Water Policy Uncorrected Proof (2016) 1–17

Allocation of water consumption in multipurpose reservoirs

Tor Haakon Bakken[a,b,*], Ingunn Saur Modahl[c], Hanne Lerche Raadal[c], Ana Adeva Bustos[a,b,d] and Silje Arnøy[c]

[a]Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology (NTNU), S.P. Andersens veg 5, Trondheim N-7491, Norway.

**Corresponding author. E-mail: tor.haakon.bakken@sintef.no*

[b]SINTEF Energy Research, Sem Sælands vei 11, Trondheim NO-7465, Norway

[c]Ostfold Research, Stadion 4, Kråkerøy 1671, Norway

[d]Departamento de Ingeniería Forestal, Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros de Montes, Madrid 28040, Spain

Abstract

The Intergovernmental Panel on Climate Change Special Report on Renewable Energy represented a benchmark in the assessment of water consumption from electricity production. The numbers for hydropower ranged from very low to much larger than the other renewable technologies, partly explained by methodological problems. One of the methodological shortcomings identified was the lack of guidance on how to allocate the water consumption rates in multipurpose reservoirs. This paper is, according to the authors' knowledge, the first attempt to evaluate, test and propose a methodology for the allocation of water consumption from such reservoirs. We tested four different allocation methods in four different cases, all serving 3–5 functions, including drinking water supply, irrigation, flood control, industrial water, ecological flow and power generation. Based on our case studies we consider volume allocation to be the most robust approach for allocating water consumption between functions in multipurpose reservoirs. The spatial boundaries of the analysis should follow the boundaries of the hydraulic system. We recommend that data should preferably be gathered from one source for all functions, to ensure a consistent calculation approach. We believe the findings are relevant for similar allocation problems, such as allocation of energy investments and green-house gas emissions from multipurpose reservoirs.

Keywords: allocation; life cycle assessment (LCA); multipurpose reservoirs; water consumption

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources (IPCC, 2011) assessed the potential of renewable energy sources to replace fossil-based sources. The renewable technologies were benchmarked with respect to a set of criteria, including

doi: 10.2166/wp.2016.009

their typical cost ranges, their energy efficiency and the water needed to produce 1 MWh of electricity, i.e. 'water consumption of electricity production'. The water consumption estimates for hydropower were based on very few studies and publications, and presented an inconsistent picture as the estimates ranged from close to 0 m^3/MWh up to a maximum 209 m^3/MWh. This was far beyond all other technologies that ended up in the range of 1–5 m^3/MWh (IPCC, 2011). Later studies on water consumption from hydropower (e.g. Mekonnen & Hoekstra, 2012; Bakken *et al.*, 2013b; Demeke *et al.*, 2013) indicate that the water consumption rates could even go far beyond the numbers published by IPCC (2011). A comprehensive review and a discussion of the applied methodology (Bakken *et al.*, 2013b) reveals that these numbers are calculated based on an immature and over-simplistic methodology or lack clarity, which is also acknowledged by other publications (e.g. IPCC, 2011; Mekonnen & Hoekstra, 2012; Demeke *et al.*, 2013; Meldrum *et al.*, 2013; Chenoweth *et al.*, 2014).

One of the main methodological shortcomings identified is the lack of guidance on how to allocate the water consumption rates in multipurpose reservoirs (Cooley *et al.*, 2011; IPCC, 2011; Pfister *et al.*, 2011; Mekonnen & Hoekstra, 2012; Bakken *et al.*, 2013b; Demeke *et al.*, 2013; Fulton & Cooley, 2015). A multipurpose reservoir is a reservoir that serves several purposes, such as flood control, drinking water supply, irrigation water, hydropower production, recreation, water aquaculture and more (IPCC, 2011), and hydropower is one of the functions in about 40% of multipurpose reservoirs (International Commission of Large Dams [ICOLD], 2014). IPCC (2011, Chapter 5, p. 44) states that 'allocation schemes for determining water consumption from various reservoir uses in the case of multipurpose reservoirs can significantly influence reported water consumption values'. Furthermore, IPCC (2011, Technical Summary, p. 74) claims that 'the multipurpose nature of most hydropower projects makes allocation of total impacts to the several purposes challenging'. Many life cycle assessments (LCAs) to date allocate all impacts of hydropower projects to the electricity generation function, which in some cases may overstate the emissions for which they are 'responsible'. Allocating all impacts of hydropower projects to electricity generation is in line with the previous requirements set by the product category rules (PCRs) for preparing an environmental product declaration of hydroelectricity (Setterwall, 2007). These PCRs have recently been updated and open up for considering allocation of burdens in multipurpose reservoirs.

The purpose of this study is to:

1. Review the most common approaches for the distribution of environmental burdens and resources consumption, based on the principles outlined by the ISO standard 14044 (2006) in the light of water consumption from multipurpose reservoirs.
2. Demonstrate the use of the various allocation approaches for water consumption based on real cases with specific water consumption datasets, and assess the appropriateness of the various allocation procedures.
3. Propose recommendations and guidelines for the operative use of the allocation procedure for water consumption in multipurpose reservoirs with hydropower production. These burden-distributing guidelines should also be considered more widely relevant for LCA studies of multipurpose reservoirs.

To the authors' knowledge there are no scientific publications attempting to allocate the burden of water consumption or any other resource consumptions or emissions from multipurpose reservoirs, except the study on Glen Canyon Dam multipurpose reservoir (Pasqualetti & Kelley, 2008) and in **Q1** the Yangtze River (Zhao & Liu, 2015). The novelty in our study is, for this reason, the application of existing data on a wide range of allocation methods, based on use of existing hydrological, technical and socio-economic data and not on the collection of new data. Rather opposite, the intention has been to apply available data in a new way, which would be the situation when this type of study is to be carried out as part, for instance, of an environmental impact assessment. We would also stress that the purpose of this study is not to identify generic allocation ratios to the various functions, but to test allocation methods. We believe hydropower projects and multipurpose projects in particular are so case-specific, that it is not possible to find generic ratios.

There is a great need to establish justifiable allocation methods for multipurpose reservoirs outside the scientific community. The recently established ISO Water Footprint Standard (ISO 14046, 2014) lacks proper allocation rules. The initiative launched by the World Water Council and their programme on water and energy coordinated by Electricity of France (http://www.worldwatercouncil.org/programs/water-energy/) underline the importance of the topic, as well as the concerns expressed by the hydropower sector (International Hydropower Association [IHA], 2011).

