Advances in Water Resources 113 (2018) 285–294

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

# The blue water footprint of the world's artificial reservoirs for hydroelectricity, irrigation, residential and industrial water supply, flood protection, fishing and recreation

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ARTICLE INFO

*Article history:*
Received 28 March 2017
Revised 31 January 2018
Accepted 31 January 2018
Available online 2 February 2018

*Keywords:*
Water footprint
Reservoirs
Water consumption
Economic value of reservoirs
Reservoir purposes
Hydroelectricity

ABSTRACT

For centuries, humans have resorted to building dams to gain control over freshwater available for human consumption. Although dams and their reservoirs have made many important contributions to human development, they receive negative attention as well, because of the large amounts of water they can consume through evaporation. We estimate the blue water footprint of the world's artificial reservoirs and attribute it to the purposes hydroelectricity generation, irrigation water supply, residential and industrial water supply, flood protection, fishing and recreation, based on their economic value. We estimate that economic benefits from 2235 reservoirs included in this study amount to $265 \times 10^9$ US$ a year, with residential and industrial water supply and hydroelectricity generation as major contributors. The water footprint associated with these benefits is the sum of the water footprint of dam construction (<1% contribution) and evaporation from the reservoir's surface area, and globally adds up to $66 \times 10^9$ $m^3$ $y^{-1}$. The largest share of this water footprint (57%) is located in non-water scarce basins and only 1% in year-round scarce basins. The primary purposes of a reservoir change with increasing water scarcity, from mainly hydroelectricity generation in non-scarce basins, to residential and industrial water supply, irrigation water supply and flood control in scarcer areas.



## 1. Introduction

Increasing the limited availability of freshwater to meet ever growing and competing demands is on many policy agendas (WEF, 2017). Drivers for the growing concern include a growing world population, increasing wealth, a transition from fossil-based to renewable energy sources and climate change (UN-WWAP, 2015). For centuries, humans have resorted to building dams to gain control over freshwater available for human consumption. Toward the middle of the 20th century, construction intensified. What started off mainly in the developed world, was soon followed by developing countries in the 1970–80s. When most suitable locations had been developed and most rivers regulated, construction slowed down. Today, new reservoirs are being built mainly for the purpose of hydroelectricity generation (Shiklomanov and Rodda, 2003; Liu et al., 2015; Timpe and Kaplan, 2017).

Dams and their reservoirs have made an important contribution to human development in many ways, such as storing, using and diverting water, for consumption, irrigation, cooling, transportation, construction, mills, power generation, fishing and recreation. Derived benefits have been – and continue to be – considerable (World Commission on Dams, 2000; Gernaat et al., 2017). Associated costs, both in (socio)economic and ecological terms, have been considerable as well (Pacca and Horvath, 2002; Gleick, 2003; Latrubesse et al., 2017). Moreover, since artificial reservoirs have become so prevalent in our modern world, it is increasingly acknowledged that reservoirs are not mere in-stream water users. They can be large water consumers, because of the water that evaporates from their surface. This consumptive term adds to the pressure on (regional) water resources (Shiklomanov, 2000; Hoekstra, 2013; Liu et al., 2015; Vanham, 2016).

A previous influential study to humanity's water footprint (WF), however, excluded the WF of reservoirs altogether (Hoekstra and Mekonnen, 2012). In addition, despite an addendum acknowledging the importance of water consumption by reservoirs through evaporation, AQUASTAT does not list them as water consumers

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https://doi.org/10.1016/j.advwatres.2018.01.028

in national statistics (FAO, 2016). About hydropower, the International Energy Agency does not even mention the term evaporation in their recent World Energy Outlook 2016 (IEA, 2016). By it, they ignore one of the most important balance terms of water for energy.

Studies that try to account for water consumption by reservoirs typically employ one of two methods, the so called net approach and the gross approach (Bakken et al., 2013, 2016). The net approach reduces evaporation from the reservoir surface with evapotranspiration in the 'natural' state before dam development (e.g. Shiklomanov and Rodda, 2003, Grubert, 2016, Scherer and Pfister, 2016 and Strachan et al., 2016). The gross approach, which most studies use, takes total evaporation from the reservoir as measure of reservoir consumption (e.g. Torcellini et al., 2003, Pasqualetti and Kelley, 2008, Mekonnen and Hoekstra, 2012 and Zhao and Liu, 2015). Although scholars debate on which approach to use, we postulate both approaches have their merit. Confusion arises because of misinterpretation of the intention for which one method is chosen over the other: the net approach is suitable for analyzing changes in hydrology on a catchment scale, while the gross approach is preferred for water footprint assessments, where the aim is to show the total volume of water appropriated to certain purposes and that is therefore not available for another purpose (Hoekstra et al., 2011; Hoekstra, 2017). This study intents the latter.

Following the global water footprint standard (Hoekstra et al., 2011), the WF related to reservoirs must include all steps of the supply chain. The total WF should afterwards be attributed to derived products and services, based on their economic value. A reservoir generally serves multiple purposes, the most common of which are hydroelectricity generation, supplying water for residential and industrial use, supplying irrigation water, regulating the flow of rivers to prevent flooding and enabling inland navigation (ICOLD, 2011). Reservoirs are rarely created for recreational and fishing purposes, but after a dam is built, these are important secondary purposes (Ward et al., 1996), and therefore share in the WF of reservoirs.

Previous studies attributed the total reservoir water footprint to purposes either partially or using simpler methods. Instead of using economic value, one purpose takes all, purposes receive an equal share, or some prioritization is set up (Mekonnen and Hoekstra, 2012; Bakken et al., 2016; Grubert, 2016; Scherer and Pfister, 2016).

The aim of this study is to estimate the blue WF of the world's artificial reservoirs, and attribute it to the purposes hydroelectricity generation, residential and industrial water supply, irrigation water supply, flood protection, fishing and recreation, based on their economic value. The blue WF refers to consumption – which includes evaporation – of blue water resources (surface water and groundwater). For each purpose, the WF is expressed in terms of water consumption per unit (that is, $m^3$ $GJ^{-1}$ for hydroelectricity generation, $m^3$ $ha^{-1}$ for irrigation water supply, and so on). This unit WF is translated into water consumption per US dollar (in $m^3$ US$^{-1}$), and its inverse, economic water productivity (in US\$ $m^{-3}$). Productivities of hydroelectricity generation are compared with both productivities found in other studies and those of other types of electricity, thereby feeding discussions on energy scenarios. Although water consumed by reservoirs is no longer available for (downstream) use, the question is how worrisome this consumption is. In water-scarce river basins, the opportunity cost of water consumption may be high and a large WF may worsen scarcity, whereas in more water-rich basins impact may be small. We therefore close with an investigation into the water scarcity levels in all river basins with reservoirs.

