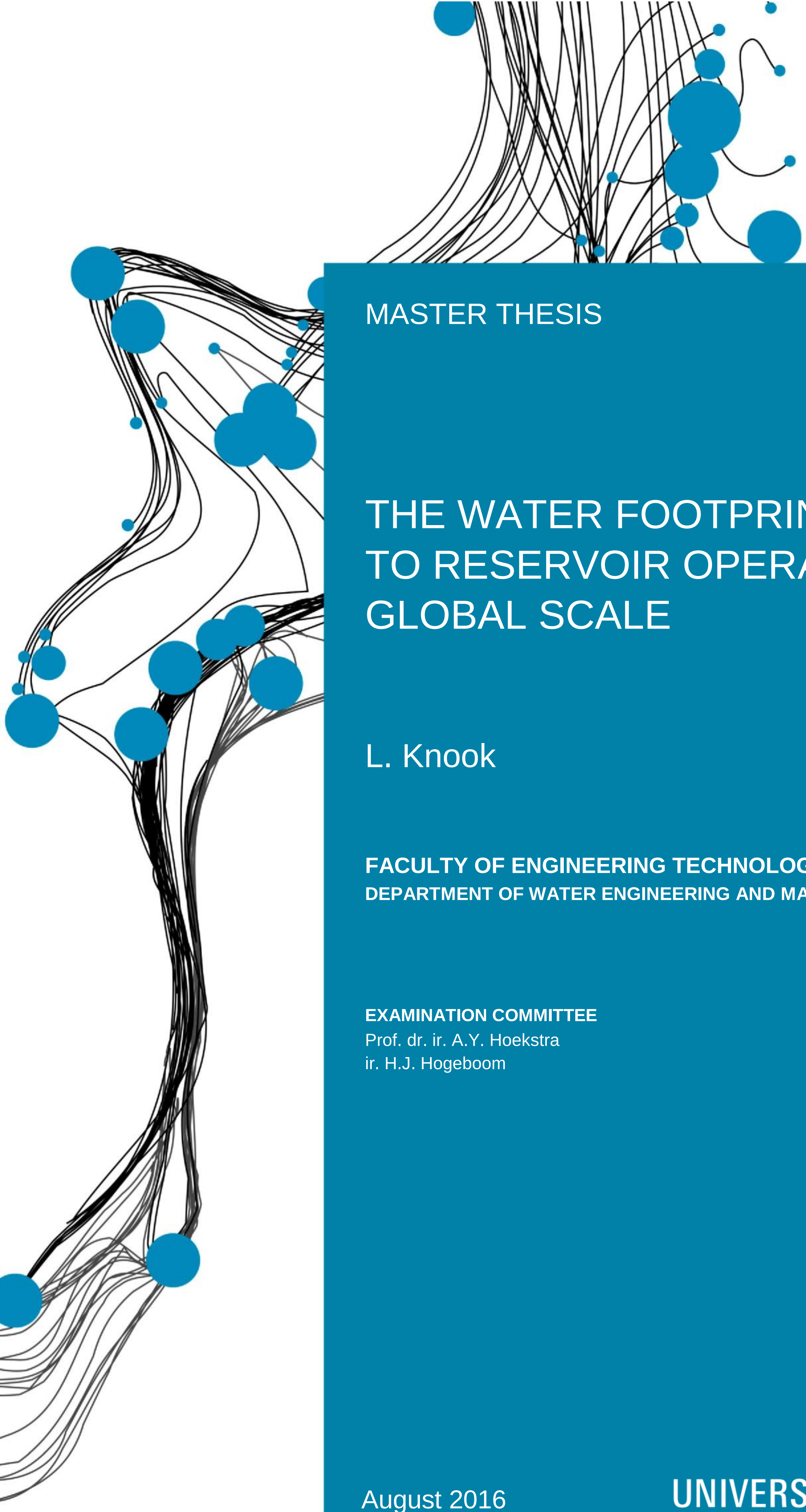

MASTER THESIS

THE WATER FOOTPRINT RELATED TO RESERVOIR OPERATION ON A GLOBAL SCALE

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I. List of symbols

A	Reservoir area	ha
E_a	Annual actual evaporation volume	m^3y^{-1}
E_d	Daily evaporation rate	mmd^{-1}
E_p	The amount of evaporation from a Class A pan	mmd^{-1}
E_y	Annual evaporation rate	mmy^{-1}
ET_c	Daily evaporation rate of the vegetation before there was a reservoir	mmd^{-1}
ET_o	Daily evapotranspiration rate	mmd^{-1}
E_v	Annual evaporation volume	m^3y^{-1}
G_{sc}	The solar constant	$MJm^{-2}min^{-1}$
J	The number of the day between 1 January and 31 December	(-)
N	The maximal number of daylight hours	h
P	Production per reservoir purpose	
P_r	Annual precipitation volume	mmy^{-1}
R_a	The extra-terrestrial radiation	$MJm^{-2}d^{-1}$
R_n	Net radiation expressed as mm evaporation	mmd^{-1}
R_s	The incoming solar radiation	$MJm^{-2}d^{-1}$
SVD	The saturation vapour density	gm^{-3}
T_a	The air temperature	°C or °K
T_d	The dew point temperature	°C or °K
U_{10}	The average wind speed at a height of 10 m	kmd^{-1}
a_s	The regression constant, expressing the fraction of extra-terrestrial radiation reaching the earth on overcast days (n = 0)	(-)
a_s+b_s	The fraction of extra-terrestrial radiation reaching the earth on clear days	(-)
d_r	The inverse relative distance Earth-Sun	(-)
e_a	The atmospheric vapour pressure	kPa
e_s	The saturation vapour pressure	kPa
e_w	The saturated vapour pressure at air temperature	kPa
k_c	The crop coefficient	(-)
n	The actual duration of sunshine in hours	h
v_i	Annual economic value per purpose	$\$y^{-1}$
v_t	Annual total economic value per reservoir	$\$y^{-1}$
y	The psychrometric constant	$kPa°C^{-1}$
Δ	The slope of the saturated vapour pressure-temperature curve	$kPa°C^{-1}$
δ	The solar decimation	rad
κ	Factor used to correct the maximal reservoir area	(-)
$η_i$	The allocation coefficient	(-)
φ	The latitude	rad
$ω_s$	The sunset hour angle	rad

II. Preface

With this thesis, I finalize my study Civil Engineering and Engineering at the University of Twente. I started with this master about 2 years ago, after I completed a bachelor Civil Engineering at the Hogeschool Utrecht and my premaster courses. This study started with a preparatory phase from September to November 2015, in which a literature review and research proposal were written and data was collected. The graduation project itself was conducted between December 2015 and July 2016. I expected beforehand that collecting the economic data, to determine the economic value of reservoirs, would be the most difficult part. But afterwards, it appeared that determining the evaporation from reservoir would be far more complex. Especially because it was difficult to extract climatological data for all the locations and the evaporation methods were not working well.

I would like to thank my supervisors from the University of Twente: Arjen and Rick. Arjen, thank you for the feedback and the suggestions on how to present my results. Rick, thank you for your advice during the whole project, your detailed feedback and your help with programming in Python. Also I would like to thank Mesfin, for his supervision during the preparatory course and the first month of my research.

I also would like to thank my housemates in both Huize Ypelobrink and Huize Opdakken, for the "*gezelligheid*" and for broadening my view on the world, in the time that I lived in both houses. I would like to thank my roommates in graduation room Z140, for their help with programming and for our talks about thesis problems. In the past year I have been in the board of S.K.V. Vakgericht and I would like to thank my fellow board members for not giving me too much "*actiepuntjes*". Finally, I would like to thank Marit, for her love, support and for reviewing my thesis.

Luuk Knook

Enschede, August 2016

III. Summary

Reservoirs are used to generate electricity, supply water to irrigation, drinking water companies and the industry, to manage the water level in rivers to prevent flooding, to recreate and to catch fish. The water stored in reservoirs will be partly lost due to evaporation and this means that products and services produced by reservoirs have a water footprint. The objective of this study is to determine the water footprint related to the production of goods and services produced by man-made reservoirs.

Based on the WRD and the GRanD reservoir databases, a reservoir database is created with 2235 reservoirs. This corresponds to 3,8% of the reservoirs and 30,1 % of the total reservoir volume in the ICOLD database. The economic value of reservoirs is determined by multiplying the annual average production per purpose with the economic value per unit of production. No production data was available for the purpose residential and industrial water supply and therefore this was estimated based on the reservoir volume.

The evaporation was determined on a daily basis using 4 different methods: Jensen and Haise, Hamon, Penman and a method provided by Kohli and Frenken. With the first 3 methods, the evaporation was estimated based on climatological data provided by the ERA Interim database. Using the method of Kohli and Frenken, the evaporation is determined based on data from the FAO global evapotranspiration map and assuming that the crop coefficient for open water is 1. The evaporation volume is determined by taking the average of the 4 evaporation figures and multiply this, with the reservoir area and a factor to correct the reservoir area for the reservoir fullness.

The total water footprint per reservoir is the sum of both the water footprint related to evaporation and the water footprint related to reservoir construction. The water footprint of reservoir construction was based on the water footprint of construction materials and the dam body volume of the dam. Allocation coefficients based on the economic value of the reservoirs are used to allocate the water footprint to each reservoir purpose.

There can be concluded that all reservoir purposes treated in this study have a water footprint. The total annual water footprint from the reservoirs in this study is 1,04 x 10^{11} m^3 and the total annual economic value of the reservoirs purposes in this study is $ 311 billion, in 2014 U.S. Dollars. The total annual water footprint related to reservoir construction is 3,96 x 10^7 m^3. The global water footprint related to: hydropower generation by reservoirs is 7,18 x 10^{10} m^3y^{-1}, for irrigation water supply by reservoirs is 8,28 x 10^9 m^3y^{-1}, for flood prevention by reservoirs is 8,7 x 10^9 m^3y^{-1}, for open water recreation on reservoirs is 2,01 x 10^9 m^3y^{-1}, for residential and industrial water supply by reservoirs is 1,32 x 10^{10} m^3y^{-1} and for commercial fishing on reservoirs is 2,08 x 10^8 m^3y^{-1}.

Lake Nasser has the highest water footprint of all the individual reservoirs in this study. Brazil has the highest water footprint related to reservoir operation for the reservoirs in this study. The differences in water footprint can be partly explained by the location of the reservoir. Reservoirs located in equatorial and arid climates have, in general, a higher evaporation figure than reservoirs located in other climates.

The largest part of annual water footprint related to reservoir operation, is located in river basins with a low water scarcity level and the main reservoir purpose in these reservoirs is hydropower generation. A smaller part, 44%, of the water footprint related to reservoir operation is located in river basins with 1 to 11 months of water scarcity and the importance of hydropower as reservoir purpose decreases as the number of months with moderate to severe water scarcity increases. Only 1% of the water footprint of the reservoirs in this study is located in river basins with 12 months moderate to severe water scarcity. For these reservoirs, residential and industrial water supply is the main purpose.

IV. Samenvatting

Stuwmeren worden gebruikt om elektriciteit op te wekken, om water op te slaan ten behoeve van irrigatie, drinkwaterbedrijven of industrie, om waterstanden in rivieren te beïnvloeden en zo overstromingen te voorkomen, om te recreëren en om vis te vangen. Het water dat in stuwmeren is opgeslagen gaat echter deels verloren door verdamping. Dit betekent dat producten en diensten die geleverd worden door stuwmeren een watervoetafdruk hebben. Het doel van deze studie is om de watervoetafdruk, van de door stuwmeren geproduceerde producten en diensten, in kaart te brengen.

Een database, bestaande uit 2235 reservoirs is samengesteld gebaseerd op gegevens uit de WRD en GRanD stuwmeren databases. Dit komt overeen met 3,8% van het totale aantal stuwmeren in de WRD-database en 30,1% van het totale stuwmeer volume in de WRD-database. De economische waarde van deze stuwmeren is bepaald door de productie per reservoir functie te vermenigvuldigen met de monetaire waarde per productie-eenheid. Er was geen productie informatie beschikbaar voor de functie drink- en industriewater onttrekking uit stuwmeren. Daarom is het onttrokken volume ingeschat op basis van het stuwmeer volume.

De verdamping uit stuwmeren is bepaald op basis van 4 verschillende methodes: Jensen and Haise, Hamon, Penman en de methode van Kolhi en Frenken. Met de eerste 3 methoden is de verdamping bepaald op basis van klimatologische gegevens uit de ERA Intrim database. De gebruikte methode van Kolhi en Frenken komt neer op het uitlezen van een FAO evapotranspiratie kaart voor elke reservoir locatie, met de aanname dat de gewas coëfficiënt voor open water 1 is. Het verdamping volume per stuwmeer is bepaald als het gemiddelde van de 4 verdampingsmethoden vermenigvuldigd met het oppervlak van het stuwmeer en een factor om het maximale stuwmeer oppervlak te corrigeren naar een jaarlijks gemiddelde oppervlak.

