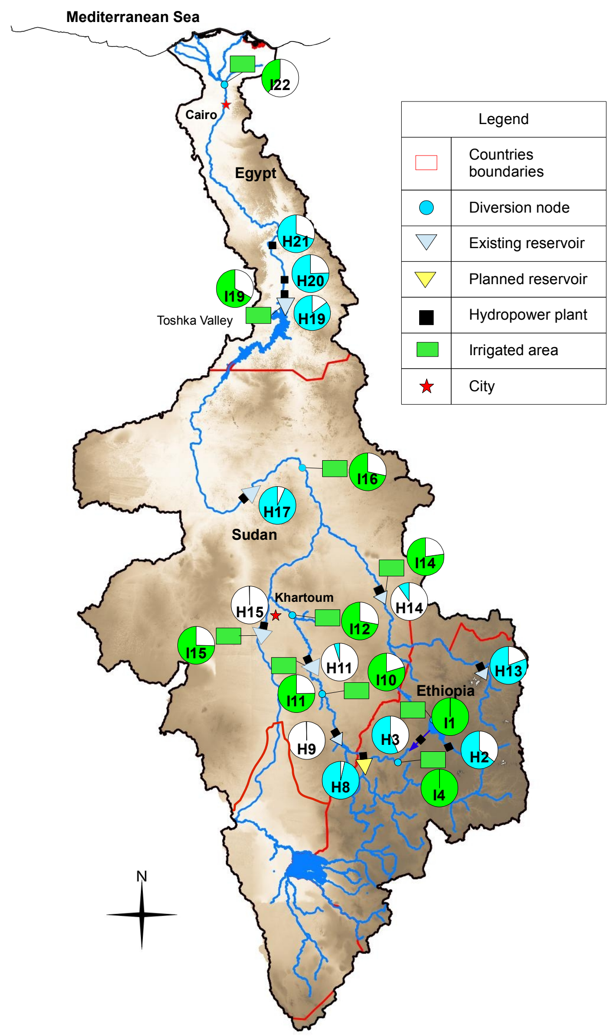

Figure 11. Percentage of unconstrained benefits claimed by agents.

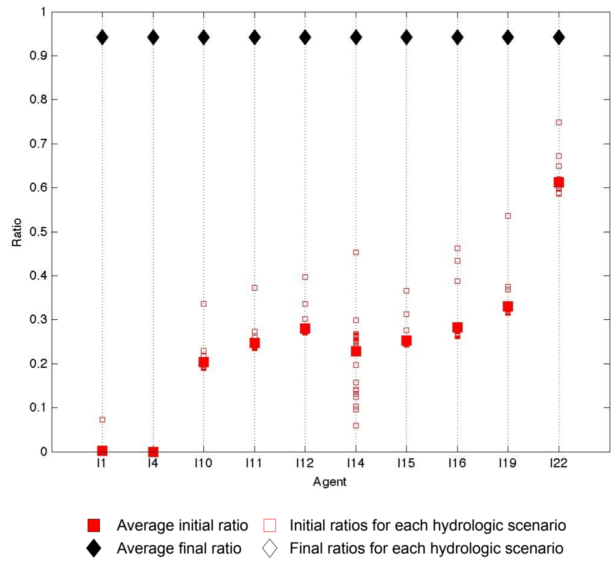

Figure 12. Initial and final ratios for irrigation agents.

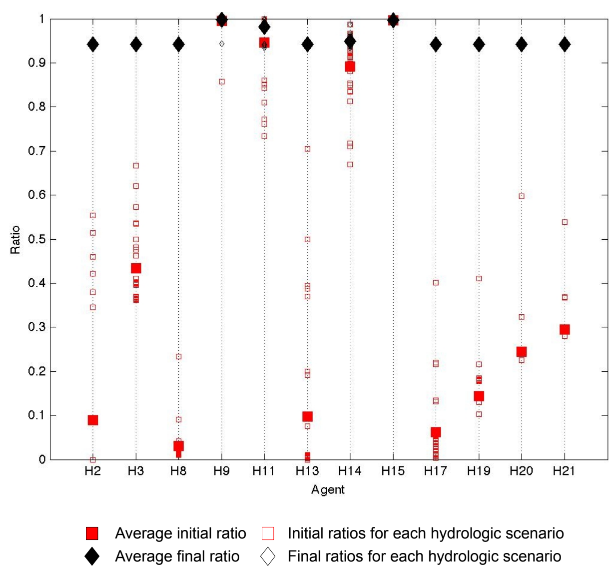

Figure 13. Initial and final ratios for hydropower agents.

variations in the marginal value of water. These results indicate that the sharing rule used is predictable in that agents can expect similar final benefits regardless of the hydrologic conditions.