## 2. Method and data

The blue water footprint related to an artificial or man-made reservoir ($WF_{res}$ [$m^3$ $y^{-1}$]) includes both an operational and a supply chain part. It thus comprises the WF related to evaporation from the reservoir surface ($WF_{evap}$ [$m^3$ $y^{-1}$]) and the WF related to reservoir construction ($WF_{constr}$ [$m^3$ $y^{-1}$]):

$$WF_{res} = WF_{evap} + WF_{constr} \quad (1)$$

$WF_{evap}$ is determined by means of the gross consumption approach:

$$WF_{evap} = 10EA\kappa \quad (2)$$

where E [mm $y^{-1}$] is the depth of water that evaporates yearly from the reservoir surface, A [ha] the maximum reservoir area and $\kappa$ an area correction factor, set to 0.5625, to correct for the fact that the reservoir surface at average filling conditions is smaller than the maximum area reported in the databases. This factor is derived from a volume-area relation that is based on the assumption that a reservoir is on average half-filled during the year (Kohli and Frenken, 2015) and is trapezoid-shaped. Multiplication by 10 adjusts the units. Since reservoir areas are considered constant in the databases (see Section 2.1) and also $\kappa$ is kept constant, we fail to capture anomalies in surface areas and hence its effect on WFs. We prudently quantified the resulting uncertainty range for two indicators, namely the global total WF and global average WF of hydroelectricity generation. For these two indicators we calculated two extreme scenarios, one in which we set $\kappa$ to 0.2 (indicating all reservoirs evaporate from a surface area that roughly corresponds to the dead storage filling, resulting in the smallest possible $WF_{evap}$), and one in which we set $\kappa$ to 1 (indicating all reservoirs evaporate from their maximum surface area, yielding the largest possible $WF_{evap}$). The resulting range should be interpreted as a preliminary estimate of uncertainty associated with fluctuating reservoir areas.

$WF_{constr}$ depends mainly on the construction material of the dam. Earth and rock fill dams are usually constructed with materials found near the dam site, whereas gravity, buttress and arc dams are mostly made of reinforced concrete (Chen, 2015; Novak et al., 2007). For earth and rock fill dams we accounted only for water consumption related to the energy used to excavate and transport the rock or earth. We took average fuel use from Ahn et al. (2009) and applied to it the WF of diesel (1058 $m^3$ $MJ^{-1}$) from Gerbens-Leenes et al. (2008) under the assumption that the material on average is sourced 20 km from the construction site. For gravity, arc and buttress dams we estimated only the WF of reinforced concrete, using the WF of cement and unalloyed steel from Gerbens-Leenes et al. (2018) and assuming a mixture of 1% steel, 29% cement and 70% aggregates. We used the WF for rock and earth as describe above also for aggregates. Water consumption related to clearing the construction site, equipment and installations either lack reliable data or were assumed negligible. We therefore did not account for these terms. Finally, the annual $WF_{constr}$ is calculated by dividing the water footprint of construction by the assumed typical lifespan of a dam of 100 years.

$WF_{res}$ is assigned to the different reservoir purposes i ($WF_i$ [$m^3$ per unit of production]) through an allocation coefficient $\eta_i$ that is based on the economic value V [US\$] of each purpose i:

$$WF_i = \eta_i WF_{res} \text{ with } \eta_i = V_i / \sum V_i \quad (3)$$

Lastly, we placed $WF_{res}$ in the context of local water scarcity. We used monthly water scarcity levels per river basin, representative of and averaged over the period 1996–2005 as provided by Hoekstra et al. (2012), to examine the scarcity level of the basin in which the reservoir is located. A basin is considered water scarce if the total blue WF of all human activities combined exceeds water

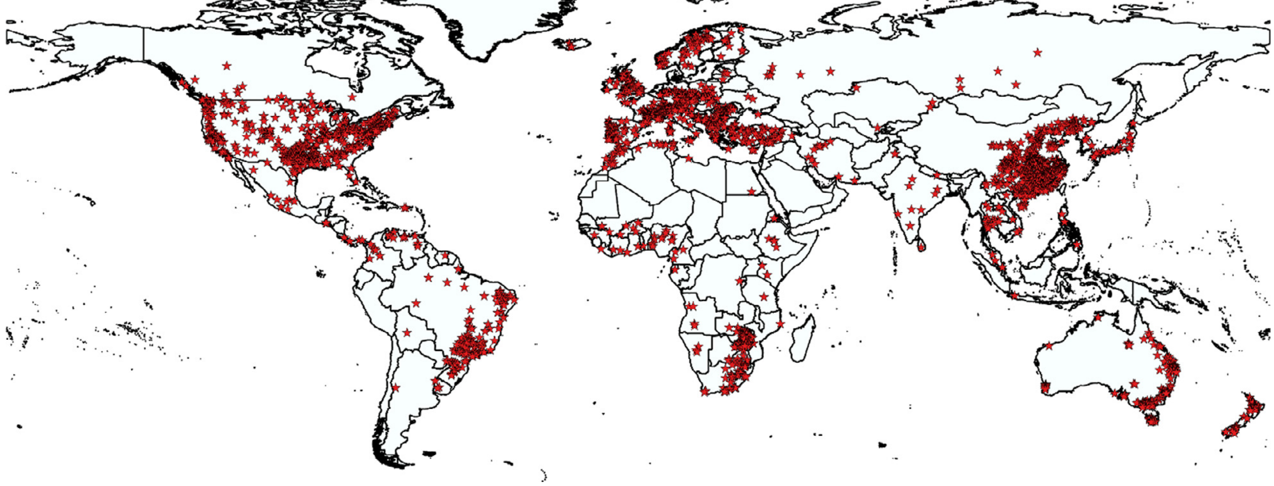

**Fig. 1.** Combining the WRD and GRanD databases yields 2235 reservoirs with full data availability.

availability (runoff minus environmental flow requirements) in any given month. Because the study by Hoekstra et al. (2012) does not cover all basins, this scarcity analysis includes 71% of reservoirs in this study that are located in basins with data available; the remaining 29% were excluded.

### 2.1. Reservoir data

Dam and reservoir data are obtained by combining two databases: the World Register of Dams (WRD) from the International Commission on Large Dams (ICOLD, 2011) and the Global Dams and Reservoirs Database (GRanD) by Lehner et al. (2011). WRD contains over 37,000 reservoirs, including information on reservoir purpose, depth and area, dam height, type and body volume, location (latitude, longitude) and production data for hydroelectricity generation, irrigation water supply and other benefits. GRanD contains information on 6854 reservoirs, including reservoir purpose, average depth and maximum area, dam height and elevation, and comes with a georeferenced vector map of reservoir-shaped polygons. Neither database reports temporal variations, either intra- or inter-annual, in any dam or reservoir variable.