De totale watervoetafdruk per stuwmeer is de som van de watervoetafdruk gerelateerd aan verdamping en de watervoetafdruk gerelateerd aan het bouwen van het stuwmeer. De watervoetafdruk van het construeren van het reservoir is gebaseerd op de watervoetafdruk van bouwmaterialen en het volume van de stuwdam. Coëfficiënten op basis van de economische waarde zijn gebruikt om de watervoetafdruk toe te schrijven aan elke functie van het stuwmeer.

Er kan worden geconcludeerd dat alle functies van reservoirs, behandeld in deze studie, een watervoetafdruk hebben. De jaarlijkse watervoetafdruk van alle reservoirs in deze studie is $1,04 \times 10^{11}$ m^3 en de totale economische waarde van de stuwmeren in deze studie is $ 311 miljard, in 2014 U.S. Dollars. De totale jaarlijkse watervoetafdruk gerelateerd aan het bouwen van stuwmeren is $3,96 \times 10^7$ m^3. De wereldwijde watervoetafdruk gerelateerd aan: het opwekken van elektriciteit door stuwmeren is $7,18 \times 10^{10}$ m^3j^{-1}, het opslaan van water ten behoeve van irrigatie is $8,28 \times 10^9$ m^3j^{-1}, voor het voorkomen van overstromingen door stuwmeren is $8,7 \times 10^9$ m^3j^{-1}, ten behoeve van het recreëren op stuwmeren is $2,01 \times 10^9$ m^3j^{-1}, het opslaan van water ten behoeve van de drinkwatervoorziening is $1,32 \times 10^{10}$ m^3j^{-1} en ten behoeve van commerciële visserij in stuwmeren is $2,08 \times 10^8$ m^3j^{-1}.

Het Nasser meer heeft van alle stuwmeren in deze studie de grootste watervoetafdruk. Brazilië heeft als land de grootste watervoetafdruk gerelateerd aan het opereren van stuwmeren, voor de stuwmeren in deze studie. De verschillen in watervoetafdrukken voor de individuele reservoirs kunnen deels verklaard worden door de locatie van het stuwmeer. Stuwmeren die zich bevinden in tropische of aride klimaten hebben in het algemeen een hogere verdamping dan stuwmeren in andere klimaten.

Het grootste deel van de jaarlijkse watervoetafdruk, gerelateerd aan het gebruik van stuwmeren, bevindt zich in stroomgebieden waar het hele jaar een laag waterschaarste niveau geldt. Elektriciteitsopwekking is de belangrijkste functie van deze reservoirs. Een kleiner deel, 44%, van de bovenstaande watervoetafdruk bevindt zich in stroomgebieden met 1 tot 11 maanden matige tot ernstige waterschaarste. Slechts 1% van de watervoetafdruk bevindt zich in stroomgebieden met het gehele jaar waterschaarste. Drink- en industriewatervoorziening is de belangrijkste functie van deze reservoirs.

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Appendix

1. Introduction

Water is the most important resource for humanity and is a good without substitution. Water is used as drinking water, to cultivate crops and serves sanitary and industrial purposes. Nature provides water by precipitation, river flow or groundwater. However, there is a large variability in the natural water supply and depending on the climate and soil conditions, water shortage or floods can appear. One way to prevent both water shortages and floods is to store water in reservoirs (World commission on dams, 2000). Reservoirs have been used in this way for millennia. Evidence of reservoirs used for both irrigation and drinking water supply are found in serval parts of the Middle East and date back to 3000 BC (Belyakov, 1991; World commission on dams, 2000; Novak, et al.,2007; Mays, 2008). The reservoir concept is simple. A dam is built in a river to block the water flow and the water accumulates upstream of the dam.

The difference in water level between the two sides of the dam increases, as the water accumulates behind the dam. This difference in water level can be used to generate energy, which is another important reason to construct reservoirs (World commission on dams, 2000,). In ancient times, the Greek used the power of falling water to turn their waterwheels, which grinded their wheat into flour (Kunar, et al., 2011). After the middle ages, turbine development exceeded and mechanical hydropower was used to drive multiple types of machines. In the late 19th century, hydropower was firstly used to generate electrical energy.

In the 20th century, the number of reservoirs increased rapidly. Around 1900 there were only several hundred dams, which increased to over 45000 dams by the end of the 20th century (World commission on dams, 2000). The construction of reservoirs peaked in the ’70s and today most dams are constructed in development countries as the most suitable locations in Europa and North America already have been developed (Shiklomanov, 2000; World commission on dams, 2000).

1.1. Problem definition

The water stored behind the dam will be partly lost due to evaporation. This leads to a decrease in available water resources and makes reservoirs water users (Shiklomanov, 2000). That water evaporates from manmade reservoirs is without discussion, but there is no consensus if this should be considered as water use and if evaporation from reservoirs is a problem (Shiklomanov, 2000; Bakken et al., 2013; Bakken et al., 2015). In the past years, several studies have shown that hydropower generation is a major water user (Pasqualetti & Kelly, 2008; Mekonnen & Hoekstra, 2012; Demeke et al., 2013; Mekonnen et al., 2015). However, these studies focus only on hydropower production and on a relatively low number of reservoirs. To get a complete picture, other reservoir purposes should be included and part of the water use should be allocated to these purposes. An integrated study, which determines the water use for a large number of reservoirs at different locations and for multiple reservoir purposes, is not yet available.

1.2. Research objectives and research questions

The objective of this study is to determine the water footprint, related to manmade reservoir operation, for a large number of reservoirs and for multiple reservoir purposes on an annual basis. This water footprint is determined over the whole supply chain of reservoir products and includes both the water footprint related to evaporation as the water footprint related to reservoir construction. The water footprint is allocated to the different reservoir purposes, based on the economic value of each purpose.

The objective is translated into the following main research question: “What is the water footprint related to the operation of manmade reservoirs?” Besides the main research question, the following sub questions are defined:

1) What is the annual economic value of product and services produced by reservoirs?
2) What is the annual amount of evaporation from reservoirs?
3) What is the annual water footprint related to reservoir construction?
4) What is the water footprint related to the use of reservoirs, in the context of water scarcity?

1.3. Introduction to the water footprint concept

The water footprint is an indicator that describes the volume of fresh water, which is not only used during the consumption or production of a good or service, but which also includes the water use during the complete production chain (Hoekstra, et al., 2011). The water footprint can be measured for a single product or service, for a production process, for an organisation or for a geographical area. Depending on the question, the water footprint is represented in m^3/production unit, m^3/economical unit, m^3/process or m^3/surface area (Hoekstra, et al., 2011).

There are three different water footprints components, depending on water source and water use. The blue water footprint refers to use of water from surface water bodies or aquifers. During the production or supply chain, this water is incorporated into a product, evaporated or returns to another catchment (Hoekstra, et al., 2011). The green water footprint refers to consumption of precipitation, before it becomes runoff. Mainly forestry, agricultural and horticultural products have a green water footprint (Hoekstra, et al., 2011). The grey water footprint refers to pollution of water resources and is defined as the amount of water that is required to assimilate the load of pollutants, given the natural background concentrations of the water body (Hoekstra, et al., 2011). The grey water footprint includes both point source and diffuse source water pollution. The grey water footprint is relevant for both agricultural and industrial water pollution.

1.4. Theoretical framework

In the past few years, several studies have been done to determine the water footprint related to reservoir operation (Gleick, 1992,1993; Pasqualetti & Kelly, 2008; Gerbens-Leenes, et al., 2009; Herath, et al., 2011; Mekonnen & Hoekstra, 2012; Mekonnen, et al., 2015; Zhoa & Lui, 2015). Most of these studies only include evaporation losses and attribute them fully to hydropower production. However, some recent studies use allocation coefficients to attribute the evaporation among the different reservoir purposes. But still, only the water footprint of hydropower is determined. This paragraph gives an overview of these studies and describes methodologies to determine the water footprint related to reservoir use.

1.4.1. Overview of reservoir footprint studies

The study by Gleick (1992, 1993) to the environmental consequences of hydroelectric development for Californian reservoirs, was the first study where reservoir evaporation was connected to a reservoir purpose. Based on figures provided by Gleick (1993) and Shiklomanov (2000), Gerbens-Leenes, et al. (2009) determined the water footprint of hydropower production using the water footprint concept. Herath, et al. (2011) determined the water footprint for 17 reservoirs in New Zealand based on measured evaporation figures. They used the 3 methods described above to determine different water footprints. Mekonnen and Hoekstra (2012) determined the water footprint for 35 major reservoirs globally, with hydropower as main function. They calculated the evaporation with the Penman-Monteith model. Table 1.1 gives an overview of the water footprint of hydropower according to several studies.

Pasqualetti and Kelly (2008) determined the water footprint for several large reservoirs in the South-western states of the U.S. They used allocation coefficients, based on the economic value of each reservoir purpose, to attribute the water use to hydropower production. Zhoa and Lui (2015) used the same methodology to determine the water footprint related to hydropower production of the Three Gorges dam. Mekonnen, et al. (2015) used allocation coefficients based on the order of reservoir purposes to determine the water footprint related to hydropower production for the 654 largest reservoirs globally. If hydropower generation was the main reservoir purpose, all evaporation was allocated to hydropower production. If hydropower generation was a secondary or tertiary purpose, 50% or 33% of the evaporation was allocated to hydropower production. Mekonnen, et al. (2015) also included the water footprint of reservoir construction in their calculation.

Table 1.1. The water footprint of hydropower according to serval studies. Based on: Mekonnen & Hoekstra, 2012; Bakken, et al., 2013; Zhoa & Liu, 2015; Mekonnen, et al., 2015.

Study	*WF of hydropower (m^3GJ^{-1})*		*Reservoir(s)*
Gleick, 1992, 1993	0	minimum	100 power hydropower plants in California, U.S.
	1,5	median	
	58	maximum	
Gleick, 1994	1,5	mean	California
	7	median	
Torcellini et al., 2003	19	mean	120 hydropower plants in the U.S.
Pasqualetti and Kelly, 2008	32	mean	Reservoirs located in Arizona, U.S.
Gerbens-Leenes et al., 2009	22		Global average
Herath, et al., 2011	6	gross average	17 reservoirs in New Zealand
	3	net average	
	2	water balance	
Mekonnen & Hoekstra, 2012	0,3	minimum	35 reservoirs, globally
	68	average	
	846	maximum	
Arnøy, 2012	1		Norway
Yesuf, 2012	16	gross average	Ethiopia
	10	net average	
Tefferi, 2012	28	w. average	Ethiopia (Blue Nile)
	411	w. average	Sudan (Blue Nile) and Roseires and Sennar irrigation reservoirs
Demeke et al., 2013	0	minimum	Austria, Ethiopia, Turkey, Ghana, Egypt and PDR Loa
	1736	maximum	
Mekonnen et al., 2015	0,3	minimum	Based on the 654 largest reservoirs, globally
	15,1	mean	
	850	maximum	
Zhoa & Liu, 2015	1,5	mean	Three Gorges reservoir, China

There are also a large number of studies available that determine only the evaporation from reservoirs and only the most relevant are mentioned here. Shiklomanov (2000) estimated the evaporation losses from reservoirs per continent. Gokbulak & Ozhan (2006) estimated the evaporation from 209 manmade reservoirs in Turkey. They found that the average evaporation from these reservoirs was 1018 mm per year. The evaporation from 3 manmade reservoirs in the Murrey-Darling was approximately 1390 mm per year. This was modelled with the Penman-Monteith method for open water (McJannet, et al., 2008).

Based on the AQUASTAT geo-referenced database of dams and the Global map of reference evaporation (FAO, 2004), Kolhi & Frenken (2015) estimated the evaporation from more than 14216 reservoirs. The intention of this study was to provide a general idea of the volume of evaporation from man-made reservoirs by country and by major AQUASTAT region. They estimated that the annual evaporation from man-made reservoirs was 346 km^3y^{-1}. The method used by Kolhi & Frenken is described by equation 1.1.

$$E_a = 0{,}4AK_cET_o \qquad (1.1)$$

Table 1.2. Reservoirs used for comparison, with reservoir data and evaporation figures based on available literature. The reservoir data is based on the GRanD reservoir database (Lehner, et al., 2011) and the climate data is based on Kott, et al. (2006).