2. Methodology for allocation of burdens in multi-output systems

2.1. Allocation models and data requirements

In order to choose the most appropriate model for distributing the environmental burdens between functions in a multi-output system, one has to take into account the scope of the study, data availability, and the characteristics of the process under study (European Commission, 2010). The starting point for a LCA-study should, however, always be the hierarchy given by ISO 14044 (ISO 14044, 2006), which means following the order given below.

If possible, allocation should be avoided by:

- 1A: Subdividing the product system
- 1B: Using system expansion/avoided burdens to include the additional functions

If allocation cannot be avoided, allocation should be based on:

- 2A: Physical relationships (mass, volume or energy)
- 2B: Other relationships (economic or other relationships, e.g. explicit prioritizing)

According to the International Reference Life Cycle Data System (ILCD) handbook (European Commission, 2010), subdividing the product system (1A) will require subdividing the multipurpose reservoir individually for those of the mono-functional processes that relate to the analysed system. The use of 1A is considered irrelevant for multipurpose reservoirs as this approach is designed for production lines that can be completely separated and the resource consumption/emissions assigned to each type of product or service. In contrast, multipurpose reservoirs hold one large pool of the same resource and cannot be separated unless the water is divided in each function based on volume of water used, which would lead to volume allocation as the approach (2A).

System expansion/avoided burdens (1B) means to add another function to make two systems comparable, or to subtract the inventory of another system (representing another way of fulfilling the not-required function) from the analysed system (European Commission, 2010). The use of 1B would imply removing and adding functions and then assessing the changes in the water consumption. The order in which this virtual 'stripping of functions' is carried out will affect how much the water consumption is reduced. To define a fair basis, not determined by the order the functions are removed or added, the use of 1B will also ultimately lead to volume allocation (2B) as the allocation method.

Using allocation is the last step in the ISO hierarchy. Allocation is also called 'partitioning' and this 'solves the multi-functionality by splitting up the amounts of the individual inputs and outputs between the co-functions according to some allocation criterion, being a property of the co-functions' (European Commission, 2010, p. 79). The European Commission (2010) also states that the underlying causal physical (including chemical and biological) relationships between the functions should be reflected in the allocation. Mass allocation (2A) is considered to give the same outcome as volume allocation for the case of water reservoirs. If physical relationships cannot be established, allocation should be based on some other relationship, which could be economic or another non-causal physical property (Table 1).

In the case of multipurpose reservoirs, explicit prioritizing between sectors is defined in some countries, e.g. India (Government of India – Ministry of Water Resources, undated) and Turkey (Şorman, 2013), as the authorities have stated clear priority rules for the allocation given by the importance for the society as a whole. Explicit prioritizing could be interpreted as meaning that the highest priority should have all the share of the water consumption (100%), the highest share (e.g. 50% if 3 or more users) or another allocation ratio, independent of how large the volumes of water are that are withdrawn to each purpose. Alternatively, a hybrid allocation version combining the priority and the volume of water withdrawn (weighted by priority) could be used. Q2

2.2. Basis for assessment

As the calculated burden-distribution from the various allocation models cannot be said to be right or wrong, the qualitative criteria formulated by the ILCD (European Commission, 2010) formed the basis for our assessment of the appropriateness of the different allocation models in the context of multipurpose reservoirs and water consumption, which are:

- Scientific robustness, i.e. how sensitive the model is to changes in input from its initial stable configuration.
- Transparency and reproducibility, i.e. how easily the assessment is understood and if it can be reproduced (with the same output) by a different and independent assessment.
- Applicability, i.e. if the use of the allocation model in a real case can be carried out in a process that is practical, cost-effective and easy to communicate.
- Level of documentation, i.e. if reliable information and data is readily available with reasonable efforts.
- Stakeholder acceptance, i.e. to what extent the model is perceived fair among the stakeholders.

3. Datasets used for demonstration and assessment

The World Register of Dams (ICOLD, 2014) is considered to hold the most complete dataset of large dams and reservoirs, and holds information about close to 39,000 dams and reservoirs among the

Table 1. The table presents all possible functions of multipurpose reservoirs, those models that are considered feasible for sharing burdens from multipurpose reservoirs, how the use of these models can be understood in the context of multipurpose reservoirs and their data needs. The list is modified based on the classification system proposed by the International Commission of Large Dams (ICOLD, 2014).

Functions in a multipurpose reservoir	2A: Volume allocation	2A: Energy allocation	2B: Economic allocation
Power generation	Volume of water used for power generation.	Power production.	Income from hydropower production.
Water supply	Volume of water used for water supply.	Power production lost by withdrawal of water for water supply.	Value of water supply. Alternatively, the value of the loss of power.
Irrigation	Volume of water used for irrigation.	Power production lost by withdrawal of water for irrigation.	Income from increased agricultural production. Alternatively, the value of the loss of power.
Flood control	Volumes available for storage of inflow.	Lost power production due to reduced head (lowered water level), and less profitable operation of the reservoir.	The value of reduced risks of floods. Alternatively, the value of the loss of power.
Transportation/ navigation	Volume of water released to downstream areas and maintenance of a certain water level in the reservoir.	Lost power production due to less profitable operation of the reservoir. For the river locks – diversion of water.	The value of providing more efficient/cheaper transportation. Alternatively, the value of the loss of power production.
Fisheries/ aquaculture (commercial)	In the case of withdrawal to external productions sites – volume of water withdrawn. In the case of aquaculture in the reservoir – maintenance of a certain water level.	Lost power production due to withdrawal of water and/or less profitable operation of the reservoir.	The value of the increased commercial and recreational fisheries. Alternatively, the value of the loss of power production.
Recreation	Maintenance of a certain water level.	Lost power production due less profitable operation of the reservoir.	The value of the recreational activities in the area. Alternatively, the value of the loss of power.
Environmental flow to downstream areas	Volume of water released to downstream areas.	Power production lost due to diversion of water.	The value of intact (or less damaged) downstream ecosystems. Alternatively the value of the loss of power production.

world's 45,000 large dams (WCD World Commission on Dams, 2000) built for the purpose of irrigation, flood control, navigation, urban water supply schemes and other purposes. Approximately 25% of the world's dams higher than 15 metres registered in the ICOLD database (i.e. close to 10,000 dams) are classified as dams with reservoirs serving multiple functions ('multipurpose reservoirs/dams'). Among the multipurpose reservoirs, irrigation is the most common purpose followed by flood control, water supply, hydropower generation, recreation and navigation/fish farming. Approximately 40% of the multipurpose dams serve hydropower production as one of several functions. Q3

The cases in our study are selected based on the fact that they should represent a diversity of multipurpose reservoirs, be located in water-stressed areas, have a different mix of functions and be geographically distributed. We have included two Spanish cases as they are in different stages, i.e. one in the planning phase and one in operation, representing different situations with respect to availability of data. We would underline that the main purpose of the study is to demonstrate the performance of the various allocation models, and not to produce exact numbers on the water consumption rates and shares.