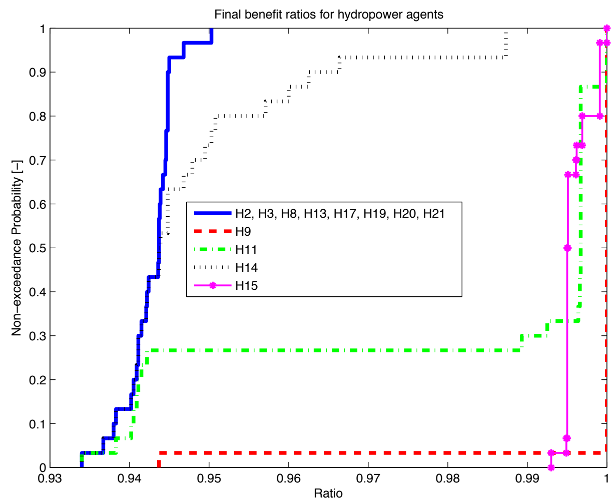

Figure 14. Final benefit ratio for hydropower agents.

Results that warrant a closer look are those for the upstream irrigation agents I1 and I4. We can conclude that, in this case study, given the economic information used in the model, it is economically inefficient to irrigate upstream in the basin regardless of the hydrologic sequence (meaning that even in situations of high flow years, there is no irrigation water allocated to these agents). However, these two irrigation agents consistently demand fairly substantial transfer payments even though they do not contribute economically to the basin. This becomes an obvious problem of fairness for the other agents. If these results persist over a number of years, the RBA could use this information for better management by ensuring that agriculture is developed downstream or that upstream agricultural sites have a high productivity value.

Finally, it should be noted that we make no attempt to compare the results of the case study with current water use in the basin. While the presented case study is hypothetical and is not consistent with the actual, current situation, it represents a possible long-term future scenario in the basin and the results reflect these assumptions. In the case study, we assume complete cooperation, there is expanded irrigation in the basin and the Grand Ethiopian Renaissance Dam is online.

5 Conclusions

The sharing of benefits among agents in a transboundary river basin is based on three fundamental questions : (i) how can the benefits of water use be quantified and monetized, ii) what mechanism can be used to allocate benefits and (iii) upon what criteria should the sharing of benefits be based to ensure efficiency and equitability. It should be noted that there is no unique response to these questions. In this paper, we propose one approach for distributing the benefits of cooperative management in a river basin system comprised of rival and non-rival uses. To illustrate the approach, we used the Eastern Nile River Basin as a case study due to the important hydropower and agricultural sectors spread over three countries.

The methodology described in this paper is based on the welfare distribution for each agent being equal to the sum of its benefits from water use plus a monetary transfer. First, efficient water allocation is implemented through the application of a hydro-economic model in order to maximize the benefits in the river basin. Second, a charge for the use of water is established. The price that agents pay for the use of water is equal to the marginal value of water at the site at which the agent receives its allocation. The total of the water charges is equivalent to the overall value of water in the basin that is used in the sectors being studied. Finally, the total of the water charges are reallocated over the basin to ensure that all agents pay the same ratio of costs to benefits, using an axiomatic approach. The whole system is overseen by an RBA.

The two main goals of benefit sharing, efficiency and equitability, are the foundation of this methodology. The hydro-economic model results are the efficient water allocations for each agent. Efficiency is also inherent in the benefit sharing rule used to implement the monetary transfers in that all of the available money is shared among the agents. The defined properties of fairness are embedded in the sharing rule through the axioms.

This methodology can be useful to policy-makers in that the solution is more likely to be perceived as equitable, resulting in water use agents being more open to cooperation. An additional advantage of this method is the predictability of the final results. These results, over varying hydrological sequences, are shown to be relatively constant.

The importance of this methodology is that it can be adopted for application in negotiations to cooperate in transboundary river basins. The methodology is flexible in that there is no set way to allocate the water over the basin. Any hydro-economic model (or another method) can be used as long as the amount of water allocated to each agent, as well as the marginal value of water for each agent, is available. As well, the development of the sharing rule can be based on stakeholder input and will depend on specific conditions in specific river basins.

One obvious constraint of this method is its dependance on the existence of a strong basin-wide authority to impose fees and that can enable negotiations between stakeholders for the development of a sharing rule. Allowing all stakeholders a place at the table might prove challenging, especially for large systems with diversified water use activities. In the irrigation sector, for instance, farmers could be represented by a water user association. For uses of water as a public good, such as for environmental flows, the representative could be the Ministry of Environment of the country of interest. For municipal uses, the system could be designed in such a way that a minimum amount of allocated water is guaranteed (a fixed constraint in the allocation system) while quantities beyond that minimum would be part of the pool for which municipalities would have to bid. Industrial and power companies are easier to handle. All users that can be rationed (mainly private water users) are allowed a place at the table for the purpose of defining fairness with respect to transfer payments. Another possibility is that the government (or at least a high level representative of the stakeholders) has the ultimate negotiation power, akin to negotiations on trade liberalizations. Clearly, different lobbies exist that would try to influence the government, implying, ultimately, some form of compensation (the analysis of which would lie outside the scope of this paper).