Reservoir or dam name	*Country*	*Reservoir size (ha)*	*Average reservoir depth (m)*	*Climate*	*Evaporation (mmy^{-1})*		*Evaporation method*	*Study*	*WF of hydro-power production (m^3GJ^{-1})*
Arapuni	New Zealand	4350	3,3	Cfb	844		Measured	Herath et al. (2011)	3
Finchaa	Ethiopia	17960	3,6	Cwh	1650		Measured	Demeke et al. (2013)	208
Guri	Venezuela	366100	36,9	Aw	2787		Modelled – PM[1]	Mekonnen & Hoekstra (2012)	72
					2042		Measured	Córdova (2006)	
Lake Mead	United States	58100	17,5	Dfa	1421 [2]			Pasqualetti & Kelly (2008)	769
					1881		Modelled – EC[3]	Moreo & Swancar (2013)	
Itaipu	Brazil / Paraguay	115650	25,1	Cfa	1808		Modelled - PM	Mekonnen & Hoekstra (2012)	8
Kariba	Zambia / Zimbabwe	527620	35,1	Aw	2860		Modelled - PM	Mekonnen & Hoekstra (2012)	633
Kulekhani	Nepal	130	65,6	Cwa	1574		Modelled - PM	Mekonnen & Hoekstra (2012)	47
Lake Nasser	Egypt	538330	30,1	BWh	3000		Measured	Demeke et al. (2013)	1736
					1700	min	Various	Sadek et al. (1997)	
					2900	max			
Nam Ngum	Laos	43680	16,1	Aw	2411		Modelled - PM	Mekonnen & Hoekstra (2012)	252
					1551		Modelled - PM	Demeke et al. (2013)	15
					1600		Measured		24
Sayano - Shushenskaya	Russia	28240	110,8	Dfc	486		Modelled - PM	Mekonnen & Hoekstra (2012)	4
Three Gorges	China	85290	46,1	Cfa	685		Measured	Zhoa & Liu (2015)	2

[1] = Penman-Monteith
[2] = Determined by dividing the total evaporation volume by the reservoir area
[3] = Eddy-covariance evaporation

Where E_a is the annual actual evaporation volume per reservoir in m^3y^{-1}. A is the reservoir area (ha), K_c is the crop coefficient (-), which is assumed to be 1 for open water and ET_o is the annual evapotranspiration per reservoir (m). The factor 0,4 was used to correct the evaporation volume because reservoirs are not always completely filled and to account for the fact that there was also evaporation from the river, before the creation of the reservoir.

Due to the scale of this study, the results are presented in multiple ways. One way is for a small number of selected reservoirs. These reservoirs are selected based on information availability in the literature, that they are located at different places around the globe, in different climates and that they differ in reservoir size and average depth. Reservoir data, evaporation figures and the water footprint of hydropower generation of these reservoir are presented in table 1.2. The average reservoir area and depth in this table are based on data from the GRanD reservoir database (Lehner, et al., 2011). The Köppen-Geiger climate classification is based on Kottek, et al. (2006).

An analyses done by Bakken et al. (2015), shows that less than 1% percent of the reservoirs from the WRD database (paragraph 2.1), with hydropower as single purpose, is located in water scare areas. The most common purposes for these reservoirs are irrigation, domestic and industrial water supply. Along with flood prevention by reservoirs, these reservoir purposes are considered as needed, because they increase the availability of water in the dry season or prevent flooding in the wet season (Bakken et al., 2015).

1.4.2. Methods to determine the evaporation from reservoirs

There are several methods to determine the evaporation from open water. It is possible to group these methods in five main categories: direct measurement, water balance, methods based on the energy budget of a reservoir, mass transfer methods and methods that combine elements from the energy budget and mass transfer methods (Shaw, 1994; McJannet, et al., 2008).

Direct evaporation measurements are mostly carried out with pans and lysimeters (Shaw, 1994; Mekonnen & Hoekstra, 2012). These measurements are rarely directly used to estimate the evaporation from large open water bodies, because the differences in size and weather conditions (Finch & Calver, 2008) and in most cases conversion factors are used to make good estimations (Allen, et al., 1998).

Methods based on the water balance are widely used to calculate the evaporation from a reservoir (Morton, 1990; Shaw, 1994; Singh & Xu, 1997; Finch & Calver, 2008). The amount of evaporation from a water body, within a certain period, can be determined by measuring the inflow, the outflow and the change in storage of the water body and the difference is the amount of evaporation. This method is simple in theory, but it is difficult the produce useful results in practice (Morton, 1990).

Energy budget methods are based on the required energy that is needed to evaporate water (Shaw, 1994; Xu & Singh, 2000; Rosenberry, et al., 2007; Finch & Calver, 2008). Based on the energy budget of a water body, the amount of evaporation can be determined if all the other energy components of the water body are known. Energy budget methods are suitable and reliable to determine the evaporation from a reservoir within different periods but are only suitable for small reservoirs (Singh & Xu, 1997; Finch & Calver, 2008). Another disadvantage is that the full energy budget equation requires much data and some of this data is difficult to obtain or measure (Shaw, 1994; Finch & Calver, 2008). Examples of energy budget methods are the method of Jensen and Haise, the method of Makkink, the method of Hamon and the method of Blaney-Criddle (Finch & Calver, 2008; Schertzer & Taylor, 2009; Majidi, et al., 2015)

The mass transfer method determines the upward flux of water vapour from the evaporating surface to the atmosphere (Shaw, 1994; Singh & Xu, 1997). All mass transfer methods are based on equation of Dalton, use simple measurable variables, have a simple form and give quite good results in most cases. Examples of the mass transfer method are: the method of Shuttleworth and the method of Ryan-Harleman (Finch & Calver, 2008; Schertzer & Taylor, 2009; Majidi, et al., 2015).

The combination method combines the mass transfer methods and the energy budget method to determine the evaporation from open water. This eliminates the requirement of the surface water temperature. (Shaw, 1994; Finch & Calver, 2008; Majidi, et al., 2015). Examples of energy budget methods are the method of Penman, the method of Penman-Monteith, the method of de Bruin-Keijman and the method of Priestly-Taylor (Finch & Calver, 2008; Schertzer & Taylor, 2009; Majidi, et al., 2015).

1.4.3. Methods to determine the water footprint related to reservoir use.

There are multiple available methods to determine the water footprint of reservoir operation. In this study, the water footprint is determined using the approach described by Hoekstra, et al. (2011). This method corresponds to the methods used by Pasqualetti and Kelley (2008) and Zhoa and Liu (2015), but includes also the water footprint related to reservoir construction.

Other methods to determine the water footprint of reservoir operation are provided by Herath, et al., (2011). They used the gross or consumptive use, the net consumptive use and the net water balance. In the first method, the total volume of evaporation is used (equation 1.2) and this method is conform to the water footprint concept (Hoekstra, et al., 2011) because the water footprint approach uses also the total evaporation volume. The second approach uses also the amount of evaporation (equation 1.3), but compares this with the amount of evapotranspiration from the vegetation before the area was a reservoir. The third method excludes the change in land use, but includes the precipitation in the reservoir (equation 1.4).

$$WF_{gross} = \frac{E_v}{P} \tag{1.2}$$

$$WF_{net} = \frac{E_v - ET_c}{P} \tag{1.3}$$

$$WF_{wb} = \frac{E_v - P_r}{P} \tag{1.4}$$

Where E_v is the annual volume of evaporation in m^3y^{-1}, P is the production unit per reservoir purpose, ET_C is the evapotranspiration from the vegetation before there was a reservoir in m^3y^{-1} and P_r is the precipitation in m^3y^{-1}.

1.5. Scope

This study includes only manmade reservoirs, were both the spatial and economic data is available. Production facilities that are using already exiting water bodies are not included, even if the dam enlarges the water body, because it is not possible to identify to non-natural evaporation from these water bodies. Reservoirs without a full data availability are excluded because it is not possible to determine the water footprint according to the method described by Hoekstra et al. (2011).

To determine the water footprint of reservoirs, both climate and economic data are required. These types of data are not on the same spatial and time scales. For example, the used temperature data is on a four-hour basis, with a spatial resolution of 0,5 arc minutes. While the economic value of agricultural production is determined on an annual basis per nation. However, assumed is that it is possible to combine data that is available on different spatial and time scales.

Electricity, residential and commercial fishing prices are not available for all reservoir purposes in all countries. If data is not available for a certain country, then data from a neighbouring country is used or an average based on neighbouring countries is used. If data is not available, then assumptions are made. These are described in detail in chapter 2. The U.S. Dollar is used as currency and all other currencies are converted using the corresponding exchange rates per year (World Bank, 2015). All economic data is corrected to the 2014 price level using corresponding inflation rates (Williamson, 2015). If data is available in a local currency, in another year then 2014, then first the currency was converted to U.S. Dollar and then the price was corrected to 2014.

1.6. Reading guide

This thesis describes what the water footprint of manmade reservoirs is and how these is determined. Chapter 2 describes which methods and data are used to determine the economic value related to reservoir use, the evaporation from reservoirs and water footprint related to reservoir use. Chapter 3 describes the results for each part of this study. Chapter 4 give the discussion of the used methodology and assumptions. Finally, chapter 5 gives the conclusions and recommendation for further research.

2. Methodology and Data

This chapter provides the data and methodology to determine the economic value of reservoirs, the evaporation from reservoirs, the water footprint related to reservoir construction and the water footprint of reservoir operation.

2.1. Reservoir data

Reservoir data is provided by several reservoir databases (table 2.1.). The most common reservoir databases are: the world register of dams (WRD), provided by the international commission of large dams (ICOLD, 2011), the global dams and reservoirs database (GRanD), provided by Lehner et al. (2011), the global lakes and wetlands database (GLWD), provided by Lehner and Döll (2004) and the dam database provided by AQUASTAT (FAO, 2015). However, the reservoir part of the GLWD is based on the GRanD database.

Table 2.1. The available data per reservoir database.

Data	*Database*			
	WRD	*GLWD*	*GRanD*	*AQUASTAT*
Number of dams and reservoirs.	37500+	654	6854	14216
Reservoir purposes	H, I, C, R, S, F, N, X.	H, I, C, R, S, F, N, P, L, X.	H, I, C, R, S, F, N, P, L, X.	H, I, C, R, S, N, P, L, X.
Average electricity generation	Partly	No	No	No
Average reservoir depth	Yes	No	Yes	No
Dam height	Yes	Yes	Yes	Yes
Dam type and dam body volume	Yes	No	No	No
Electricity generation capacity	Partly	No	No	No
Elevation	Partly	Yes	Yes	No
Flood storage volume	Partly	No	No	No
Irrigated area	Partly	No	No	No
Location of the dam*	No	No	Yes	Yes
Reservoir area	Yes	Yes	Yes	Yes
Reservoir volume	Yes	Yes	Yes	Yes
Reservoir originally a natural lake	No	No	Yes	No
Spatial reservoir data*	No	Yes	Yes	No

*For the reservoir purposes: H: Hydro energy, I: Irrigation, C: Flood prevention, R: Recreation, S: Industrial and residential water supply, F: Commercial fishing, N: Navigation, P: Pollution control, L: Livestock water supply, X: Other. *: The difference between the location of the dam and spatial reservoir data is the spatial reservoir data provides the borders of the reservoir while the dam location is only a single point.*

The most economical reservoir data is provided by the WRD database (table 2.1.). However, the reservoirs in the WRD database are not georeferenced, which is required to determine the evaporation. Reservoir locations are available in the GRanD database and therefore, the WRD database and the GRanD database are combined, based on the name and the country of each dam. In both databases, 4864 dams have exactly the same name and are located in the same country. Beside the exact name, 81 reservoirs were selected based on the alternative dam name in the GRanD database and county. Finally, another 683 dams were selected manually based on minor differences in name, different use of abbreviations and missing words and their nation.

None of the reservoir databases is complete and if data for a reservoir was not available in the WRD database, but is available in the GRanD database, then information from the GRanD database was used. Based on information from the GranD database, reservoirs with a natural origin were excluded from the database. However, most reservoirs with a natural origin are still in the database, because there is no proper information about this subject in both databases. Also river and coastal barrages were excluded, because these structures do not actually store water. Totally, this resulted a usable database of 5502 reservoirs. However, not all required economic data was available for these 5502 reservoir and the final reservoir database only includes 2235 reservoirs with full data availability. The location of these reservoirs is shown in figure 2.1. This corresponds to 3,8% of the reservoirs available in the WRD database and to 30,1% of the total reservoir volume of all reservoirs in the WRD database.

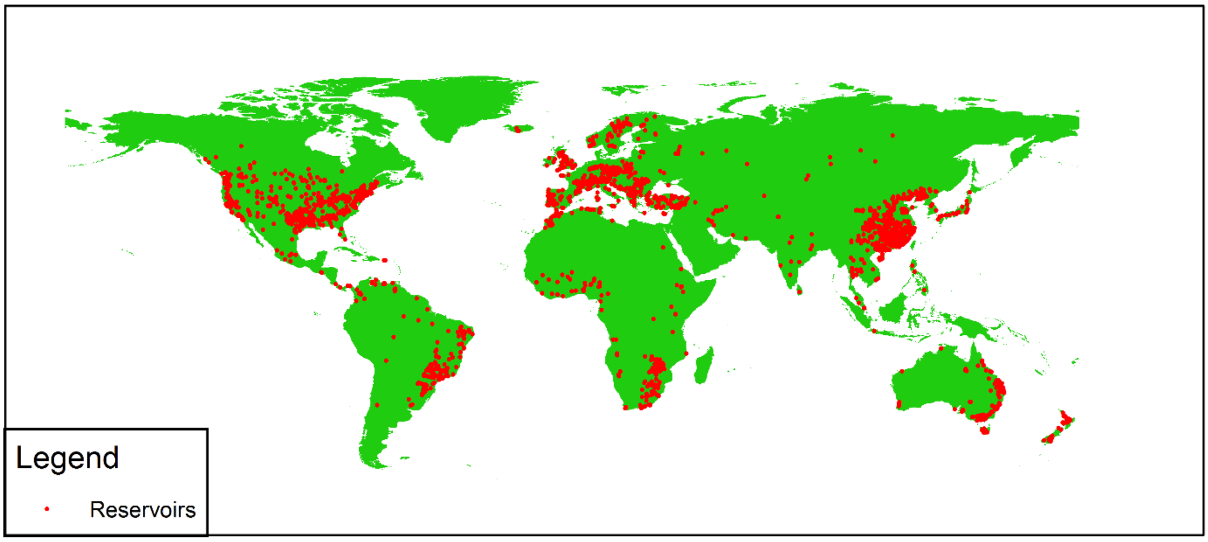


Figure 2.1. The location of the 2235 reservoirs globally.