It should be noted that the water consumption values given in Table 2 are provided on the following basis; (1) the water consumption values are calculated by the 'gross evaporation approach' (Bakken *et al.*, 2013b), (2) all the losses are assigned to power production, and (3) only losses in the operational phase are included. All numbers in the Tables 2–6 are given as typical numbers or long-term annual averages to the extent that such numbers have been available. If data for a specific procedure of allocating losses is not available or the allocation method is not considered feasible for other reasons, this is indicated by N.A. in the table.

3.1. Sri Ram Sagar Project, India

The Sri Ram Sagar Project (SRSP) is a multipurpose project, located across the Godavari River near Pochampad of Nizamabad District in Andhra Pradesh, India. The catchment area at the dam site is

Table 2. Characteristics of the cases used in this study[1]. Further description is provided in Sections 3.1–3.4.

Data	SRSP, India	Aswan High Dam Project, Egypt	Mularroya Dam, Spain	Porma Dam and Reservoir, Spain
Evaporation rate [mm]	1,696	2,850	1,100	858
Surface area [km^2]	453	3,330	4.63	12.5
Total annual evaporation [mill. m^3]	768.3	9,500	5.09	10.7
Installed capacity [MW]	36	2,580	23.5	23.2
Annual power production [GWh]	236.5	9,700	25.9	48.8
Water consumption rate [m^3/MWh]	3,248	979	196.6	255.9

[1]The numbers for SRSP are from Bakken *et al.* (2013a) and Sauterleute *et al.* (2012), for Aswan High Dam they are derived from data provided by Abu-Zeid & El-Shibini (1997), Food and Agriculture Organization of the UN (FAO) (2015) and Demeke *et al.* (2013), while the sources of information on Mularroya dam are Peláez (2007) and the Viability Plan Mularroya Dam (2007). The numbers for the Porma Dam and reservoir are based on numbers provided by Peláez (2007) and CHD (Duero River Management Confederation) (2012a).

Table 3. Data for the various purposes/functions and allocation models of the SRSP.

Functions in the multipurpose reservoir	2A: Volume allocation [mill. m^3/year]	2A: Energy allocation [GWh/year]	2B: Economic allocation [mill. US $ /year]	2B: Explicit prioritizing
Power generation	3,398.4	236.5	18.9	3
Water supply	241.2	16.8	1.34	1
Irrigation	5,029.2	350.0	28.0	2

Table 4. Data for the various purposes/functions and allocation models of the Aswan High Dam.

Functions in the multipurpose reservoir	2A: Volume allocation [bill. m^3/year]	2A: Energy allocation [GWh/year]	2B: Economic allocation [mill. EGP/year]	2B: Explicit prioritizing
Power generation	50	9,700	100	N.A.
Irrigation	46	8,924	140	N.A.
Flood control	47	9,118	10	N.A.
(Domestic) water supply and industries	5	970	N.A.	1
Navigation	1	194	5	N.A.

Table 5. Data for the various purposes/function and allocation models of the planned Mularroya Dam.

Functions in the multipurpose reservoir	2A: Volume allocation [hm^3/year]	2A: Energy allocation [GWh/year]	2B: Economic allocation [Euro/year]	2B: Explicit prioritizing
Power generation	1.29	25.9	138,000	3
Water supply	1.55	31.1	83,000	1
Irrigation	59.38	1,200	3,168,000	2
Industrial uses (excl. hydropower)	0.20	4.0	54,000	3
Flood control	20.66	414.6	7,000	(Restriction)

Table 6. Data for the various purposes/function and allocation models of the Porma Dam.

Functions in the multipurpose reservoir	2A: Volume allocation [hm^3/year]	2A: Energy allocation [GWh/year]	2B: Economic allocation [mill. Euro/year]	2B: Explicit prioritizing
Power generation	98.2	48.8	1.8	3
Water supply	13.4	6.7	20.1	1
Irrigation	297	9.9	2.2	2
Ecological flow	47	23.4	8.2	(Restriction)
Flood control	19.5	9.7	0.35	(Restriction)

91,751 km^2, and the average inflow to the reservoir is at 283.4 m^3/s, given an annual volume of 8,937 mill. m^3/year (Sauterleute *et al.*, 2012).

According to the state policy of India (Government of India – Ministry of Water Resources, undated), drinking water is the top priority, followed by irrigation, hydropower, industrial and other uses. In the case of SRSP, drinking water supply, irrigation and power production are the uses, and the water is withdrawn directly from the reservoir. The water used for hydropower production is released directly into one of the irrigation canals (Kakatiya canal), hence this volume of water is 'double counted' in our study. This is not considered problematic as it is the share per function that is relevant for the water consumption calculations.

The data provided on 'volume allocation' are water requirements (demand fulfilment) (Sauterleute *et al.*, 2012), which match fairly well the available water volume in a typical hydrological year, taking into account evaporation from the surface and periods of spill. As the inflow can vary considerably from a wet to a dry year, the actual allocation for a particular year might deviate from the numbers given in Table 3. According to the rules of allocation, the volumes of water for domestic supply will persist, while irrigation, and possibly hydropower depending on to which canal the water will be released, will be reduced.

As the energy allocation is directly derived from the volume allocation and does not take into account the variation in head, the share will stay identical to changes in the volume allocation. Similarly, since the calculated economic allocation is based on the 'loss of energy production' where a constant electricity price is assumed, the share will follow the change in water volumes. The average electricity price for India (2011) is taken from the website 'Shrink that footprint' (http://shrinkthatfootprint.com/average-electricity-prices-kwh). The more time-consuming method of obtaining data on economic benefits based on data from the individual sectors will provide a different picture as this will not be directly linked with the changes in withdrawal from the reservoir taking into account other factors that also might influence the outcome.