WRD and GRanD are combined, since neither one is complete nor contains all information required. We linked the two databases based on the name and country of each dam. Also, we put in a manual effort to match as many entries as possible based on alternative or slightly different dam or country names. If an element, such as height or area, was present in both databases, GRanD entries were selected because of its perceived higher quality. After excluding reservoirs with a reported natural origin, river and coastal barrages and entries with missing production data, our final database contained 2235 reservoirs with full data availability (Fig. 1). These 2235 reservoirs cover a maximum surface area of 129,000 km$^2$ (~50% of total GRanD database surface area of man-made reservoirs).

### 2.2. Evaporation estimation

Many methods exist to calculate evaporation. To prevent bias toward any one method, we estimated open water evaporation from the 2235 reservoirs as an ensemble mean of four different methods: the ones provided by Kohli and Frenken (2015), Jensen and Haise (1963), Hamon (1961) and a modified version of Penman (Kohler et al., 1955; Harwell, 2012).

The Kohli and Frenken (KF) method is straightforward:

$$E_{\mathrm{KF}} = \sum_{j=1}^{365} k_c ET_0 \tag{4}$$

where $k_c$ is a crop coefficient, set to 1 for open water, and $ET_0$ [mm d$^{-1}$] the daily FAO reference evapotranspiration rate.

The Jensen and Haise (JH) method is an energy budget based method which has proven accurate under limited data availability (Rosenberry et al., 2007; Majidi et al., 2015):

$$E_{\mathrm{JH}} = \sum_{j=1}^{365} 0.03523 R_s (0.014 T_a - 0.37) \tag{5}$$

where $R_s$ [W m$^{-2}$] is incoming solar radiation and $T_a$ [°F] mean daily temperature. If $T_a$ becomes lower than 26.5 °F, evaporation becomes negative, in which case evaporation becomes zero.

The Hamon (H) method calculates evapotranspiration based on the relation between maximum incoming energy and the moisture capacity of the air. It assumes open water evaporation is equal to evapotranspiration. We took the modified version of this method as used by the US Army Corps of Engineers (Harwell, 2012):

$$E_{\mathrm{H}} = \sum_{j=1}^{365} 13.97 \left(\frac{N}{12}\right)^2 \left(\frac{SVD}{100}\right) \tag{6}$$

where N is the maximum number of daylight hours and SVD [g m$^{-3}$] the saturation vapor density.

The modified Penman (P) method combines mass transfer and energy budget methods, which expels the need for the surface water temperature, to determine open water evaporation (Harwell, 2012; Majidi et al., 2015):

$$E_{\mathrm{p}} = \sum_{j=1}^{365} \left( \frac{\Delta}{\Delta + \gamma} R_{\mathrm{n}} + \frac{\gamma}{\Delta + \gamma} E_a \right) \tag{7}$$

where $\Delta$ is the gradient of saturated vapor pressure, $\gamma$ the psychrometric constant, $R_n$ [mm d$^{-1}$] the effective net radiation and $R_a$ [mm d$^{-1}$] the evaporation from a Class A pan.

Climate data necessary to evaluate the four evaporation methods was taken from the ERA-Interim database (Dee et al., 2011), with a spatial resolution of $5 \times 5''$, for the period 1981–2010. We aggregated sub-daily data to daily values, because not all variables were available on a daily same time step. For each variable, we calculated average daily values over the period 1981–2010 to yield evaporation estimates for one (climate-averaged) year. Evaporation was evaluated at the midpoint of each reservoir.

### 2.3. Economic value and attribution

The WRD database states the purposes of a reservoir and provides production information on hydroelectricity generation, irrigation water supply and flood control storage, if present. For some reservoirs, production information was conflicting with purpose data. As a rule, we recognized hydroelectricity generation, irrigation water supply and flood control storage as a purpose if production data was available – even if the database did not explicitly list it as a purpose. We excluded navigation as a reservoir purpose, because only a few reservoirs are reported to serve this purpose. Besides, no data are reported on the economic value of reservoirs for the specific purpose of navigation. We converted and discounted all prices to represent 2014 equivalent US dollars, using inflation correction factors and exchange rates from the World Bank (2015) and Williamson (2015).

#### 2.3.1. Hydroelectricity generation

The economic value of hydroelectricity generation [US$ $y^{-1}$] is calculated by multiplying the mean annual electricity generation [GWh $y^{-1}$] with the economic value of electricity in the country where the reservoir is located [US$ $GWh^{-1}$]. For some reservoirs (984 in total), WRD reports both mean annual electricity generation and production capacity. For reservoirs with only a production capacity reported (359 reservoirs), we assumed mean annual electricity generation as 34% of the production capacity. This percentage is based on the ratio between mean and capacity production for reservoirs which have both metrics stated. National electricity prices were taken from IEA (2012), RCREEE (2013) or EUROSTAT (2015) or, if not available in these, based on prices found for comparable neighboring countries.

#### 2.3.2. Irrigation water supply

The economic value of irrigation water supply [US$ $y^{-1}$] is calculated by multiplying the irrigated area serviced by the reservoir as provided by WRD [ha] with the average economic value of agricultural land in the country where the reservoir is located [US$ $ha^{-1}$ $y^{-1}$]. The latter is a proxy for the value of crops that are actually being irrigated with water from the reservoir, because the databases are limited to reporting general servicing area for agricultural purposes. The average economic value of agricultural land is estimated per country by dividing the value of agricultural production of all crops in the country [US$ $y^{-1}$] by the production area of all crops in the country [ha]. Agricultural value and harvested area per crop per country were taken from FAOSTAT (2015) for the year 2013.

#### 2.3.3. Flood control storage

The economic value of flood control storage [US$ $y^{-1}$] is calculated by multiplying the available flood storage volume as provided by WRD [$m^3$] with the economic value of flood storage [US$ $m^{-3}$ $y^{-1}$]. The only study plainly stating economic value of flood storage to our knowledge is by Zhao and Liu (2015), who found a value of 0.16 US$ $m^{-3}$ $y^{-1}$ for the Three Gorges reservoir in China. The US Army Corps of Engineers (USACE, 2016) reports on prevented flood damage since the year of completion for several of its projects, most noticeably 24 reservoirs in the North-East US. Translated to mean annual values, their study yielded estimates of 0.002 to 0.58 US$ $m^{-3}$ $y^{-1}$, with an average of 0.117 US$ $m^{-3}$ $y^{-1}$, which is similar to the aforementioned estimate by Zhao and Liu (2015). We used 0.117 US$ $m^{-3}$ $y^{-1}$ as a proxy for all reservoirs globally that have flood control as a stated purpose.