2.2. Methodology and data to determine the economic value of reservoirs

It is common for a reservoir to have multiple purposes and within the water footprint concept, the water use is allocated to each purpose based on economic value of each purpose. This paragraph describes how the economic value of reservoirs is determined and gives the allocation coefficients to attribute the water use to each reservoir purpose.

The most common reservoir purposes are: generate hydro-electricity, supplying water for residential and industrial use, supply irrigational water, regulate the flow of rivers to prevent flooding and enable inland navigation (U.S. Army Corps of Engineers, 1997; International Commission on Large Dams 2000). Reservoirs are rarely created for recreational and fishing purposes, but after creation these are important secondary purposes (Ward, et al., 1996; Weinin, et al., 2006). Other rare reservoir purposes are pollution control and life stock feeding (Lehner, et al., 2011). In this study navigation is neglected as purpose, because before the reservoir was constructed, the river could have a navigation function. Other purposes are neglected because they are unspecified in the WRD database. The total economic value per reservoir is the sum of the economic value of all reservoir purposes.

Production information for hydropower generation, irrigation and flood control storage are provided by the WRD database per reservoir. For some reservoirs this information is conflicting with the reservoir purpose data, also provided by the WRD database. For example: hydropower generation is not a reservoir function, but for the same reservoir production figures are given. To solve this, hydropower generation, irrigation and flood control storage are recognized as purpose if production data is available. Also if this is not a reservoir purpose according to the WRD.

2.2.1. The economic value of hydropower generation

The generation of electricity is one of the most common reservoir purposes. Energy generated by hydropower plants in considered as renewable energy and hydropower production is the largest supplier of renewable energy (ICOLD, 2000). The economic value of hydropower generation per reservoir is determined, by multiplying the mean annual electrical generation per reservoir (in $GWhy^{-1}$), with the economic value of electricity per country (in $\$kWh^{-1}$).

The WRD database provides the mean annual electricity generation and the production capacity for 984 reservoirs and for another 359 reservoirs, only the production capacity is available. For reservoirs with only the production capacity, the assumption is made that these reservoirs are generating energy 34% of the time on full production capacity. This percentage is based average productivity/production capacity ratio of the first 984 reservoirs. Prices for electric energy are provided by Eurostat (2015), RCREEE (2013), IEA (2012), Statista or local sources for different years (Appendix B). If the electricity price is not available for a country, then prices of neighbouring countries are used to determine an average price for that nation.

2.2.2. The economic value of irrigation water supply

Irrigation water storage is the most common reservoir purpose and globally 48 percent of the reservoirs have this function (ICOLD, 2011). The irrigated area per reservoir (ha) is provided by the WRD database for 763 reservoirs. The economic value of irrigation water supply by reservoirs is determined by multiplying the irrigated area per reservoir with the average economic value of agriculture land per hectare per country ($\$ha^{-1}y^{-1}$).

The average economic value of agricultural land is determined per nation, based on the value of annual agricultural production per crop (in $unit of production$^{-1}y^{-1}$) and the annual harvested area per crop (ha). Both are provided by FAOstat (2015) until the year 2013. Based on the values per crop, one average annual value per hectare per nation is determined. The annual average economic value per hectare per nation are shown in appendix C. Assumed is that the economic value of irrigated land is fully depended of irrigation water.

2.2.3. The economic value of flood control storage

Dams and reservoirs are an effective measure to regulate water levels in rivers and prevent flooding by storing the discharge peaks (ICOLD, 2011). This study only accounts the economic value of flood prevention, because it is not possible to determine the economic value of water level regulation. The economic value of flood prevention is determined by multiplying the available flood storage volume with the economic value of flood storage. The WRD database provides for 648 reservoirs the available flood storage capacity (m^3).

The economic value of flood storage capacity is based on the prevented damage by 23 dams, constructed between 1941 and 1972 in the United states. Annually, the economic value of flood storage capacity for these reservoirs varies between $0,002 to $0,58 per cubic meter, with an average of $\$0,117/m^3y^{-1}$ (appendix D). This is of the same order of magnitude to the value of $0,16 per m^3 provided by Zhoa and Liu (2015) for the Three Gorges reservoir. The determined economic value is used for all reservoirs globally that have flood control as stated purpose.

2.2.4. The economic value of residential and industrial water supply

There is a large variation in the volume of water supplied by nature and to prevent residential and industrial water shortages, water is often stored in reservoirs. The economic value of residential and industrial water supply by reservoirs is determined by multiplying the estimated annual abstracted volume (m^3y^{-1}) with the economic value of residential water per country ($\$m^{-3}$). Water supply prices per cubic meter are provided Danilenko et al. (2014), IWA (2012) and the OECD (2010) for different years. If for a certain country the price is not available, then prices of neighbouring countries are used to determine an average price for that nation. The used prices are given in appendix E.

Figures about the abstraction of water from reservoirs used for residential and industrial water supply are not available. This is estimated based on data from 132 reservoirs in the United States and 30 reservoirs in Australia, the ratio between the amount of abstracted water per reservoir and the reservoir volume is determined. These ratios show a large variation, which is mainly depended on reservoir volume and climate. Small reservoirs in humid climates have a generally high abstraction/volume ratio, while large reservoirs located in arid climates have generally small ratio. Based on these ratios, two exponential formulas, one for humid climates and one for arid climates, are used to estimate the volume abstracted from reservoirs (appendix F).

2.2.5. The economic value of recreation

All over the world, open water is used for recreation (Costanza, et al. 1997). Open water provided by reservoirs are used for swimming, sailing, motor boating, water skiing and recreational fishing (Ward et al., 1996; Bhat et al., 1998). The economic value of recreation is determined by multiplying the economic value of recreation with the reservoir surface. Several scientific sources provide the economic value of open water recreation. However, only the economic value provided per square meter is useful and this is only provided by Costanza, et al. (1997), which gives a value of \$230y^{-1} for open water recreation per hectare in 1994 U.S.\$. This value is used globally because better data is not available. The reservoirs area per reservoir is provided by ICOLD (2011).

2.2.6. The economic value of commercial reservoir fishing

Besides recreational fishing, commercial fishing is an important secondary reservoir purpose. Reservoir facilitate both aquaculture and traditional wild catch fishing (Weimin et al., 2006; van Zwieten, et al., 2011) with aquaculture have a far higher yield compared to traditional fishing. However, the aquaculture yields are not applicable to most reservoirs globally and therefore only wild catch fishing yields are used. Yields are provided per nation for all caught species. The economic value of commercial reservoir is determined by multiplying the fishing yield (kgha^{-1}yr^{-1}) with the reservoir area (ha) and the average price of fresh water fish (\$kg^{-1}). The reservoir area is provided by ICOLD (2011). Both the fishing yield and average price per fresh water fish is provided by multiple sources (appendix G).

2.2.7. Allocation coefficients

For reservoirs with only a single purpose, the amount of evaporation is fully contributed to this purpose. When a reservoir has multiple purposes, an allocation coefficient is required to divide the amount of evaporation among the purposes (equation 2.1).

$$\eta_i = \frac{V_i}{\Sigma V_i} \tag{2.1}$$

Where η_i is the allocation coefficient and V_i is the economic value of a purpose. The sum of all economic values per purposes gives the total economic value of all reservoir purposes.

2.3. Method and data to estimate the evaporation from reservoirs

The evaporation from the 2235 reservoirs with allocation coefficients is determined in four different ways: with a method provided by Kohli and Frenken, with the method of Jensen and Haise, with the method of Hamon, and with a modified version of the Penman method. None of the used methods includes the thermal heat storage in reservoirs, which can result in a deviation in the determined evaporation figure (Finch, 2001). With each of these methods the evaporation is determined on a daily basis. If the daily evaporation was negative, then the evaporation figure was set to zero (Finch & Hall, 2001). The annual reported evaporation is the sum of the daily evaporation for 365 days. The evaporation per reservoir is the average of the annual evaporation determined with the 4 used methods. Each evaporation method is described below together with the used climate data.

2.3.1. The method by Kohli and Frenken

Based on data from the FAO global evapotranspiration map (2004) the evaporation is determined using equation 1.1. The assumed the crop coefficient for open water is 1, this gives an evaporation in mmy^{-1}. With ArcGIS, the annual evapotranspiration was determined for the midpoints of each reservoir.

2.3.2. The method of Jensen and Haise

The method of Jensen and Haise was developed in the early ’60 to determine the water requirements for irrigation projects in the western part of the United States (Jensen & Haise, 1963). However, the method can also be used to determine open water evaporation. This method is chosen because it is simple and has proved to be the most accurate under limited data availability and if data is used from a distant climate station (Winter, et al., 1995; Rosenberry, et al., 2007 and Majidi, et al., 2015). It is an energy budget method and the evaporation is estimated based on solar radiation and average daily temperature, for a minimal period of 5 days (Jensen & Haise, 1963). However, it is also possible to use is for shorter periods of minimal 1 day (Rosenberry, et al., 2007 and Majidi, et al., 2015). The method of Jensen and Haise is given by equation 2.2 (Majidi, et al., 2015).

$$E_d = 0{,}03523 R_s (0{,}014 T_a - 0{,}37) \tag{2.2}$$

Where E is the amount of evaporation in mmday^{-1}, R_s is the incoming solar radiation in Wm^{-2} and T_a the mean daily temperature in F°. If the mean daily temperature is lower than -3,06 °C (26,5 °F) the evaporation becomes negative and the negative daily evaporation figures were set to zero. With Rs in MJm^{-2}d^{-1} , T_a in °C and with a minimal daily temperature, the equation of Jensen and Haise becomes:

$$\begin{aligned} &if\ T_a \geq -3{,}06\ °C\ then\ E = 0{,}4087 R_s\ (0{,}014\ ((1{,}8T_a) + 32) - 0{,}37) \\ &if\ T_a < -3{,}06\ °C\ then\ E = 0 \end{aligned} \tag{2.3}$$

The evaporation was determined per reservoir on a daily basis and the daily figures where summed to an annual evaporation. The required input variables are the mean air temperature and the incoming solar radiation. Equations to determine the incoming solar radiation are provided by appendix H.

2.3.3. The method of Hamon

The method of Hamon (1961) was developed to estimate evapotranspiration on a daily basis, based on the relation between the maximal incoming energy and the moisture capacity of the air (Hamon, 1961; Harwell, 2012; Majidi, et al., 2015). Assumed is that the evaporation from open water is equal to evapotranspiration and a modified version of this method is used within the U.S. Army Corps of Engineers, to estimate evaporation from reservoirs (Harwell, 2012). Equation 2.4 presents the Hamon methods as used to determine daily evaporation in millimetres (Schertzer & Taylor, 2009; Harwell, 2012; Majidi, et al., 2015).

$$E_d = 13{,}97 \left(\frac{N}{12}\right)^2 \left(\frac{SVD}{100}\right) \tag{2.4}$$

Where E is the daily evaporation in mm, N is the maximal number of daylight hours, and SVD is the saturation vapour density in gm^{-3}. Equations to determine the maximal number of daylight hours and the saturation vapour density are provided by appendix H.

2.3.4. The modified Penman method

Penman was the first to combine the mass transfer and energy budget methods (Shaw, 1994; Majidi, et al., 2015). This elimated the need of the surface water temperature to determine the evaporation from open water. In this study, a modified version of the Penmen equation is used. This version was developed by the U.S. weather bureau to estimate lake evaporation based on evaporation from pans (Kohler, et al, 1955; Harwell, 2012). The daily evaporation is estimated based on the average daily air temperature, the average daily windspeed at 10 meter, the dewpoint temperature and solar radiation. Kohler et al. (1955) assumed that the energy storage in reservoirs does not influence the amount of evaporation from reservoirs. Equation 2.5. presents the modified Penman method (Harwell, 2012).

$$E_d = 0{,}7 \left(\frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} E_a\right) \tag{2.5}$$

Where E is the daily evaporation in mm, Δ is the gradient of saturated vapour pressure, γ is the psychrometric constant, R_n is the effective net radiation in mmd^{-1}, E_a is the amount of evaporation from a Class A pan in mmd^{-1}. Equations to determine the effective net radiation and the evaporation from a Class A pan are provided by appendix H.

2.3.5. Climatological data

Climatological data were obtained from the ERA Interim database (Dee, et al., 2011) with a resolution of 0,5 arc minute for the years 1981-2010. The 4 hourly data was averaged to daily figures, because not all variables were available on the same time step. Secondly, one daily average was determined for the 1981-2010 period. Values on mean air temperature, dew point temperature, wind speed in U and V direction and the actual hours of sunshine were obtained for the midpoints point of all 2235 reservoirs.