3.2. Aswan High Dam, Egypt

The Aswan High Dam is an embankment dam situated across the Nile River in Aswan, Egypt, by the border of Sudan, built just upstream of the Old Aswan Dam. The large upstream reservoir has the capacity to store 162 km^3 and is the major reservoir providing regulated flow to both power plants as the smaller reservoir between the dams can only hold 1 km^3 of water (ICOLD, 2014). The annual power production of Aswan High Dam and Old Aswan Dam is 7.0 TWh and 2.7 TWh, respectively, and, in the context of water consumption, these two plants are assessed as one production unit. High Aswan Dam is a multipurpose project and the main reason for construction was to develop irrigation systems for increasing rice and sugar-cane cultivation. The construction of the dam enabled perennial irrigation, whereby water is available at any time throughout the year (Abu-Zeid & El-Shibini, 1997). Other objectives enabled by flow regulation of the Nile River are flood protection, hydroelectricity generation and improved navigation (Abu-Zeid & El-Shibini, 1997). The plants further downstream on the Nile (Assiut Barrage, Esna Barrage, Nag-Hamady Barrage and New Esna Barrage) might also benefit from the regulation provided by the Aswan High Dam, but except for Esna Barrage (600 GWh/year) (ICOLD, 2014), the production is unknown.

The volume of water used for power production comes from Oven-Thompson *et al.* (1982), the volume set aside for flood protection is from ICOLD (2014), while the values for irrigation, domestic water supply and navigation are from Oosterbaan (1999). The water used for power production is returned to the river basin and released for other purposes downstream, and hence 'double-counted' in our study. Similar to the study in India, this is not considered problematic as it is the share per function that is relevant for the water consumption calculations. The numbers on power production are from Abu-Zeid & El-Shibini (1997), while the other numbers used in the energy allocation are derived from this and the ratios calculated for volume allocation.

All the data for the economic allocation are from Biswas & Tortajada (2004). This source does not **Q4**
include economic benefits for industries and municipalities, which are hard to obtain. We have not been able to obtain information on priority of water use, but it is likely that domestic water supply has the highest priority as in the other cases investigated.

The numbers on allocation of water volumes and economic benefits vary a lot between the different sources visited, which might be due to high uncertainty in the calculations, different approaches for calculation and the fact that there might be great differences from year to year due to climatic and hydrological conditions. As an example, Strzepek *et al*. (2008) estimate the value of the Aswan High Dam to the Egyptian economy to be in the range of 2.7 to 4.0% of gross domestic product (GDP). The sum of the estimates of economic values for each function given by Biswas & Tortajada (2004) in Table 4 is 255 mill. EGP/year, which corresponds to approximately 0.05% of GDP.

3.3. Mularroya Dam, Spain

Mularroya Dam is presently under planning as part of the Bajo Jalón regulation system in the region of Zaragoza in the north-eastern part of Spain. The entire system regulates a 7,088 km^2 watershed with an average yearly inflow of 315.6 hm^3, which corresponds to an average discharge of 10.0 m^3/s (Viability Plan Mularroya Dam, 2007). The system is composed of the Mularroya Reservoir in the Grío River, which will receive water by a diversion channel via a dam in the Jalón River, one of the principal tributaries of the Ebro.

The water volume transferred from the Jalón River to the Mularroya Reservoir is annually around 58.8 hm^3, and the annual inflow from Grío to Mularroya is 20.4 hm^3 (natural inflow) giving a total inflow to Mularroya Reservoir equal to 79.2 hm^3. A total of 26,340 hectares of land are irrigated based on water from the reservoir.

The Plan of Viability (Viability Plan Mularroya Dam, 2007) describes the economic benefits obtained from the different water services offered by Mularroya multipurpose reservoir, and the priority is given by the Ebro Basin Hydrologic Management Plan (CHE (Ebro River Management Confederation), 2011) **Q5**
(Table 5).

The water supply of the population includes the water needs of those industries located in urban areas and with limited water requirements. The environmental flows and flood control are not considered as water uses, but as restrictions that must be fulfilled as soon as the needs for drinking water are met.

All the numbers on volume allocation are from Fernández González (2011). The volume for flood **Q6**
control is set as a certain percentage (20%) of the total storage capacity (Viability Plan Mularroya Dam, 2007). The estimated power generation is from Fernández González (2011), while the 'lost' energy production due to releases for other purposes is calculated using the same ratio as for power generation. The allocated volume for flood control is considered lost for power production. This is a conservative assumption, which will imply that a conservatively high energy allocation is assigned to the purpose of flood control. It is not known if any of the purposes use the same water volumes, e.g. that the hydropower generation and irrigation canals are linked. The numbers on economic allocation are for power generation from the Viability Plan (Viability Plan Mularroya Dam, 2007), while the others are from Fernández González (2011).

3.4. Porma Dam, Spain

Porma Dam is located in the north-western part of Spain within the Duero River Basin. Porma Dam is part of the water regulation system known as Elsa-Valderey, where Porma Dam is located between Puebla de Lillo and Boñar (León). The Elsa Valderey system is composed of four reservoirs: Riaño, Porma, Casares and Ricobayo, where Riaño and Porma are the most important reservoirs in the regulation of the system. The yearly average inflow is 311.6 hm^3 which corresponds to an average discharge of 9.9 m^3/s.

The Porma Reservoir serves a vital mission in the regulation of the rivers in León and has reduced the risk of floods to the downstream areas that historically have suffered from severe flood events. The reservoir provides water to irrigate about 35,990 hectares and the reservoir is used for energy production, water supply and recreational activities, such as water sports (CHD (Duero River Management Confederation), 2012a) (Table 6). Q7

The water volume allocated for power production is obtained from Pérez *et al*. (2008), verified against data received from Duero Basin authorities (CHD, Technical Directorate of Public Participation and Citizen Information Service), and the water volume is estimated assuming full power production for 19 weeks. The water volumes for water supply and ecological flows are taken from the Duero Basin Hydrologic Management Plan (CHD (Duero River Management Confederation), 2012a), numbers on irrigation water have been received from Juan Ignacio Pérez (Pérez, 2013), and the volumes for Q8 flood control are based on De la Torre *et al.* (undated). It should be noted that the numbers on water Q9 supply include the industrial uses in urban areas. Data on the energy generation from the hydropower plants is from Pérez *et al*. (2008), and the numbers on energy allocation for the other functions are calculated based on the same water volume-energy ratio as the power production, except for irrigation where the energy allocation is calculated as the loss of energy due to the dependence of irrigation. It is assumed that the water and energy allocation for the different purposes are independent of each other. The numbers on economic allocation are for power generation from Hydrographic Demarcation of Duero River (DHD (Duero Hydrographic Demarcation), 2005), and water supply and irrigation from Q10 CHD (Duero River Management Confederation) (2012b). Numbers on the economic benefits from Q11 release of ecological flow, which also include the benefits of recharging aquifers, are from Fernández González (2011). The data on economic benefits (reduced risk) of the flood control project in the Benavente region (the confluence of five major rivers, one of them Porma River) is set based on the cost of the project. These data are provided by the Ministry of Environment (EL MUNDO, 2010), and are estimated at 2.3 million Euros. According to the Significant Risk Areas of Potential Flood (MAGRAMA, undated), 93 historic floods have been documented in Benavente, 14 of which were in Porma, therefore a recalculation of the amount of investment required by the Ministry due to Porma flooding has been carried out. The prioritizing is given by Duero Basin Hydrologic Management Plan (CHD (Duero River Management Confederation), 2012c). Q12

It should be mentioned that the volume of water allocated to hydropower depends on the amount of water designated to irrigation, i.e. the regulation in irrigation will affect the energy production. After the summer, the reservoir normally holds a minimum volume of water due to the supply of irrigation water and low inflow during the preceding months. If the reservoir volume falls below 50 hm^3 or 30 hm^3 the irrigation flow will be reduced by 20% to 50%, respectively. This illustrates the complexity of finding the 'correct' volumes of water for the various functions.