#### 2.3.4. Residential and industrial water supply

The economic value of residential and industrial water supply from reservoirs [US$ $y^{-1}$] is calculated by multiplying the estimated yearly abstracted volume [$m^3$ $y^{-1}$] with the economic value of residential water in the country where the reservoir is located [US$ $m^{-3}$]. However, estimates of yearly abstracted volumes are not readily available. Based on data from 132 reservoirs in the United States (IWR, 2012) and 30 in Australia (Knook, 2016), the ratio between abstracted volume over reservoir volume was determined. These ratios showed a large variation, mainly because of size of the reservoir and climate: small reservoirs in humid climates typically have higher ratios than large ones in arid regions. Based on the set of 162 reservoirs, we drew two rating curves – one for humid and one for (semi-) arid regions. Depending on the climate zone of individual reservoirs, either curve prescribes the estimated abstracted volume. Note that in this procedure, other factors that might influence abstracted volumes are not considered. National water prices were taken from Danilenko et al. (2014), IWA (2012) and OECD (2010) or, if not available, based on prices found for comparable neighboring countries.

#### 2.3.5. Recreation

The economic value of recreation [US$ $y^{-1}$] is calculated by multiplying the economic value of recreation [US$ $ha^{-1}$ $y^{-1}$] with the reservoir surface area [ha]. Although expressing values of recreation in terms of surface area is rare, Costanza et al. (1997) gave a value of 368 US$ $ha^{-1}$ in 2014 net present value. For lack of better estimates, we applied this value to all reservoirs with recreation as stated purpose.

#### 2.3.6. Commercial fishing

The economic value of recreation [US$ $y^{-1}$] is calculated by multiplying the average economic value of wild caught freshwater fish [US$ $kg^{-1}$] with the reservoir surface area [ha] and the fishing yield [kg $ha^{-1}$ $y^{-1}$]. Economic values were obtained from The World Fish Center (2008), Mitchell et al. (2012) and FAO (2015). Fishing yields depend on multiple factors such as water body volume, food supply and climate (Marmulla, 2001), but country-average yields were the best metric we could find. Average national fishing yields were taken from Marmulla (2001), Van Zwieten et al. (2011) and Mitchell et al. (2012) or, if not available, based on prices found for comparable neighboring countries. For lack of reliable data, we excluded aquaculture in our analysis.

## 3. Results

### 3.1. The water footprint related to artificial reservoirs

The global water footprint of evaporation from the 2235 reservoirs in this study, averaged over the four estimation methods, is $65.7 \times 10^9$ $m^3$ $y^{-1}$. Fig. 2 shows the evaporation distribution for each method over all reservoirs. Table 1 gives the $WF_{evap}$ aggregated to the continent level. We grouped the reservoirs by climate class following the Köppen–Geiger classification (Kottek et al., 2006) in Fig. 3. The different methods vary in their resulting estimates of evaporation. Typically, the straightforward Kohli and Frenken method gives the highest evaporation estimates (especially in warm arid climates). The Hamon method yields the lowest estimates, which was anticipated by previous studies by Harwell (2012) and Majidi et al. (2015). The Jensen-Haise method estimates higher evaporation rates in equatorial climates compared to other methods, possibly because the Jensen-Haise method was originally developed for more arid regions (Jensen and Haise, 1963). Given that this study included only those reservoirs for which all data were available, the total, global water footprint of reservoirs must be substantially higher than the number presented here.

The global water footprint of reservoir construction for the 2235 reservoirs in this study is $39.6 \times 10^6$ $m^3$ $y^{-1}$ (Table 1). This number represents 0.05% of $WF_{evap}$ and thus hardly contributes to

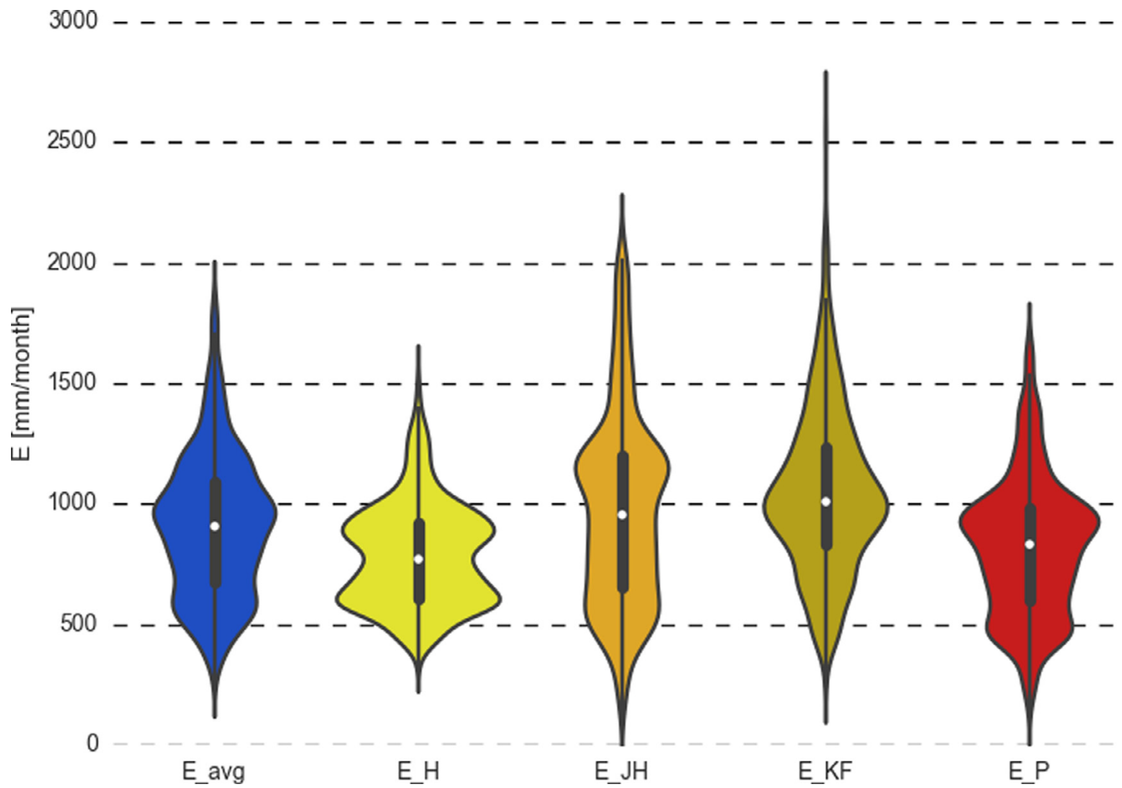


**Fig. 2.** Comparison of estimated distribution functions and quartiles of different evaporation (E) methods (average [avg], Hamon [H], Jensen-Haise [JH], Kohli-Frenken [KF] and Penman [P]) over all reservoirs.