These reservoir midpoints were determined using ArcGIS and for not all reservoirs the midpoint was located on the water surface. Reservoir attitude, reservoir depth and reservoir area were obtained from the combined WRD and GRanD databases.

The global evapotranspiration map to estimate the reference evaporation was obtained from the FAO (2004) with a resolution of 10 arc minute. The evapotranspiration was determined with ArcGIS, using the reservoir midpoints.

2.4. Method and data to determine the water footprint related to reservoir construction

The water footprint of reservoir construction depends mainly on the construction material of the dam. Earth and rock fill dams are mainly constructed with material that is found in the surrounding area of the construction site (Novak et al., 2007; Chen, 2015). Gravity, buttress and arc dams are mainly constructed of reinforced concrete. Other aspects of reservoir construction like removal of trees and other objects from the reservoir zone are neglected, because the water use during these activities is relatively low.

The water footprint of embankment dams depends mainly on the energy used to excavate the used rock or earth. These materials are excavated in the surrounding area of the construction site (Novak, et al., 2007; Chen, 2015). The assumption is made that the excavation site is located on an average distance of 20 km from the construction site. No useful data is available about the fuel use during excavation works, but one study is done to the CO_2 emissions during excavation works (Ahn, et al., 2009).

During this study 4747 m^3 of earth was excavated, moved over 1 km and dumped with a total emission of 1700 kg CO_2. Diesel is the main fuel used in the construction industry (Ahn, et al., 2009). On average, the CO_2 emission from 1 litre fuel is 2,65 kg (ACEA, 2013), which means that on average, 0,15 l fuel is used to move 1 m^3 of earth over a distance of 1 km. The water footprint of crude oil is 1058 m^3/MJ (Gerbens-Leenes, et al., 2008). Diesel has a calorific value of 45,5 $MJkg^{-1}$ (ACEA, 2013) and a density of 0,84 kgl^{-1} (ISO, 1998), so the water footprint of diesel is 40 l/l. This gives an estimated water footprint for earth or rock moving operations of 6 $lkm^{-1}m^{-3}$. For earth or rock that is excavated 20 km from the construction site, the water footprint is 0,12 m^3/m^3.

Gravity, arc and buttress dams have reinforced concrete as their main construction material. Reinforced concrete is a composite material composed of cement, steel and aggregates. Bosman (2016) gives for Portland cement a water footprint of 415 m^3/m^3 and the water footprint for unalloyed steel is 18254 m^3/m^3. For the aggregates, the water footprint of earth and rock are used. Assumed is that the concrete used in dams, exists out of 1 % steel, 29 % cement and 70 % aggregates, this gives a water footprint of 303 m^3/m^3.

To determine the water footprint of dam construction, only the dam body is included. Other parts of the dam, like the hydro mechanical structures and the electromechanical equipment, are excluded because there is no data available. The design lifespan of de dam body is typically 100 years (Wieland, 2010), which means that the annual water footprint of construction is the construction water footprint divided by 100 years. Assumed is that the full dam volume is filled with the construction material. The volumes of the dam body are provided by ICOLD (2011).

If the dam volume was not available for a certain dam in the database, then the volume of the dam body was estimated based on the dam height and a factor based on the dam construction type (embankment, gravity, buttress or arch dam). The dam type factor is the ratio between the dam volume and the dam height and based on the ratios of the dams with an available dam volume and dam height (appendix I). Table 2.2. gives for all dam types the main construction material and the dam type factor. The dam types are provided by ICOLD (2011).

The water footprint of dam construction is the volume of the dam body multiplied with the water footprint of the construction material. Earth and rock filled dams have in most cases a filter or a concrete element to make the dame water tight (Novak et al., 2007; Chen, 2015). These concrete elements are neglected because no data is available about the volume of these elements.

Table 2.2. Construction material and the dam typed factor to estimate the dam volume.

Dam type	*Construction material*	*Dam type factor*
Embankment dam, earth fill	Earth	71038
Embankment dam, rock fill	Rock	35177
Gravity dam	Reinforced concrete	18027
Buttress dam	Reinforced concrete	6970
Arch dam	Reinforced concrete	2874

2.5. Method to determine the water footprint related to reservoir operation

The water footprint approach described by Hoekstra, et al. (2011) is used to determine the water footprint of reservoir products. Based on the evaporation per reservoir, the annual blue water footprint related to evaporation (WF_E) is determined using equation 2.6. Were E_y is the mean evaporation in mmy^{-1} and A is the reservoir area in ha. Because the area corresponds the maximal reservoir volume, a factor κ is used to correct the reservoir area, to resemble average filling conditions. In this study, κ has a value of 0,5625 and this value is determined in appendix L.

$$WF_E = 10 \times E_y \times A \times \kappa \tag{2.6}$$

To determine the water footprint of a certain product, the whole production process should be taken into account (Hoekstra, et al., 2011). This means that for reservoir products, the water footprint of reservoir construction should be included. So, the total water footprint per reservoir (WF_t) is the sum of the blue water footprint related to evaporation (WF_E) and the water footprint related to reservoir construction (WF_C). This is presented in equation 2.7. The annual water footprint related to reservoir construction is determined per reservoir in paragraph 2.4.

$$WF_t = WF_E + WF_c \tag{2.7}$$

According to the water footprint approach, the water footprint related to a production process should be allocated to each of the products, based on its economic value (Hoekstra, et al., 2011). So, when a reservoir has only one purpose, then the water footprint is totally contributed to that purpose. When a reservoir has multiple purposes, the water footprint is allocated to each purpose based on its economic value. This method is presented in equation 2.8, where WF_P is the water footprint per purpose and η_p is the allocation coefficient per reservoir purpose (-). The methodology used to determine the total economic value of reservoirs and the allocation coefficients is presented in paragraph 2.2.

$$WF_p = WF_t \times \eta_i \tag{2.8}$$

2.6. Method to determine the water footprint related to reservoir operation in the context of water scarcity

Water that evaporates from reservoirs will no longer be available for use downstream of the reservoir. This can make water scarcity more serious, in river basins with already water scarcity problems. Reservoirs with the purposes irrigation water supply and residential and industrial water supply, increase the availability of water in the dry season (Bakken et al., 2015). Secondly, reservoirs prevent flooding by managing the water level in the wet seasons. Reservoirs are the only available 'tool' to provide these products and services and therefore, they are considered as needed (Bakken et al., 2015). Reservoirs with the purposes hydropower generation, recreation and commercial fishing are considered as not needed purposes, because there are alternative ways to produce energy, food or to provided recreational services.

In this analyse is investigated with part of the annual water footprint, related to reservoir operation, is located in river basins per water scarcity level. The water scarcity level per river basin is expressed in number of months with moderate to severe water scarcity. Also is analysed what the water footprint is per reservoir purpose, per water scarcity level. The number of months with moderate, significant or severe water scarcity per river basin, are provided by Hoekstra and Mekonnen (2011). In the study of Hoekstra and Mekonnen, a river basin is considered moderate, significant or severe water scare, if the blue water footprint is higher than 20% of the natural runoff. If the blue water footprint is lower than 20% of the natural runoff and does not exceed the blue water availability, then the blue water scarcity is classified as low. Only 71% of the reservoirs in this study is located in river basins treated in the study of Hoekstra and Mekonnen (2011). The other 29% of the reservoirs are excluded from this analyses.

3. Results

In this chapter, the results are presented per sub question. So, in the first paragraph the results are presented of the economic study. In the second paragraph the results are presented of the evaporation part of this study. The third paragraph presents water footprint related to reservoir operation. In the last paragraph, the water foot print related to reservoir operation in the context of water scarcity is presented.

3.1. Economic value of reservoirs and allocation coefficients

The total annual economic value of the reservoirs in this study are $ 311 billion in 2014 U.S. dollars. In table 3.1. the total economic value and allocation coefficients are presented per continent. In general, most economic value is generated by hydropower generation, irrigation water supply and residential and industrial water supply. Interesting is the low economic value of the reservoirs in this study in North America compared to the number of reservoirs. Table 3.2. shows the total economic value and allocation coefficients for 11 selected reservoirs.

Table 3.1. The total annual economic value and allocation coefficients per continent and globally.

	Number of reservoirs	*Total economic value (mln US$\$y^{-1}$)*	*Allocation coefficients per purposes*					
			H	*I*	*P*	*R*	*S*	*F*
Africa	203	$20.064	19%	15%	30%	0,0%	36%	0,0%
Asia	653	$93.539	21%	52%	17%	0,1%	10%	0,9%
Europe	519	$53.708	19%	3%	13%	0,0%	65%	0,0%
North America	549	$30.686	20%	0%	0%	0,7%	80%	0,0%
Oceania	171	$24.684	9%	3%	0%	0,0%	88%	0,0%
South America	140	$88.135	77%	0%	1%	0,1%	22%	0,0%
Global	2235	$310.818	35%	17%	9%	0,1%	38%	0,3%

For the reservoir purposes: H: Hydro energy, I: Irrigation water supply, P: Flood prevention, R: Recreation, S: Industrial and residential water supply, F: Commercial fishing

Table 3.2. The total annual economic value and allocation coefficients per purpose, for 11 selected reservoirs.

Dam or reservoir name	*Total economic value (mln US$\$y^{-1}$)*	*Allocation coefficients per purposes*					
		H	*I*	*P*	*R*	*S*	*F*
Arapuni	$ 90	85%	15%				
Finchaa	$ 20	100%					
Guri	$ 1.612	100%					
Lake Mead	$ 713	85%[1]			0%	15%	
Itaipu	$ 7.560	100%					
Kariba	$ 576	100%					
Kulekhani	$ 14	100%					
Lake Nasser	$ 8.031	4%	28%	68%			
Nam Ngum	$ 35	100%					
Sayano-Shushenskaya	$ 1.279	100%					
Three Gorges	$ 6.907	51%		37%	0%	9%	3%

For the reservoir purposes: H: Hydro energy, I: Irrigation water supply, P: Flood prevention, R: Recreation, S: Industrial and residential water supply, F: Commercial fishing. [1]: The WRD does not gives data hydropower generation data for the Hoover dam. Therefore, data from Pasqualetti & Kelley (2008) is used to determine te economic value and allocation coefficients for the Hoover dam.

The results for the Three Gorges reservoir are compared with the annual averaged economic value and allocation coefficients available for this reservoir (Zhoa & Liu, 2015). This is the only comparable study, were the economic value per reservoir purpose is known. According to the WRD database, the reservoir purposes of the Three Gorges reservoir are hydropower generation, irrigation, flood control storage and commercial fishing. This does not correspond to the purposes gives by Zhoa and Liu (2015). So, the purposes provided by Zhoa and Liu (2015) are used, because this gives an opportunity to compare the results. For the purposes hydropower generation, flood control storage and commercial reservoir fishing, the determined annual economic value are within the range of the “real” economic value (figure 3.1). The economic value of recreation is underestimated, which is probably caused by the used global average economic value of open water recreation. The economic value of residential and industrial water supply is heavily overestimated, which is mainly caused by relatively low water supply abstraction from the Three Gorges reservoir compared to the size. The determined total economic value of the Three Gorges reservoir is of the same order of magnitude as the total economic value determined by Zhoa and Liu (2015).

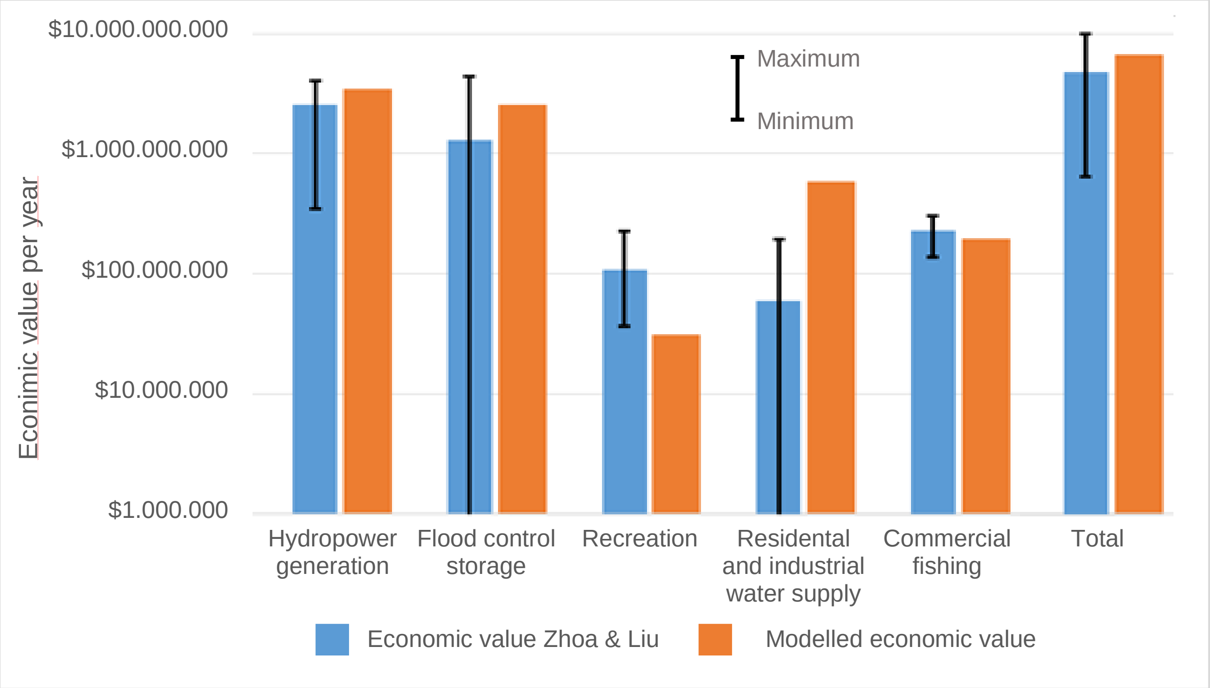


Figure 3.1. The modelled and annual economic value per purpose for the reservoir of the Three Gorges dam, provided by Zhoa and Liu (2015). Zhoa and Liu presents the economic value for multiple years. Therefore a minimum and a maximum economic value is given. The minimum economic value for flood control storage and residential and industrial water supply is $0,-. The total economic value provided by Zhoa and Liu includes also the economic value of navigation on the three Gorges dam.