4. Results and discussion

The data for each case have been systemized in order to find each function's share of the water consumption for each burden-distributing model used (Figure 1). In Table 7 the numbers for the hydropower function are shown alone, as absolute numbers.

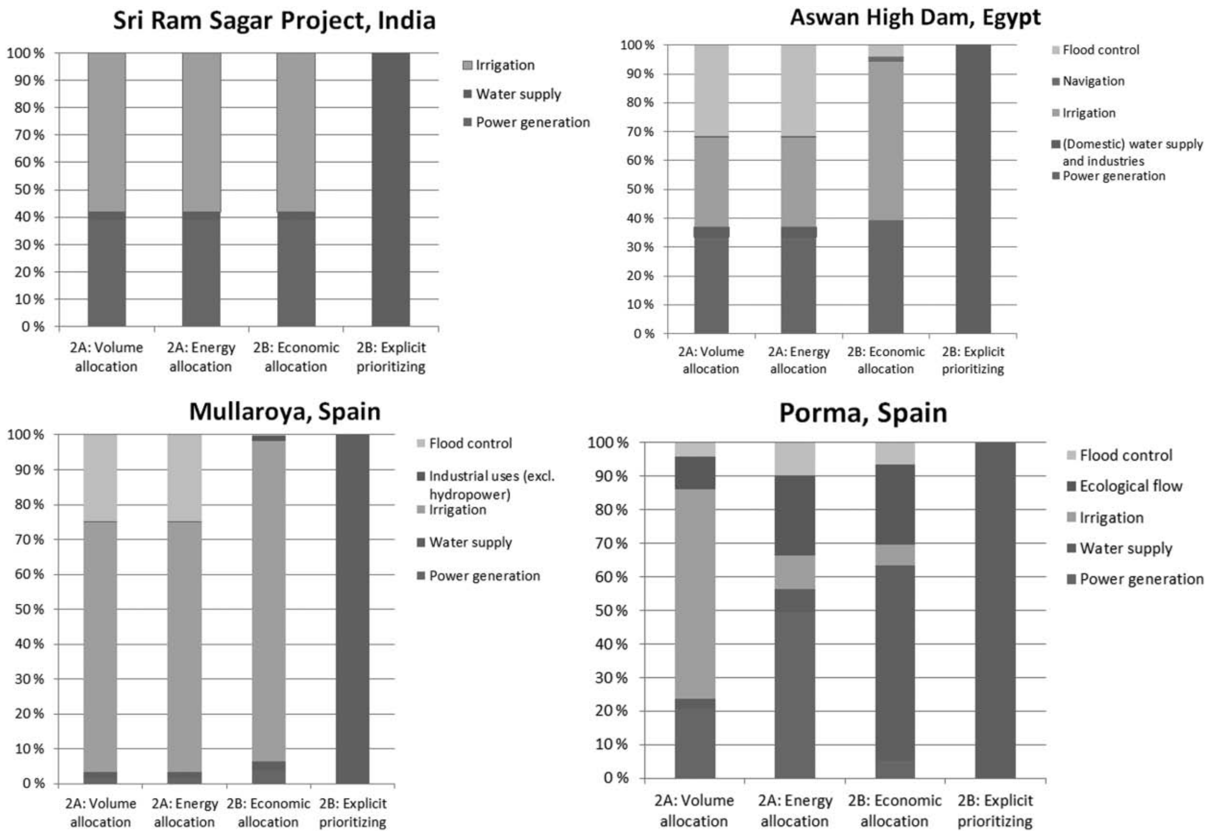

Fig. 1. The panel of figures presents the allocated share [%] of the gross water consumption rates for the different functions in the four case studies of multipurpose reservoirs, based on the various burden-distributing models.

Table 7. Water consumption rates for hydropower [m^3/MWh] for the demonstration cases applying the various allocation models. It should be noted that the 'gross evaporation values' are used as the basis for calculating the total water losses.

Case	2A: Volume allocation	2A: Energy allocation	2B: Economic allocation	2B: Explicit prioritizing
SRSP, India	1,273	1,273	1,273	0
Aswan High Dam, Egypt	329	329	384	0
Mularroya Dam, Spain	3	3	8	0
Porma Dam, Spain	45	109	11	0

Figure 1 and Table 7 show that for the volume allocation model, power generation gets from 2 to 39% of the water consumption. For energy allocation, the lower number is 2% while the upper is close to 50% of the total gross water consumption. Using economic allocation, power generation is allocated 4 to 39% of the gross water consumption. As water supply has in all cases the highest priority, explicit prioritizing leads to zero water losses allocated to power production in all cases. For three of the four cases, the differences between allocation based on volume and energy are small. For the Porma case, however, all these three allocation models (volume, energy and economy) give quite diverging results. For power production, the resulting gross water consumption varies by a factor of almost ten, from 11 to 109 m^3/MWh. The explanation is that the diversity of literature sources calculating the water volumes consumed, economic benefits, etc. is the highest for this case, which gives very inconsistent outcomes. For all cases, explicit prioritizing is the burden-distribution model that stands out from the others, which is due to the simplistic approach we have selected for it of allocating all the loss to only one function.

The volume allocation model appears more feasible as data on water volumes for irrigation, power production, etc. are very basic in planning and management of reservoirs. The difficulties encountered during application of this model are related to setting appropriate system boundaries. Water use is not always consumptive as water could be returned to the downstream river. In the case of hydropower, all the water that is diverted into the inlet structure of the plants is released downstream. The water used for domestic supply will also often ultimately return to the basin, but often with reduced quality. The water volumes for flood control are not withdrawn nor used, but treated as the other functions as it could be argued that this volume could not be used for other purposes. Environmental flows and navigation simply releases water to the downstream areas, and the use of the reservoir water can hence be considered very similar to hydropower production.