~~This paper~~ Another constraint is the availability of reliable data. Some information such as market prices, either national or international, can be observed and transportation costs can be estimated, allowing for an approximation of the mark-up that may accrue to farmers, for example. This paper describes a system in which it is assumed that there is cooperation over the whole basin and that water users have agreed to bid for water and to supply the information that is necessary to make the methodology work. Increasingly, the information required is becoming available through the use of remote sensing and monitoring of river basins.

Incentives for water users to cheat, with respect to the data they provide, will remain even if the river basin authority is able to audit the bids. For industrial uses, including hydropower generation, cheating might be more difficult because the market prices and production functions are often well characterized. The main challenge is to be found in the agricultural sector because (a) it is often the largest water use in a basin (and, hence, cheating might have serious basin-wide consequences), and (b) the heterogeneity in terms of cropping patterns and irrigation efficiency requires that significant data be collected and analyzed to audit the demands. We argue that the incentives to cheat might not be eliminated but they can be suppressed, or at least kept within limits, through a robust monitoring system and a strong RBA to negotiate disputes. An example of how this has worked, with good success, is the Indus River basin. Zawahri (2009), in discussing the Permanent Indus Commission, states "The commission's ability to monitor development of the shared river system has permitted it to ease member states' fear of cheating and confirm the accuracy of all exchanged data. Finally, its conflict resolution mechanisms have permitted the commission to negotiate settlements to disputes and prevent defection from cooperation."

This paper adds to the analysis of the sharing of economic benefits in transboundary river basins by describing a methodology for efficient and equitable benefit sharing based on operating the river basin as a water pseudo-market with the advantages of resource use optimization, improved resource reliability and enhanced security of resource supply. As well, we impose specific axioms, based on a stakeholder vision of fairness, on the compensation scheme and derive a unique solution for the distribution of monetary payments. This technique may lead to a sharing solution that is more acceptable to shareholders because the definition of the sharing rule is not in question, as would be the case if we applied existing bankruptcy rules or other game theory solutions with their inherent definitions of fairness.

6 Appendix

Hydro-economic modelling is a common tool used to analyze river basin systems and, specifically, water resources allocation problems. These models use a network representation of the system in order to physically connect various sources of supply with scarcity-sensitive water demands. Reviews of hydro-economic models can be found in Harou et al. (2009) and Brouwer and Hofkes (2008). Two classes of hydro-economic models exist: optimization-based and simulation-based. Both approaches have advantages and disadvantages but the allocation decisions and the marginal costs of the binding constraints (the limiting resources or factors that prevent further improvement of the objective function) determined by an optimization model makes this type of model attractive in the proposed methodology. In the system network, a water balance is evaluated at each node to determine the amount of water available for the demand sites connected to that node. The mass balance equation ensures that water is allocated to the connected water users to the extent permitted by water availability at the node. In the case of water scarcity, the marginal cost associated with the water balance indicates the shadow price of water or what the users would be willing to pay for an additional unit of water (Young, 2005).

In a hydro-economic water resource optimization problem, the objective function Z to be maximized includes the economic net benefits across all water uses over a given planning period.

$$Z^* = \max_{x_t} \left\{ \mathbb{E}_{q_t} \left[\sum_{t}^{T} \alpha_t b_t(\mathbf{w}_t, \mathbf{x}_t) + \alpha_{T+1} \nu(\mathbf{w}_{T+1}) \right] \right\} \tag{9}$$

where b_t is the basin-wide net benefits at time t, x_t the vector of allocation decisions, w_t the vector of state variables, α a discount factor, ν a terminal value function, $\mathbb{E}$ the expectation operator capturing he uncertainty that governs the hydrologic inflow q_t and Z the total benefit associated with the optimal allocations (x_1^*, x_2^*, ..., x_T^*).

This function is maximized to the extent permitted by physical, institutional or economic constraints :

$$g_{t+1}(\mathbf{x}_{t+1}) \leq 0 \tag{10}$$

$$h_{t+1}(\mathbf{w}_{t+1}) \leq 0 \tag{11}$$

$$\mathbf{w}_{t+1} = f_t(\mathbf{w}_t, \mathbf{x}_t, \mathbf{q}_t) \tag{12}$$

where g is a set of functions constraining the allocation decision, h a set of functions constraining the state of the system and f a set of functions describing the transition of the system from time t to time $t+1$.

Included in the functions in Eq. (12) are the mass balance equations for the river basin :

$$s_{t+1} - R(r_t + l_t) - I(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t \tag{13}$$

where s_t is the storage at time t, r_t the controlled outflows, l_t the uncontrolled outflows, i_t the water withdrawals, R and I the connectivity matrices representing the topology of the system (including return flows), and e_t the evaporation losses.

At the optimal solution of the problem (Eqs. (9) to (12)), the solver provides the allocation decisions (x_1^*, x_2^*, ..., x_T^*) and the marginal values of water (shadow prices) (λ_1, λ_2, ..., λ_T) of the constraints. For the constrains in Eq. (12), the shadow prices correspond to the marginal resource opportunity cost at the sites where water balances are computed.

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