3.2. Evaporation from reservoirs

The total annual evaporation volume from the 2235 reservoirs in this study is 1,04 x 10^{11} m^3. Table 3.3. shows the minimal, mean and maximal total evaporation volumes from reservoirs in this study per continent. The mean total evaporation volume is the mean of the four used evaporation methods, while the minimal and maximal evaporation volume are provided by a single method. For all continents, the minimum evaporation volume is determined with the method of Hamon and the maximal evaporation volume is determined by the Penmen method.

In table 3.4 the evaporation figures for 11 selected reservoirs are presented for each used evaporation method, as average of these methods and together with evaporation figures from the literature. From most of the selected reservoirs, the evaporation provided by the literature is of the same order of magnitude as the determined evaporation figures. Exceptions are Lake Mead, the Kariba dam and the Three Gorges dam.

Table 3.3. The evaporation volume from reservoirs per continent and globally.

	Minimal evaporation volume ($10^9\ m^3y^{-1}$)	*Mean evaporation volume* ($10^9\ m^3y^{-1}$)	*Max evaporation volume* ($10^9\ m^3y^{-1}$)
Africa	19,7	28,9	38,7
Asia	16,2	22,4	30,4
Europe	2,4	2,7	3,4
North America	4,0	6,2	7,9
Oceania	1,5	2,2	2,8
South America	27,8	42,0	55,0
Global	76,1	104,4	138,2

Table 3.4. The reservoirs evaporation for 11 selected reservoirs.

Dam or reservoir name	*Evaporation in mmy*$^{-1}$					
	Kohli & Frenken	*Jensen-Haise*	*Hamon*	*Penman*	*Mean*	*Literature (table 2.2)*
Arapuni	755	843	624	944	792	844
Finchaa	1340	1572	826	1765	1376	1650
Guri	1556	2407	1210	2524	1924	2042
Lake Mead	1013	1086	661	1334	1024	1652[a]
Itaipu	1248	1903	1042	1988	1545	1808
Kariba	1693	2017	1212	2666	1897	2860
Kulekhani	1032	1799	910	2181	1481	1574
Lake Nasser	2643	2152	1435	3947	2544	2350[a]
Nam Ngum	1362	2149	1114	2114	1685	1710[a]
Sayano - Shushenskaya	584	427	363	622	499	486
Three Gorges	875	1233	767	1257	1033	685

[a]: average of the minimal and maximal values from table 2.2

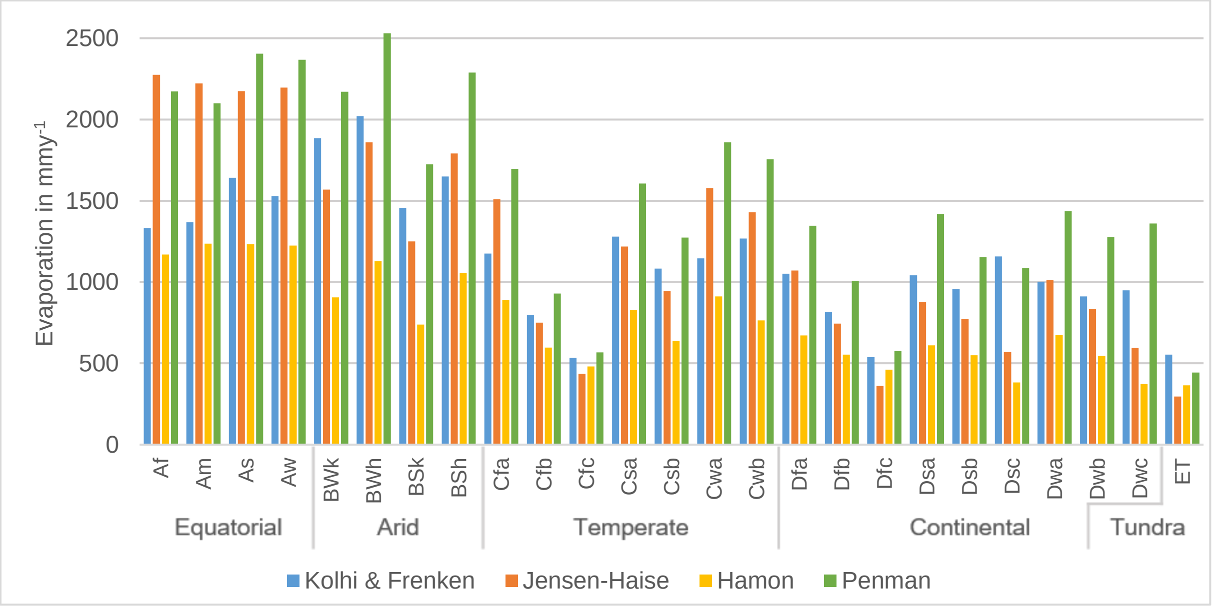


Figure 3.2. The average evaporation per climate Köppen-Geiger climate class (Kottek, et al., 2006), for the four used evaporation methods. The main climates classes are shown below the climate classes.

Figure 3.2 shows the average evaporation per climate Köppen-Geiger climate class (Kottek, et al., 2006), for the evaporation methods used in this study. In general, the modified Penman method gives the highest evaporation figures, while the Hamon method produces the lowest evaporation figures. It is known that the original Hamon method tends to underestimates the evaporation (Harwell, 2012; Majidi, et al., 2015). For warm arid climates (BWh and BWk) the modified Penman gives very high evaporation figures compared to the other used methods. This is also visible in the evaporation values for lake Nasser in table 3.4. The method of Jensen and Haise gives high evaporation figures for equatorial climates (Af to Aw). A possible reason for this is that this method was originally developed for more arid regions (Jensen & Haise, 1963).

Figures 3.3. to 3.5. show for three individual reservoirs, the monthly evaporation determined with three evaporation methods and compares it with literature data. The method of Kolhi and Frenken is not used because it gives only annual evaporation data. Reservoirs are selected based on data availability in both the literature and the used reservoir database. For the reservoir of the Guri dam (figure 3.3.), the evaporation data is provided by Códova (2006) for the year 2002. For the whole year the evaporation provided by Códova (2006) is located between the higher and lower evaporation estimations.

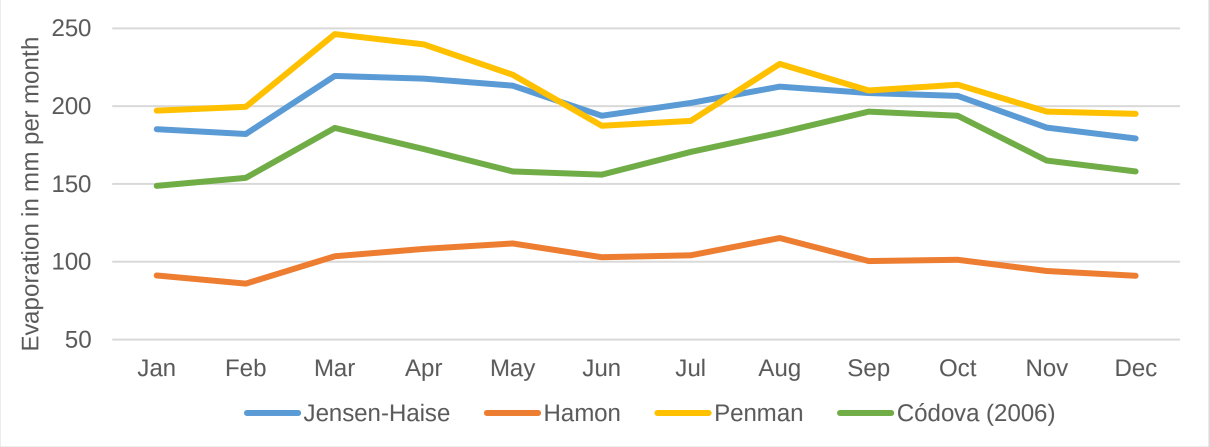


Figure 3.3. The monthly evaporation for the reservoir of the Guri dam per evaporation method, these figures are compared with evaporation figures provided by Códova (2006) for the year 2002.

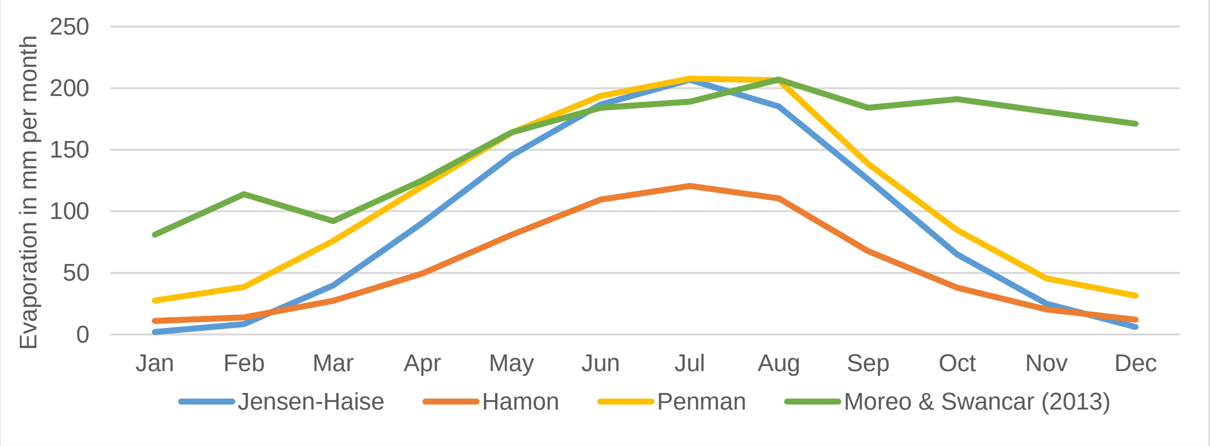


Figure 3.4. The monthly evaporation for lake Mead per evaporation method, these figures are compared with evaporation figures provided by Moreo and Swancar (2013) for the year 2012.

For lake Mead (figure 3.4.), the evaporation data is provided by Moreo and Swancar (2013) for the year 2012. Between March and August, the evaporation determined with the Penman method is almost the identical to the provided evaporation data. However, for the other months, the determined evaporation figures are lower than the evaporation provided by Moreo and Swancar (2013). For lake Mead, a possible explanation for this difference is that the literature data is for just a single year, while this study uses the annual averaged climate data over 30 years. For lake Nasser (figure 3.5.), the evaporation data is provided by Omar and El-Bakry (1980) for the year 1971. Between January and April, the evaporation determined with the method of Jensen and Haise is almost the same as the provided evaporation data. However, for the other months, the evaporation provided by Omar and El-Bakry (1980) is located between the higher and lower evaporation estimations.

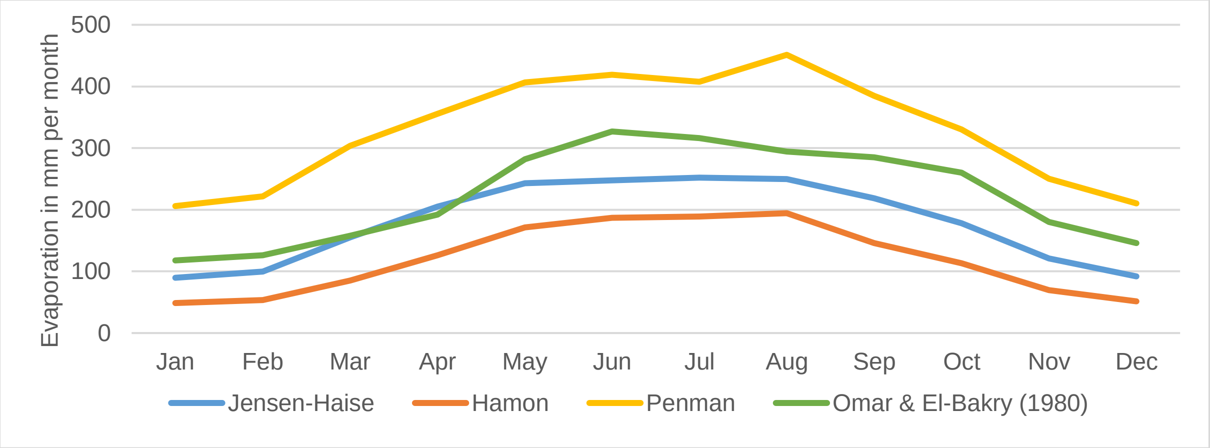


Figure 3.5. The monthly evaporation for lake Nasser per evaporation method, these figures are compared with evaporation figures provided by Omar and El-Bakry (1980) for the year 1971.