**Table 1**
Estimated evaporation volumes from reservoirs for each continent.

| | $WF_{evap}$ [$10^9$ $m^3$ $y^{-1}$] | | | $WF_{constr}$ [$10^6$ $m^3$ $y^{-1}$] |
|---|---|---|---|---|
| | Minimum | Average | Maximum | |
| Africa | 15.6 | 18.8 | 25.1 | 0.38 |
| Asia | 15.3 | 18.0 | 22.3 | 33.4 |
| Europe | 2.9 | 3.8 | 4.7 | 0.74 |
| North America | 2.9 | 3.5 | 4.3 | 4.62 |
| Oceania | 1.0 | 1.2 | 1.5 | 0.18 |
| South America | 16.4 | 20.5 | 25.6 | 0.35 |
| Global | 54.1 | 65.7 | 83.6 | 39.6 |

the total yearly WF of reservoirs. Each reservoir individually shows such insignificant $WF_{contr}$ share of the total as well. Note, however, that $WF_{constr}$ is only trifling because we discounted it over the dam's lifespan. Water consumption could be significant still during the period of actual dam construction.

### 3.2. Allocation of $WF_{res}$ to purposes based on economic value

The total economic value of the reservoirs in this study, spawned by hydroelectricity generation, irrigation water supply, flood control, domestic and industrial water supply, recreation and fishing, is US$ $265 \times 10^9$ in 2014 dollars. Table 2 shows the total economic value and allocation coefficients for each continent. Hydroelectricity generation, irrigation water supply and residential and industrial water supply account for the largest part of reservoirs' economic value. These are also the most common reservoir purposes.

With the water footprint and allocation coefficients of each reservoir, we calculated the WF per purpose per reservoir. Table 3 summarizes the results at the continental level. The global water footprint study by Hoekstra and Mekonnen (2012) – which ignored water losses from reservoirs by evaporation – estimated the blue water footprint of crop production at $899 \times 10^9$ $m^3$ $y^{-1}$ and the blue water footprint of industrial and domestic water supply at $80 \times 10^9$ $m^3$ $y^{-1}$ (on average, over the period 1996–2005). To be complete, the evaporation from reservoirs assigned to irrigation water supply ($4.45 \times 10^9$ $m^3$ $y^{-1}$) must be added to the WF of crop production. Likewise, the WF of reservoirs assigned to residential and industrial water supply ($6.47 \times 10^9$ $m^3$ $y^{-1}$) and hydroelectricity generation ($48.4 \times 10^9$ $m^3$ $y^{-1}$) must be added to the WF of industrial and domestic supply. If we do so, the global blue WF of crop production is roughly 0.5% higher than estimated by Hoekstra and Mekonnen, and the global blue WF of industrial and domestic water supply even 69% higher. Note that these are still conservative estimates, since our study includes only 30% of the world's reservoir area.

Table 4 shows the global average WF per unit of production for each purpose, using the lowest, the highest and the average evaporation estimate of the four evaluated evaporation methods. Note that results are not comparable among purposes, because the unit of production or the unit interpretation differ (for example, for flood control a cubic meter refers to a volume stored, while for residential and industrial water supply it refers to a volume delivered). The right-hand side of Table 4 shows that the WF per unit of production not only differs for each evaporation method, but also from reservoir to reservoir. The 66% range around the median – that is, 66% of the reservoirs in this study with the stated purpose have a WF per unit of production between the reported high and low value – demonstrates the large variability found among reservoirs. This variability is mainly owing to reservoir surface size in relation to each purpose's production size, rather than to climate (cf. Liu et al., 2015; Mekonnen and Hoekstra, 2012). Moreover, variation in reservoir surface area itself, induced by seasonality or reservoir regulation, leads to uncertainty around our es-

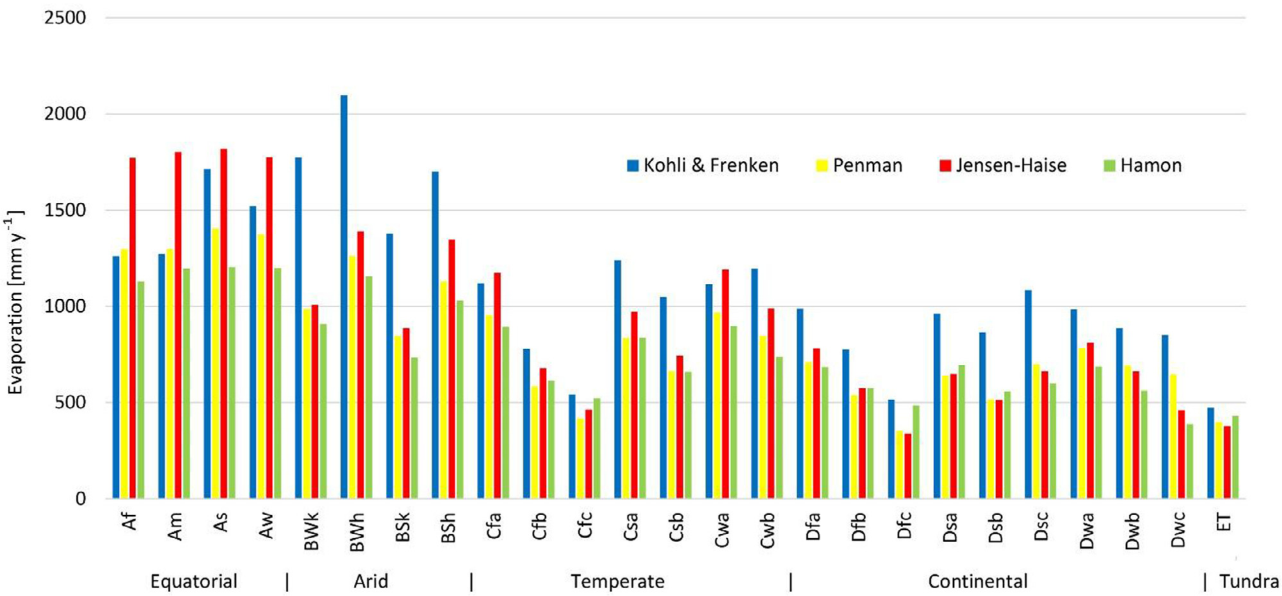


**Fig. 3.** Average evaporation rate per climate class for the four evaporation methods.

**Table 2**
Total annual economic value generated and allocation coefficients for each continent.

| | Number of reservoirs | Economic value [$10^9$ US$ $y^{-1}$] | Allocation coefficients ($\eta$) per purpose [%] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Hydro-electricity generation | Irrigation water supply | Flood control | Residential/industrial water supply | Recreation | Fishing |
| Africa | 203 | 16.5 | 23 | 18 | 37 | 22 | 0.0 | 0.0 |
| Asia | 653 | 92.8 | 21 | 52 | 17 | 10 | 0.0 | 0.5 |
| Europe | 519 | 39.2 | 27 | 4 | 17 | 53 | 0.0 | 0.0 |
| North America | 549 | 20.5 | 30 | 0 | 0 | 70 | 0.4 | 0.0 |
| Oceania | 171 | 15.1 | 14 | 5 | 0 | 80 | 0.0 | 0.0 |
| South America | 140 | 80.8 | 84 | 0 | 1 | 15 | 0.1 | 0.0 |
| Global | 2235 | 264.8 | 41 | 20 | 11 | 27 | 0.1 | 0.2 |