Our approach of calculating the energy allocation was by using the numbers on volume allocation and the ratio between volume and energy generation for hydropower and imposing the same ratio of the other functions. This is an approach that is easy to use as long as numbers on volumes of water and hydropower production are available, and assuming that the relation between volume and energy production/loss is constant, i.e. not taking into account variations in head (variation in water level).

The economic allocation can be based on the energy calculation (‘loss of energy’) and the ratio of power generation and economic benefit, which was done in the SRSP case. This approach holds the same assumptions and limitations as the energy calculations, but ignores the effect of potential variation in power price over time. In the three other cases, the numbers on economic value are calculated by the referred sources, with limited information on how these numbers are established. The direct economic value often underestimates the real value of the resource, and the social value of water can be very high (e.g. Kadigi *et al.*, 2008), especially in countries with an agricultural sector providing food to the under-privileged. We would underline that great caution should be made when introducing numbers calculated by different studies/sources, such as in the Mularroya case, where we can see from Table 5 that there are very large differences in the estimates of the economic value of irrigation and industrial uses/flood control, as the numbers can be established based on very different assumptions and methodological approaches. This problem is also illustrated by compiling numbers from different sources on the Aswan High Dam case. The study by Pasqualetti & Kelley (2008) on Glen Canyon Dam multipurpose reservoir used economic value (2B) to allocate the burden of the water consumption, assigning 55% of the burden to hydropower production. Due to the site-specific nature of multipurpose reservoirs, the transferability of the numbers by Pasqualetti & Kelley (2008) is considered limited. Zhao & Liu (2015) also used economic allocation in their study assessing the water footprint of hydropower production in the Yangtze River. Applying economic allocation might also have the undesired effect that those functions that generate the highest economic income per m^3 (most cost-efficient) are ‘punished’ by taking a higher burden of the water consumption than those functions generating the least income per m^3.

The volume allocation model will also often form the basis for calculation of energy allocation (as in our study), and will in some cases also be the starting point (or a proxy) for the use of the economic allocation model (2B). Referring to the assessment criteria in Section 2, the volume allocation is considered to be more scientifically robust, is more transparent and easier to reproduce, as well as being more easily applicable with a better level of documentation (data are more easily accessible and more precise) than energy and economic allocation. It could be questioned if volume allocation has a higher stakeholder acceptance, as some stakeholders might argue that activities (functions) with a high economic profit should take a larger burden of the resources consumption due to their financial strength.

Explicit prioritizing is not given as an allocation procedure in ISO 14044 (ISO, 2006), but was tested in this study due to its relevance for multipurpose reservoirs. The results presented in Figure 1 show that 'explicit prioritizing' with a 100% burden on the top priority appears as an over-simplistic model as the top priority takes all the burden from all the other functions, even when the volumes of water for this purpose can be very limited. As domestic water supply has the highest priority in all our cases, this sector will then take a very large burden of the water consumption. The method is very simple and quick to apply as long as the priorities are clearly given by water management authorities. We believe, however, that the scientific robustness and the stakeholder acceptance of the method could be questioned, as the sector given the highest priority might feel that their burden for the resource consumption ends up being too high. The decision on setting the priorities is exclusively political, not based on any physical or economic analysis of the system.

The assessors' prior knowledge of a system will affect the resources needed to find reliable data/information about the case. For the cases presented in this article, one of the authors had prior knowledge about the SRSP and had carried out a site visit. For the Spanish cases most of the documentation was only available in Spanish.

Setting proper system boundaries is a well-known challenge in LCA-studies (Modahl *et al.*, 2013), is also discussed in the context of calculating water consumption (Bakken *et al.*, 2013b) and is a problem we encountered in this study too. Setting proper spatial boundaries for the volume calculation is very important. Key questions to be raised when drawing the boundaries on volume allocation are from where is the water withdrawn? Is the withdrawn water returned into the river basin and hence available for downstream users? Does the water evaporate and return as precipitation elsewhere in the river basin? In the case of Aswan High Dam, this reservoir regulates the flow and secures reliable access to water to the downstream areas all the way to the Mediterranean Sea all-year around. Just a portion of the water is withdrawn directly from the reservoir, but provides regulated flow several kilometres downstream of the dam. Proper spatial system boundaries might hence include the reservoir and all downstream areas benefitting from it. Adding further complexity to this, water might have reduced quality when returned, described as the 'grey water footprint' according to the water footprint terminology (Hoekstra *et al.*, 2011).

A similar methodological challenge to assessing the right volumes appears in the next step when allocating the losses based on energy (loss of energy) and economic value. As the lost energy generation is calculated directly from volumes of water, the spatial boundaries would be directly adopted from the calculation of volumes. In the case of economic value these will be calculated directly on lost energy generation and the spatial boundaries will also follow the boundaries of the flow of water. If the economic value is calculated with use of more comprehensive macroeconomic models, similar decisions must be made with respect to which benefits should be included.

Many parts of the world experience large seasonal variations in hydrology, having a distinct wet season contrasted by a longer dry season with limited access to water, where the construction of reservoirs is a common way of securing adequate supply all-year around. This would mean that high water consumption in periods with abundant water resources would be unproblematic, while the water resources must be managed with greater care in periods of water stress, unless storage overcomes the seasonal differences. It could then be argued that consumption of water in periods with abundant sources should be 'fined' less than use of water in periods with deficit, i.e. weighting the water consumption by availability of water over time.

5. Conclusions and recommendations

The examination of the four cases of multipurpose reservoirs with hydropower was used to examine the appropriateness of different burden-distribution models in the context of water consumption. Based on our study we recommend the following:

- We consider volume allocation to be the most robust approach for allocating water consumption between competing functions in multipurpose reservoirs.
- We recommend that data should preferably be gathered from one source for all functions, to ensure a consistent calculation approach.
- The system boundaries of the analysis should be defined with great care, but typically be set equal to the hydraulic system boundaries.
- We propose that a site visit should be undertaken if an allocation study is carried out, as this will reduce the uncertainties and inconsistencies in the calculations, quality assure assumptions and possibly remove errors in the data.

We also tested other allocation methods described in ISO 14044 (ISO, 2006), and our findings were:

- Systems expansion/avoided burdens: these allocation approaches are both considered inappropriate for our need, as multipurpose reservoirs share one common pool of water and separate production lines cannot be identified (1A), nor can a single function easily be added or removed (1B).
- Energy allocation: in all the examined cases this approach is based on the results of the volume allocation, while introducing simple assumptions on the relation between volume allocation and loss of energy production. This approach will hence experience the same methodological challenges as volume allocation, but will introduce additional uncertainties.
- Economic allocation: this approach can be based on results from volume and energy allocation, thus inheriting all the methodological challenges from these approaches as well as incurring new uncertainties. Alternatively, macroeconomic analysis can be applied with a different set of uncertainties. These two approaches can possibly produce very different results.
- Explicit prioritizing: This is a very simplistic approach that is easy to apply, but does not capture the multipurpose aspects of reservoirs if the top priority is assigned 100% of the burden.