3.3. The water footprint related to reservoir operation

The total annual water footprint from the 2235 reservoirs in this study is 1,04 x 10^{11} m^3. Table 3.5. shows the total annual water footprint and the water footprint related to reservoir construction per continent and globally. Table 3.3. shows the both the minimal and the maximal evaporation estimations per continent. The total annual water footprint of the reservoirs in this study, related to reservoir construction is 3,95 x 10^7 m^3. In general, the water footprint related to reservoir construction is very small compared to the total water footprint. This is the case for all reservoirs in this study.

Table 3.5. The total water footprint related to reservoir operation and the water footprint related to reservoir construction per continent.

	Mean total WF (10^9 m^3y^{-1})	*WF related to reservoir construction (10^5 m^3y^{-1})*
Africa	28,9	3,8
Asia	22,4	334,0
Europe	2,7	7,4
North America	6,2	46,2
Oceania	2,2	1,8
South America	42,0	3,5
Global	104,4	396,7

Table 3.6. The total water footprint per reservoir purpose per continent for the reservoirs in this study.

	Hydropower generation (10⁸ m³)	*Irrigation (10⁸ m³)*	*Flood prevention (10⁷ m³)*	*Recreation (10⁷ m³)*	*Water supply (10⁸ m³)*	*Commercial fishing (10⁶ m³)*
Africa	172,0	38,0	689,1	13,1	7,7	7,7
Asia	126,9	33,6	147,9	0,8	47,1	124,0
Europe	10,6	4,4	11,1	0,8	9,0	0,1
North America	9,8	-	-	180,0	34,0	7,6
Oceania	7,7	6,3	0,4	0,5	8,2	-
South America	391,1	0,5	21,4	6,3	25,9	-
Global	718,1	82,8	869,9	201,5	131,9	139,4

Table 3.6. gives the total annual water footprint per reservoir purpose, per continent and globally. These results can be compared to the water footprint of humanity, determined by Hoekstra and Mekonnen (2012). They determined that the blue water footprint related to crop production is 899 x 10^9 m^3y^{-1} and that the water blue water footprint related to domestic and industrial water supply is 80 x 10^9 m^3y^{-1}. However, Hoekstra and Mekonnen did not include the water footprint related to water storage in reservoirs. This means that the blue water footprint related to crop production, should be 1% higher and the blue water footprint related to domestic and industrial water supply should be 16 % higher, if the results for the reservoirs in this study should be included.

Table 3.7. shows the mean water footprint per unit of production per purpose. The results per purpose are not comparable due to different units and if the same units are used, they mean different things. Hydropower generation is presented in the volume of water used to generate 1 GJ electricity. Irrigation water supply is presented as the volume of water used to irrigate 1 ha of irrigated area. Water management to prevent flooding, is presented as the volume of water used to store 1 cubic meter of water. Recreation is presented as the volume of water used to recreate on 1 ha of reservoir area. Residential and industrial water supply is presented as the volume of water used store 1 cubic meter of water. Commercial fishing is presented as the volume of water used per ton of caught fish.

Table 3.7. The global mean water footprint per unit of production per reservoir purpose, for the minimal, the mean and the maximal evaporation volume. The ranges in the right half of the table are with respect to the median.

Reservoir purpose	*Min. E. volume*	*Mean E. volume*	*Max. E. volume*	*Within 66% range*		*Within 95% range*	
				min	*max*	*min*	*max*
Hydropower gen. (m^3GJ^{-1})	15	21,5	28	0,34	12,2	0,03	263
Irrigation (m^3ha^{-1})	334	515	724	100	2061	20	13644
Flood control (m^3m^{-3})	0,021	0,035	0,053	0,003	0,051	0,001	0,434
Recreation (m^3ha^{-1})	1301	1952	2522	16,7	6591	1,1	8726
Water supply (m^3m^{-3})	0,119	0,169	0,219	0,017	0,193	0,005	0,601
Fishing (m^3ton^{-1})	0,78	1,09	1,44	0,11	1,15	0,05	24,3

In table 3.7., the water footprint per unit of production per purpose is shown for the evaporation method that gives the lowest evaporation volume, for the mean evaporation volume of the 4 used methods and for the method that estimates the largest evaporation volume. The water footprint per unit of production per purpose is determined by dividing the global production per purpose for the reservoirs in this study, by the total amount of evaporation allocated to that purpose. The ranges shown in the right half of table 3.7., show the minimum and maximal value, for the 66% and 95% ranges, with respect to the median. This means that 66% of the reservoirs in this study, with hydropower generation as purpose for example, has a water footprint per unit of production, that is located between the minimum and maximum value of the range. The same applies to the 95% range.

Table 3.8. shows the water footprint per economic unit and the productivity for the evaporation method that gives the lowest evaporation volume, for the mean evaporation volume of the 4 used methods and for the method that estimates the largest evaporation volume. The water footprint per economic unit is determined as the total water footprint per purpose for the reservoirs in this study, divided by the total economic value per purpose in 2014 U.S. dollar. The water productivity is the opposite as the mean water footprint per economic unit. Compared to the prices of residential and industrial water supply, the productivity presented in $/m^3 is for most purposes high except for recreation.

Table 3.8. The minimal, mean and maximal WF per economic unit per purpose and the minimal, mean and maximal economic productivity.

Reservoir purpose	*WF per economic unit ($m^3\$^{-1}$)*			*Productivity ($\$m^{-3}$)*		
	Min. E. volume	*Mean E. volume*	*Max. E. volume*	*Min. E. volume*	*Mean E. volume*	*Max. E. volume*
Hydropower generation	0,46	0,66	0,85	1,17	1,52	2,18
Irrigation	0,10	0,15	0,22	4,62	6,50	10,03
Flood control	0,18	0,30	0,45	2,22	3,31	5,49
Recreation	3,54	5,30	6,85	0,15	0,19	0,28
Water supply	0,08	0,11	0,14	6,91	8,92	12,72
Commercial fishing	0,17	0,24	0,32	3,14	4,13	5,80

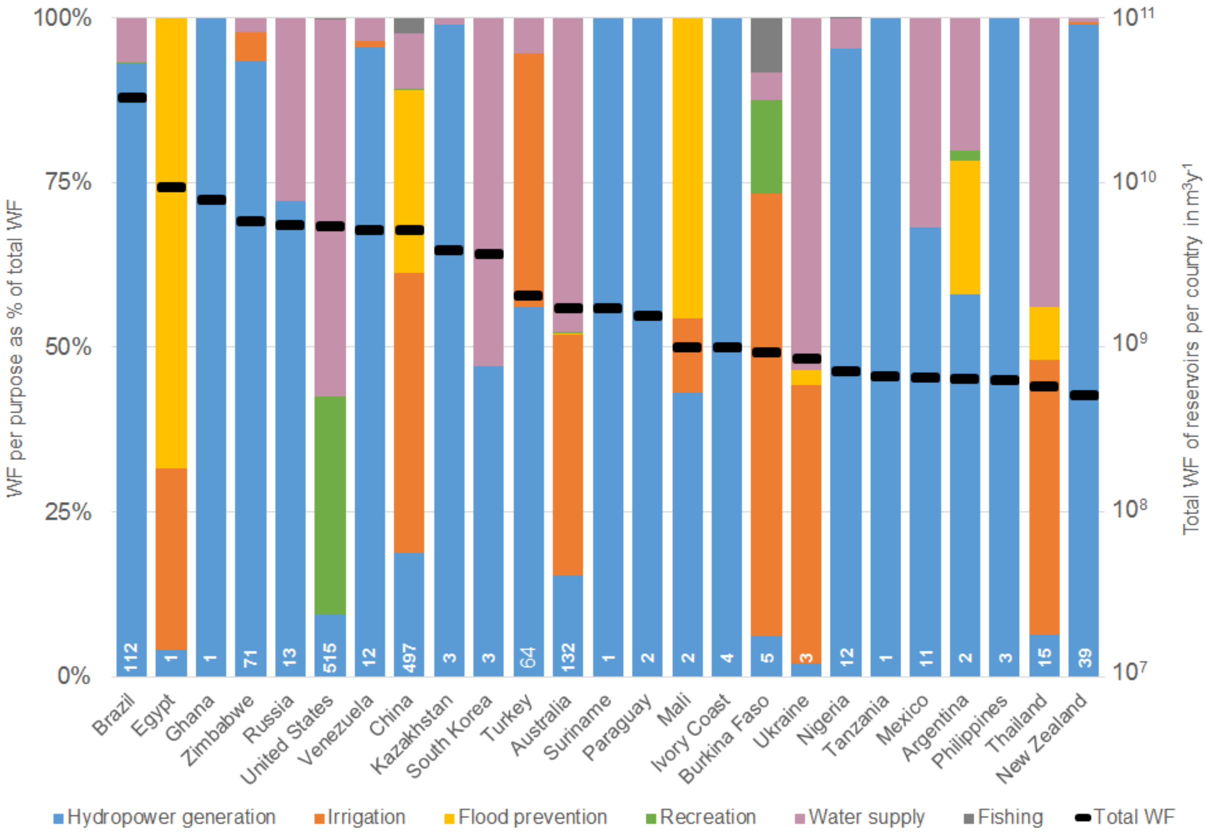


Figure 3.6. The total water footprint related to reservoir operation and percentage of the total water footprint per purpose for of 25 selected countries. The numbers on the bottom of each bar are the number of reservoirs per country included in this analyse.

Figure 3.6 shows the total water footprint related to the use of reservoirs, per country and the percentage of the total water footprint per reservoir purpose for 25 selected countries. These countries are selected based on the largest total water footprint related to reservoir operation. Brazil has the largest total water footprint related to the use of reservoirs for the reservoirs in this study. For some countries only one reservoir is included and for all cases this corresponds to a very large reservoir combined with a high evaporation figure. For example: for Egypt, Lake Nasser, for Ghana Lake Volta and for Suriname, the Brokopondo reservoir. The total water footprint related to reservoir operation of Zimbabwe is largely influenced by the water footprint of the Kariba reservoir.

Figure 3.7 presents the average water footprint for hydropower production, per unit of production for selected countries, for the reservoirs in this study. For this purpose, Suriname has the highest mean water footprint and this caused by evaporation from the Brokopondo reservoir. China has the lowest average water footprint for hydropower generation per unit of production. The average water footprints per country for the other reservoir purposes are available in the appendix K.

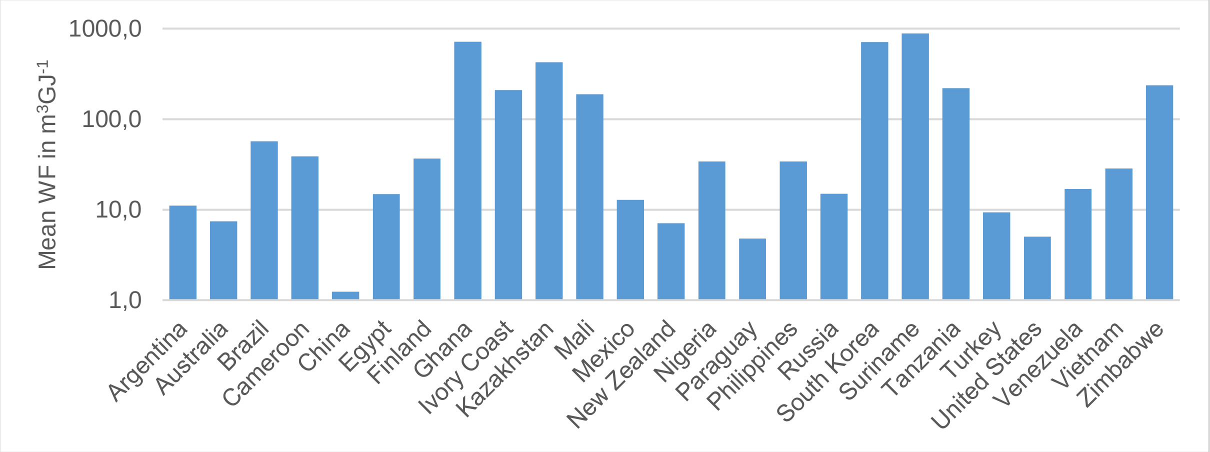


Figure 3.7. The average water footprint of hydropower production for selected countries.

3.4. The water footprint related to reservoir operation in the context of water scarcity

The largest part of the annual water footprint related to reservoir operation, for the reservoirs in this study, is located in river basins with a low water scarcity level (figure 3.8). A further 34% of the annual water footprint related to reservoir operation, for the reservoirs in this study, is located in river basins with 1 to 3 months moderate to severe water scarcity. Seven percent is located in river basins with 4-6 months water scarcity and 3% in river basins with 7-11 months water scarcity. Only 1% of the annual water footprint related to reservoir operation, for the reservoirs in this study, is located in river basins with 12 months moderate to severe water scarcity.