**Table 3**
Water footprint of reservoirs per reservoir purpose for each continent. Dashes imply reservoirs do not serve the specified purpose and/or lack sufficient data on the purpose according to the used datasets.

| | Hydroelectricity generation [$10^9$ $m^3$ $y^{-1}$] | Irrigation water supply [$10^9$ $m^3$ $y^{-1}$] | Flood control [$10^9$ $m^3$ $y^{-1}$] | Residential/ industrial water supply [$10^9$ $m^3$ $y^{-1}$] | Recreation [$10^6$ $m^3$ $y^{-1}$] | Fishing [$10^6$ $m^3$ $y^{-1}$] |
|---|---|---|---|---|---|---|
| Africa | 12.3 | 1.95 | 4.01 | 0.39 | 53 | 31 |
| Asia | 12.7 | 2.09 | 1.21 | 1.96 | 3 | 66 |
| Europe | 2.54 | 0.06 | 0.06 | 1.09 | 3 | 0 |
| North America | 0.97 | – | – | 1.64 | 863 | 3 |
| Oceania | 0.38 | 0.32 | 0.01 | 0.52 | 3 | – |
| South America | 19.4 | 0.03 | 0.13 | 0.86 | 3 | – |
| Global | 48.4 | 4.45 | 5.42 | 6.47 | 928 | 100 |

**Table 4**
Global average WF per unit of production per reservoir purpose, as it varies across evaporation methods (columns 2–4) and across reservoirs (columns 5–8).

| Reservoir purpose | Evaporation method | | | Reservoirs in 66% range | | Reservoirs in 95% range | |
|---|---|---|---|---|---|---|---|
| | Minimum | Average | Maximum | Low | High | Low | High |
| Hydroelectricity generation [$m^3$ $GJ^{-1}$] | 12.1 | 14.6 | 18.3 | 0.3 | 10.0 | 0.1 | 207.1 |
| Irrigation water supply [$m^3$ $ha^{-1}$] | 229 | 277 | 368 | 94 | 1634 | 21 | 10,989 |
| Flood control [$m^3$ $m^{-3}$] | 0.018 | 0.022 | 0.031 | 0.003 | 0.044 | 0.001 | 0.358 |
| Residential/ industrial water supply [$m^3$ $m^{-3}$] | 0.071 | 0.090 | 0.112 | 0.015 | 0.177 | 0.003 | 0.538 |
| Recreation [$m^3$ $ha^{-1}$] | 2013 | 2321 | 2833 | 18 | 11,360 | 2 | 41,532 |
| Fishing [$m^3$ $ton^{-1}$] | 0.81 | 0.94 | 1.12 | 0.10 | 0.99 | 0.04 | 26.95 |

**Table 5**
Scenarios regarding the variation of evaporative surface areas of reservoirs. The ranges between brackets refer to uncertainties due to the evaporation estimation method.

| | Reservoir areas at 20% of max. capacity | Reservoir areas averaging 56.25% of max. capacity | Reservoir areas at max. capacity |
|---|---|---|---|
| Global $WF_{evap}$ [$10^9$ $m^3$ $y^{-1}$] | 23.4 (19.2–29.7) | 65.7 (54.1–83.6) | 117 (96.2–149) |
| WF hydroelectricity generation [$m^3$ $GJ^{-1}$] | 5.2 (4.3–6.5) | 14.6 (12.1–18.3) | 25.9 (21.4–32.5) |

**Table 6**
WF per dollar of economic output and economic water productivity per purpose.

| Reservoir purpose | WF per dollar [$m^3$ US$^{-1}$] | Economic water productivity [US$ $m^{-3}$] |
|---|---|---|
| Hydroelectricity generation | 0.44 | 2.26 |
| Irrigation water supply | 0.08 | 12.1 |
| Flood control | 0.19 | 5.32 |
| Residential/ industrial water supply | 0.09 | 11.2 |
| Recreation | 6.31 | 0.16 |
| Fishing | 0.21 | 4.81 |

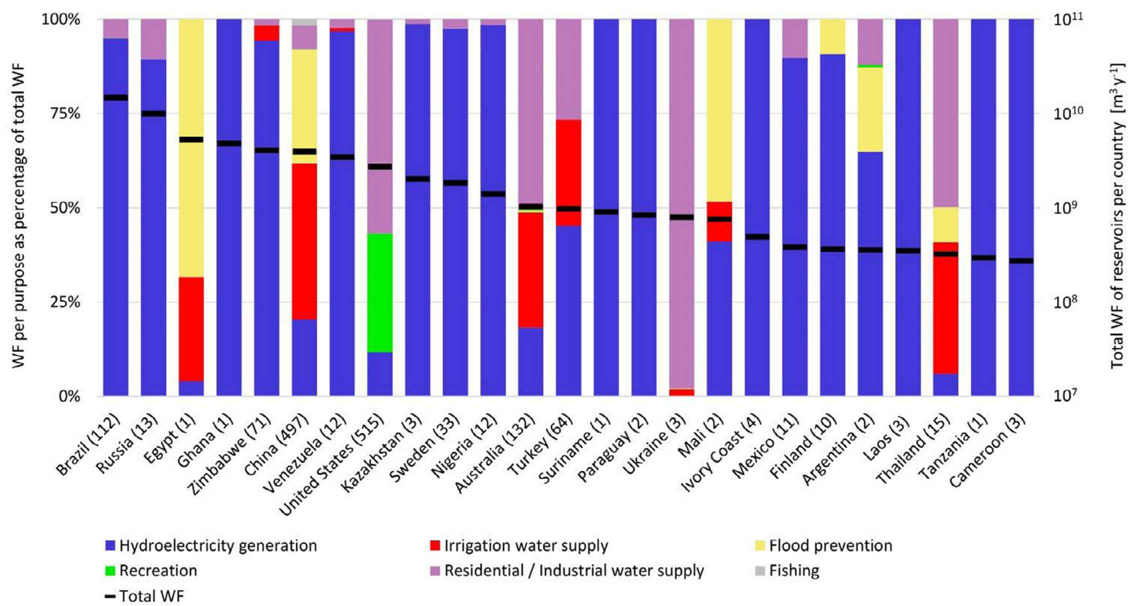


**Fig. 4.** The total water footprint of reservoirs per country and the share of different reservoir purposes in the total for the 25 countries with the largest total water footprint. The number between brackets refers to the number of reservoirs in the country included in the study.

timates. Table 5 shows the uncertainty associated with the global total WF and the global average WF of hydroelectricity.