In this paper, the allocation challenges have been highlighted by using water consumption as an indicator. There is, however, no difference between allocating water consumption and other substances (resources or outputs) from a multipurpose process in LCA. The conclusions and recommendations in this paper should, therefore, just as well be seen as recommendations for allocation of energy investments, green-house gas emissions, other resources, waste and emissions to air and water, for building and use of a multipurpose reservoir.

Acknowledgements

The study has received financial support via EcoManage, funded by the Research Council of Norway (contract no: 215934/E20). EcoManage is organized under the research centre CEDREN (Centre for Environmental Design of Renewable Energy – www.cedren.no). We would also like to thank Juan Ignacio Pérez, Department of Hydraulic and Energy Engineering at the Technical University of Madrid (UPM) for providing useful information about the Spanish cases.

References

Abu-Zeid, M. A. & El-Shibini, F. Z. (1997). Egypt's Aswan high dam. *Water Resources Development 13*(2), 209–217.

Bakken, T. H., Skarbøvik, E., Gosain, A. K., Palanisami, K., Sauterleute, J., Egeland, H., Kakumanu, K. R., Nagothu, U. S., Harby, A., Tirupataiah, K. & Stålnacke, P. (2013a). Water allocation with use of the building block methodology (BBM) in the Godavari Basin, India. *Journal of Sustainable Development 6*(8), 93–107.

Bakken, T. H., Killingtveit, Å., Engeland, K., Alfredsen, K. & Harby, A. (2013b). Water consumption from hydropower plants – review of published estimates and an assessment of the concept. *Hydrology and Earth System Sciences 17*, 3983–4000. doi:10.5194/hess-17-3983-2013.

Biswas, A. K. & Tortajada, C. (2004). *Hydropolitics and Impacts of the Aswan High Dam*. Submitted to: Advisory Panel Project on Water Management, Ministry of Water Resources and Irrigation, Cairo, Egypt.

CHD (Duero River Management Confederation) (2012a). Duero Basin Hydrologic Management Plan. Appendix 1, Modified water bodies. Confederación Hidrográfica del Duero. Ministerio de Medio Ambiente y Medio Rural y Marino. Gobierno de España.

CHD (Duero River Management Confederation) (2012b). Duero Basin Hydrologic Management Plan. Appendix 9, Cost Recovery. Confederación Hidrográfica del Duero. Ministerio de Medio Ambiente y Medio Rural y Marino. Gobierno de España.

CHD (Duero River Management Confederation) (2012c). Duero Basin Hydrologic Management Plan. Technical report. Confederación Hidrográfica del Duero. Ministerio de Medio Ambiente y Medio Rural y Marino. Gobierno de España.

CHD Technical Directorate of Public Participation, Citizen Information Service (2014). Average daily flow total output, instant data output rate and the average flow turbinated data for hydrological year 2012-2013. Received 7 January 2014. **Q13**

CHE (Ebro River Management Confederation) (2011). Ebro Basin Hydrologic Management Plan. Technical report. Confederación Hidrográfica del Ebro. Ministerio de Medio Ambiente y Medio Rural y Marino. Gobierno de España.

Chenoweth, J., Hadjikakou, M. & Zoumides, C. (2014). Quantifying the human impact on water resources: a critical review of the water footprint concept. *Hydrology and Earth System Sciences 18*, 2325–2342. doi:10.5194/hess-18-2325-2014.

Cooley, H., Fulton, J. & Gleick, P. H. (2011). *Water for Energy: Future Water Needs for Electricity in the Intermountain West*. Pacific Institute, Oakland, CA, USA. ISBN: 1-893790-36-3, ISBN 13: 978-1-893790-36-0.

De la Torre, A. J. R., Castro, L. A., Lasso, J. R. P. & de Grad, J. P. (undated). Comité Nacional Español De Grandes Presas. Gestión De Avenidas Y Normas Para Elaccionamiento De Compuertas En La Presa De Juan Benet (Spanish National Committee of Large Dams. Flood Management and Gating Rules at Juan Benet Dam).

Demeke, T. A., Marence, M. & Mynett, A. E. (2013). Evaporation from reservoirs and the hydropower water footprint. In: *Proc Africa 2013*, 16–18 April 2013, Addis Ababa, Ethiopia.

DHD (Duero Hydrographic Demarcation) (2005). Summarize report Articles 5 and 6 of Water Frame Directive. Chapter 5: Economical Analysis. Ministerio de Medio Ambiente. Gobierno de España.

EL MUNDO (2010). The Ministry of Environment will invest 2.3 Million of Euros to reduce the flood risk in Benavente and Los Valles. http://www.elmundo.es/elmundo/2010/05/20/castillayleon/1274375566.html. (accessed 9 January 2016).

European Commission (2010). ILCD Handbook. International Reference Life Cycle Data System. General Guide for Life Cycle Assessment – Detailed Guidance.

FAO (2015). Food and Agriculture Organization of the UN. AquaMaps. http://www.fao.org/nr/water/aquamaps (accessed 9 January 2016).

Fernández González, M. (2011). Análisis socioeconómico de viabilidad del proyecto de presa de Mularroya, azud de derivación y conducción de trasvase (Socioeconomic Feasibility Analysis of Mularroya Dam, Diversion Dam and Conducting Transfer Project). Masters in Hydrology and Management of Water Resources. Postgraduate Studies at the University of Alcalá and Rey Juan Carlos (coordinated by University of Alcalá).

Fulton, J. & Cooley, H. (2015). The water footprint of California's energy system, 1990-2012. *Environmental Science and Technology 49*(6), 3314–3321. doi:10.1021/es505034x.

Government of India – Ministry of Water Resources (undated). State Water Policies and the National Water Policy for water management practices. http://wrmin.nic.in/writereaddata/linkimages/anu29668628373.pdf. (accessed 9 January 2016).

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M. & Mekonnen, M. M. (2011). *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan, London, UK.

ICOLD (2014). World Register of Dams. Data accessed 18 June, 2014. This is a database with restricted access.

IHA (2011). World Congress Bulletin: Summary of the International Hydropower Association Paper presented at the World Congress on advancing sustainable hydropower, New York. http://www.iisd.ca/ymb/hydro/iha2011/html/ymbvol139-num7e.html. (accessed 9 January 2016).

IPCC (2011). Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S. & von Stechow, C. E. IPCC Special Report on Renewable Energy Sources and Climate Change **Q14**
Mitigation. Cambridge University Press, Cambridge, UK and New York, NY, USA.

ISO 14044 (2006). Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006). Standard Norge, Lysaker.

ISO 14046 (2014). ISO International Organization for Standardization. Environmental management – Water footprint – Principles, requirements and guidelines. Draft version August 2014.

Kadigi, R. M. J., Mdoe, N. S. Y., Ashimogo, G. C. & Morardet, S. (2008). Water for irrigation or hydropower generation? Complex questions regarding water allocation in Tanzania. *Agricultural Water Management 95*, 984–992.

MAGRAMA (undated). Cartographic Viewer Floodplain, (SNCZI-Inventario de Presas y Embalses). http://sig.magrama.es/snczi/visor.html?herramienta=DPHZI. (accessed 9 January 2016).

Mekonnen, M. M. & Hoekstra, A. Y. (2012). The blue water footprint of electricity from hydropower. *Hydrology and Earth System Sciences 16*, 179–187. doi:10.5194/hess-16-179-2012.

Meldrum, J., Nettles-Anderson, S., Heath, G. & Macknick, J. (2013). Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters 8*, 015031. (18pp) doi:10.1088/1748-9326/8/1/015031.

Modahl, I. S., Raadal, H. L., Gagnon, L. & Bakken, T. H. (2013). How system boundaries affect the energy indicator results for different electricity generation technologies. *Energy Policy 63*, 283–299. dx.doi.org/10.1016/j.enpol.2013.09.005.

Oosterbaan, R. J. (1999). Hydrological and Environmental Impacts of the Irrigation Improvement Projects in Egypt. ILRI, Wageningen, 51 pp. Report of an Egyptian-Dutch Drainage Panel consultancy assignment. On line: http://www.waterlog.info/pdf/irrimpr.pdf. (accessed 9 January 2016).

Oven-Thompson, K., Alercon, L. & Marks, D. H. (1982). Agricultural vs. hydropower tradeoffs in the operation of the high Aswan dam. *Water Resources Research 18*(6), 1605–1613.

Pasqualetti, M. J. & Kelley, S. (2008). *The Water Costs of Electricity in Arizona*. Arizona Department of Water Resources, Phoenix, AZ.

Peláez, J. R. T. (2007) Consideraciones prácticas sobre la evaporación en los embalses de la España peninsular. Practical considerations about evaporation in Spanish reservoirs. Centro de Estudios Hidrográficos del CEDEX. Col. 1.947.

Pérez, J. I. (2013). Personal Communication. Irrigation data used in 2000 for the calculation of the dam head in Porma Reservoir. UPM Madrid.

Pérez, J. I., José, R., Wilhelmi, J. R. & Maroto, L. (2008). Adjustable speed operation of a hydropower plant associated to an irrigation reservoir. *Energy Conversion and Management 49*, 2973–2978.

Pfister, S., Saner, D. & Koehler, A. (2011). The environmental relevance of freshwater consumption in global power production. *International Journal of Life Cycle Assessment 16*, 580–591. doi:10.1007/s11367-011-0284-8.

Sauterleute, J., Skarbøvik, E., Bakken, T. H., Egeland, H., Harby, A., Stålnacke, P., Nagothu, U. S., Palanisami, K., Krishna Reddy, K. & Gosain, K. (2012). *Application of the Building Block Methodology to the Sri Ram Sagar Project*, SINTEF Report No. TR A7181, Trondheim, Norway, p. 44.

Setterwall, C. (2007). Electricity, steam and hot/cold water generation and distribution. PCR CPC code 171 and 173. http://epdsystem.it/en/PCR/Detail/?Pcr=5802#.Uv4Zsv58O70. (accessed 9 January 2016).

Şorman, A. Ü. (2013). Presentation at Workshop on allocation and water transaction; Ankara, 15-17 April 2013 organized by the State Hydraulic Works (DSI) in Turkish.

Strzepek, K. M., Yohe, G. W., Tol, R. S. J. & Rosegrant, M. (2008). The value of the Aswan high dam to the Egyptian economy. *Ecological Economics 66*(1), 117–126.

Viability Plan Mularroya Dam (2007). Informe De Viabilidad Proyecto De Presa De Mularroya, Azud De Derivación Y Conducción De Trasvase. (Zg/La Almunia De Doña Godina Y Otros).

WCD World Commission on Dams (2000). *Dams and Development: A New Framework for Decision-Making*. Earthscan Publications Ltd, London.

Zhao, D. & Liu, J. (2015). A new approach to assessing the water footprint of hydroelectric power based on allocation of water footprints among reservoir ecosystem services. *Physics and Chemistry of the Earth 79–82*, 40–46. doi:10.1016/j.pce.2015.03.005.

Received 9 January 2016; accepted in revised form 13 January 2016. Available online 19 February 2016

Author Queries

Journal: Water Policy

Manuscript: WPOL-D-16-00009

Q1 Pasqualetti and Kelly (2008) has been changed to Pasqualetti and Kelley (2008) as per the reference list.

Q2 A. Ü. Şorman, personal communication (2013) has been changed to Şorman (2013) as per the reference list.

Q3 World Commission on Dams [WCD] (2000) has been changed to WCD World Commission on Dams (2000) as per the reference list.

Q4 Biswas and Totajada (2004) has been changed to Biswas and Tortajada (2004) as per the reference list.

Q5 CHE (2011) has been changed to CHE (Ebro River Management Confederation) (2011) as per the reference list.

Q6 Fernandez González (2011) has been changed to Fernández González (2011) as per the reference list.

Q7 CHD (2012a) has been changed to CHD (Duero River Management Confederation) (2012a) as per the reference list.

Q8 Pérez, J.I., personal communication (2013) has been changed to Pérez (2013) as per the reference list.

Q9 de la Torre (undated) has been changed to De la Torre *et al.* (undated) as per the reference list.

Q10 Duero Hydrographic Demarcation [DHD] (2005) has been changed to DHD (Duero Hydrographic Demarcation) (2005) as per the reference list.

Q11 CHD (2012b) has been changed to CHD (Duero River Management Confederation) (2012b) as per the reference list.

Q12 CHD (2012c) has been changed to CHD (Duero River Management Confederation) (2012c) as per the reference list.

Q13 CHD Technical Directorate of Public Participation and Citizen Information Service (2014) is not cited in the main text. Please confirm where it should be cited, or delete the reference.

Q14 Please check this author names for IPCC (2011).