The purposes become mutually comparable if we consider the WF per dollar of economic output [$m^3$ US$^{-1}$], or its reverse, the economic water productivity [US$ $m^{-3}$]. Table 6 shows the WF per dollar production, based on WFs per purpose averaged over the four evaporation methods. The WF per dollar of economic output is relatively low (high productivity) for residential and industrial water supply and irrigation water supply, and relatively high (low productivity) for recreation. Except for recreation, all purposes yield at least several dollars in revenue for each cubic meter of water evaporated.

Zooming in to the country level, we find that Brazil has the largest total WF related to reservoirs, followed by Russia and Egypt (Fig. 4). This is a different list than that of countries with the highest installed reservoir area, which is headed by Russia, Brazil and China. This difference can be explained by the climatic conditions, which favor high evaporation in these high WF countries. For some countries, our database included only one reservoir, which usually is a very large reservoir that experiences high evaporation rates. Examples are Lake Nasser in Egypt, Lake Volta in Ghana and the Brokopondo reservoir in Suriname. Although there are 71 reservoirs included in Zimbabwe, the total WF of reservoirs there largely results from the Kariba reservoir. Results per reservoir and per country area available in the Supplementary Materials.

### 3.3. The water footprint of reservoirs in the context of water scarcity

The largest part (57%) of the WF of reservoirs is located in river basins with a low water scarcity level (Fig. 5a). The other part is located in basins facing 1–3 months (29%), 4–6 months (7%) or 7–11 months (5%) of moderate to severe water scarcity a year. Moderate to severe water scarcity here means that more water is consumed than sustainably available – that is, environmental flow requirements are violated (Hoekstra et al., 2012). About 1% of the WF of reservoirs lies in basins with year-round moderate to severe water scarcity. We further find that in river basins with low water scarcity throughout the year, hydroelectricity generation constitutes the largest part of $WF_{res}$. The relative contribution of hydroelectricity generation to the total decreases with increasing water scarcity levels (Fig. 5b–f). In river basins with more than 7 months of moderate to severe water scarcity, residential and industrial water supply are the primary reservoir purposes. This finding confirms a previous assessment by Bakken et al. (2015), who found

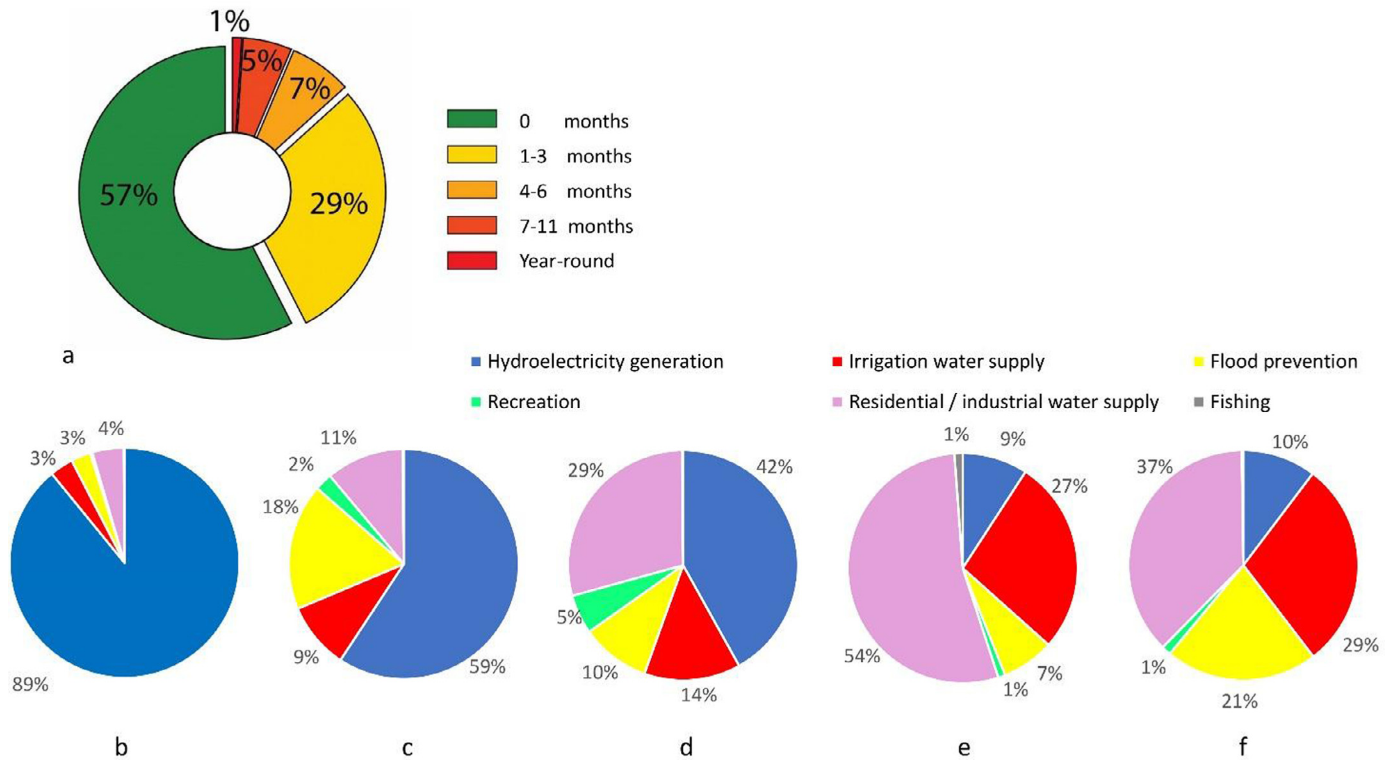


**Fig. 5.** The share of the global WF of reservoirs in river basins facing moderate to severe water scarcity during 0, 1–3, 4–6, 7–11 or 12 months per year (a); and the WF share per purpose located in basins facing moderate to severe water scarcity during zero (b), 1–3 (c), 4–6 (d), 7–11 (e) or 12 (f) months per year.

few reservoirs used for hydroelectricity generation are located in water-scarce areas.

## 4. Discussion

We have chosen four different evaporation methods to calculate $WF_{evap}$ out of a host of other available approaches. We anticipated these methods would vary – as indeed they did – so we calculated an ensemble mean. However, ambiguity remains on what method(s) to choose to assess open water evaporation. In addition, adding effects such as thermal heat storage, which was disregarded in this study, both complicates and improves evaporation estimations (Finch, 2001; Majidi et al., 2015). It is worth noticing that the simple Kohli and Frenken method – which is often used to calculate open water evaporation – turned out to be the most deviant method.

Beside methodological considerations, resulting evaporation fluxes depend to a large extent on the shape and surface area of the reservoir, as is shown in Table 5. Although we touched on the uncertainty associated with reservoir area variations, adding time series on fluctuating reservoir areas would reduce uncertainty and allow for more detailed, time-dependent WF estimations.

The difficulty to determine surface area (or any dam or reservoir parameter for that matter) became clear when we combined the ICOLD and GRanD databases. Incompleteness and differing definitions, naming or surveying methods between the two, inevitably propagated to our resulting reservoir database. Especially the lack of data on abstractions for domestic and industrial water supply took away from ICOLD's usefulness. Moreover, data availability of most variables needed to estimate economic value of reservoirs was low. Especially national values of recreation and of fishing yields and prices were often approximated, and data on volumes abstracted for industrial and residential supply should be considered with caution.

The estimated global WF of reservoirs is based on a selected set of reservoirs for which enough data was available. This set represents a combined surface area of 129,000 km$^2$ (~50% of full GRanD database surface area of manmade reservoirs or ~30% if all GRanD reservoirs are included). Shiklomanov and Rodda (2003) estimated an installed reservoir area of 500,000 km$^2$ around the beginning of the 21st century, which according to their estimate evaporated $208 \times 10^9$ m$^3$ y$^{-1}$. The total $WF_{res}$ of $66 \times 10^9$ m$^3$ y$^{-1}$ found in this study could prudently be extrapolated to account for the excluded reservoir surfaces. A tentative estimate of global reservoir WF, then, is about $250 \times 10^9$ m$^3$ y$^{-1}$. This final figure corresponds to ~25% of the total human blue water consumption ($1025 \times 10^9$ m$^3$ y$^{-1}$) as estimated by Hoekstra and Mekonnen (2012).

We found the global average WF of hydroelectricity is 14.6 m$^3$ GJ$^{-1}$ (Table 4), and varies highly among reservoirs. Gerbens-Leenes et al. (2008) report 22 m$^3$ GJ$^{-1}$, Mekonnen et al. (2015) 15.1 m$^3$ GJ$^{-1}$, Scherer and Pfister (2016) 17.1 m$^3$ GJ$^{-1}$ (median) or 38.9 m$^3$ GJ$^{-1}$ (global average), and Bakken et al. (2017) give a range of WF of hydroelectricity (determined via the gross approach) of 1.5–65 m$^3$ GJ$^{-1}$. Despite the differences in methods and data used, these values indicate that hydroelectricity is a water intensive form of energy compared to other energy sources (cf Mekonnen et al., 2015). If we again extrapolate our findings, by applying the average WF of hydroelectricity generation of 14.6 m$^3$ GJ$^{-1}$ to the global hydroelectricity production of 3940 TWh in 2015 (World Energy Council, 2016), we prudently estimate the global WF of hydroelectricity production is $207 \times 10^9$ m$^3$ y$^{-1}$ – adding over 20% to the total global blue water footprint as estimated earlier by Hoekstra and Mekonnen (2012).

We confined the spatial system boundaries to the reservoir. The influence of reservoirs on evaporation, especially in cascaded systems, extends beyond the reservoir to the rivers below, because of a change in flow regime (Bakken et al., 2013). Depending on the system, this regime change can lead to decreased downstream evaporation (because of decreased flood duration and associated evaporation from flooded land), or an increase in evaporation (because of raised groundwater levels due to additional percolation and associated evaporation from groundwater). Although these processes and their importance differ at the individual reservoir level, they may cancel out at the larger scale (Shiklomanov and Rodda, 2003).

This study gives a first glimpse of how the beneficiary purposes of reservoirs share the burden of water consumption. The reservoir and climate data are all taken from global databases, with all accompanying restraints. For individual reservoirs – both those covered in this study and those to be developed in the future – we recommend to redo this analysis using local data whenever possible.

## 5. Conclusion

Building a dam and reservoir can be a valuable measure to address a host of water related issues. This study estimates the economic benefits from reservoir products and services is US$ $265 \times 10^9$ globally, mainly because of value added by hydroelectricity generation, residential water supply and industrial water supply. We also show that these benefits come at a significant cost in terms of water loss. The total blue water footprint of 2235 reservoirs included in this study, related to both dam construction and evaporation losses from reservoir surfaces, is $66 \times 10^9$ $m^3$ $y^{-1}$. Water use studies, dam development plans, and water-for-energy scenarios seldom account for this reservoir water footprint. Paradoxically, a reservoir may be an apt measure to increase water availability during a certain time of the year, but only at the cost of reducing total water availability over the whole year.

Since reservoirs typically serve multiple purposes, the total WF of reservoirs must be assigned to those purposes. Rather than leaving them implicit, we explicated quantitative WFs per reservoir purpose, by attributing the total WF to purposes based on their estimated economic value – for the first time, and on a global scale. From the reservoir purposes considered, hydroelectricity generation constitutes the largest share of the total WF, followed by residential and industrial water supply. The global average WF of hydroelectricity is estimated at 14.6 $m^3$ $GJ^{-1}$, which is in line with estimates by previous studies. It demonstrates that hydroelectricity – on average – is a water intensive form of energy. On the positive side, economic water productivity [US$ $m^{-3}$] is high for all purposes except recreation.

For each reservoir purpose, the WF per unit of production shows substantial variability around the global average. One factor contributing to the spread is the choice of method to estimate open water evaporation. Another is climate, because cold temperate climates give rise to low WFs and equatorial and arid climates to high WFs. However, the reservoir surface size in relation to the production size of each purpose contributes most to the variability.

We investigated the water scarcity levels of the basins in which reservoirs are located and found the majority (57%) of reservoir-related WFs is located in water-abundant basins. The remainder is located in basins with one or more months of moderate to severe water scarcity. The primary reservoir purpose changes with changing water scarcity levels. While hydroelectricity generation is the primary purpose in non-scarce basins, in scarcer areas residential and industrial water supply and irrigation water supply are the purposes for which the reservoir is mostly used.

Because of growing freshwater demand, increasing water-scarcity levels worldwide, and continuing dam developments, water consumption from artificial reservoirs needs to be accounted for. All value-generating purposes of a reservoir share in this WF burden. We therefore recommend to build on this methodology, and apply it to future dam development and water-for-energy scenario studies in specific, and to water use assessments in general.

## Acknowledgments

This research was partially funded by NWO Earth and Life Sciences (ALW), project 869.15.007. The work was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS).

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2018.01.028.

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