Figure 3.9 shows the percentage of annual water footprint, related to the use of reservoirs, per reservoir purpose, per water scarcity level. In river basins with a low water scarcity level, the largest part of the water footprint is allocated to hydropower generation. However, the importance of this purpose decreases is the water scarcity level increases. In river basins with more than 9 months of moderate, significant or severe water scarcity, the largest part of the water footprint related to reservoir use is allocated to residential and industrial water supply.

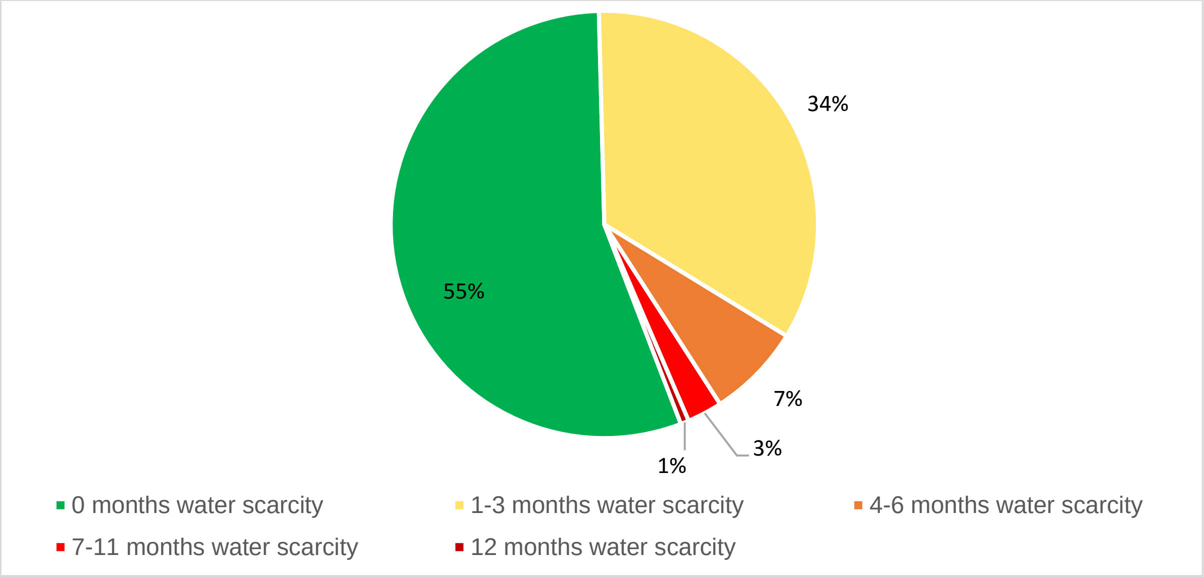
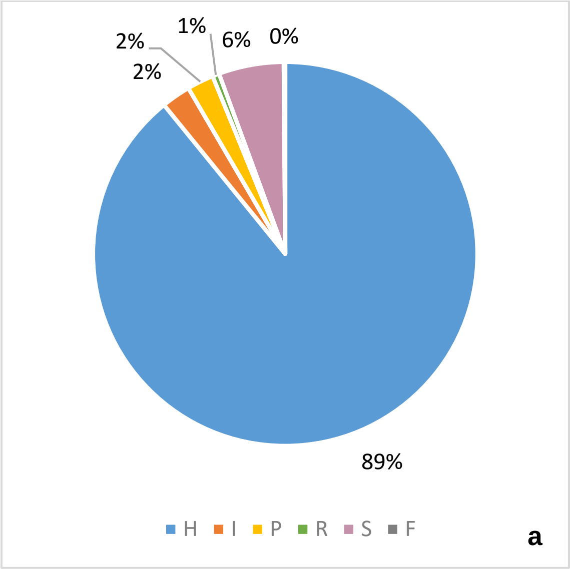
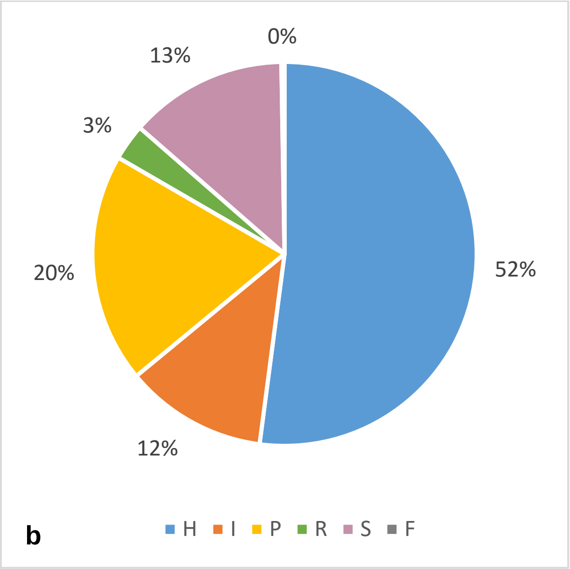
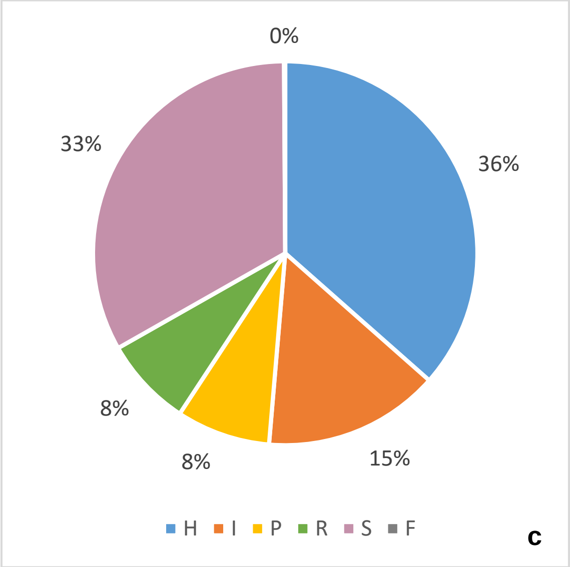
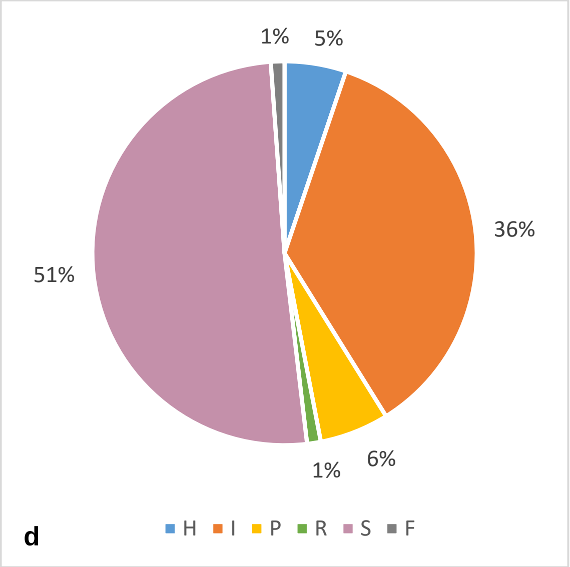


Figure 3.8. Percentage of the total global water footprint located in river basins per number of months with moderate, significant or severe water scarcity.









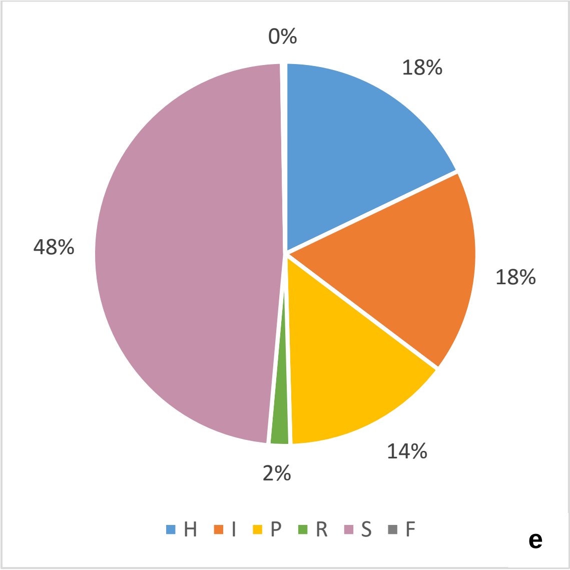


Figure 3.9. a: percentage of total water footprint per purpose for reservoirs located in river basins with 12 months low water scarcity, **b:** percentage of total water footprint per purpose for reservoirs located in river basins with 9 to 11 months low water scarcity, **c:** percentage of total water footprint per purpose for reservoirs located in river basins with 6 to 8 months low water scarcity, **d:** percentage of total water footprint per purpose for reservoirs located in river basins with 1 to 4 months low water scarcity, **e:** percentage of total water footprint per purpose for reservoirs located in river basins with 0 months low water scarcity. For the reservoir purposes: H: Hydro energy generation, I: Irrigation water supply, P: Flood prevention, R: Recreation, S: Industrial and residential water supply, F: Commercial fishing.

4. Discussion

Within this study are several points of discussion and these are mainly related to the used data, the made assumptions, the used method and some of the results. The points of discussion are described in this chapter.

The WRD database was used as main source of reservoir data, but the information in this database is not consistent. For each reservoir, the reservoir purposes are provided and for some reservoir purposes the production data is also provided. However, in some cases production figures are provided for a purpose, while that purpose is not listed as a purpose in the database. For some reservoirs, the data provided by the WRD database does not match with data provided by the GRanD database. The connection between the WRD database and the GRanD database is made based on dam name and the country where the dam is located. However, it is possible that within a single country there are 2 reservoirs with the same name. This will result in the wrong climatological data for that reservoir.

Because not all production or price data was available for each reservoir purpose, estimations and assumptions were made (paragraph 2.2). These estimations or assumptions can result of over or underestimations. Within this study, one national price was used for both electricity and residential water supply. In most cases this was the average price for that country (Danilenko, et al., 2014; Eurostat, 2015). Because these prices varie within a country, the economic value can be over- or underestimated for reservoirs on a local scale. The economic value of flood storage in reservoirs is based on the economic value of flood storage in the United States. This can result in an over- or underestimation of the economic value of flood prevention for other countries. The drink water abstraction from reservoirs is estimated based on the reservoir volume and climate class. However, it is possible that in reality the abstraction is higher or lower than estimated. Secondly, the abstraction can vary annually (Zhoa & Liu, 2015).

Some reservoirs are located in multiple countries. However, the WRD database provides only the main country. For the economic analyses, only the production figures and prices for these counties are used. This can result on a deviation because the wrong prices are used for a part of the production. Assumed is that products and services produced by reservoirs are not exported.

In this study the full economic value of irrigated agriculture is used to determine the economic value of irrigation water supply. This is in most cases an overestimation because it excludes the labour, land and fertilizer from the agricultural production costs. For reservoirs with recreation as purpose, one global average economic value is used to determine the economic value of that purpose. Because this value is based on reservoirs in the United States, it can result in an over- or underestimation of the economic value of recreation in other nations. Navigation is not considered as a reservoir purpose because it is possible the navigate the river before the reservoir was created. However, after the creation of a reservoir, larger and more ships can use the reservoir as waterway and the transport over the waterway can increase (Wang, et al., 2014). This increases also the economic value of the waterway and so of the reservoir.

The climatological data is extracted from the ERA Interim database for the midpoint of each reservoir. The ERA Interim database consist of a grid, with a spatial resolution of 0,5 arc minute. It is possible for large or elongated reservoirs that these are located in multiple grid cells. This means that for parts of the reservoir other climatological conditions are applicable then the used conditions. This can result in a deviation in the estimated evaporation. Assumed is that the reservoir area is constant over the year, but in reality the reservoir area varies over the year. For most climates this is not the case in the largest area is reached in spring, while the reservoir area will be on its smallest in autumn. Because in most climates the highest evaporation rates are reached in the end of the summer, this will overestimate the evaporation from reservoirs.

The original version of the Hamon method was used in this study to estimate the evaporation from reservoirs. This method is also in use with the U.S. Army corps of engineers (Harwell, 2012), but they added a reservoir specific factor to estimate the evaporation. It is known from the original Hamon method that it underestimates the evaporation (Harwell, 2012; Majidi, et al., 2015). None of the used evaporation methods includes the energy storage in the reservoir. For deeper reservoirs, which have in general a large energy storage capacity, this can result in a deviation of the estimated evaporation (Finch, 2001).

To determine the water footrpint related to reservoir construction, the dam body volume was estimated based on dam height, if the dam body volume was not provided by the WRD database (paragraph 2.4). However, the dam body volume depends also on dam length. So, for some reservoirs, this resulted in an over- or underestimation of the dam body volume.

Within this research project the water footprint methodology (Hoekstra, et al., 2011) is used to determine the water use by reservoirs. According to Herath, et al. (2011) there are two more methods to determine the water use by reservoirs (subparagraph 1.4.3.). Using these methods will result in a lower water footprint per reservoir purpose, compared to the methodology by Hoekstra, et al., (2011).

For some of the reservoirs in this study, the evaporation figures provided by the literature are much higher or lower, compared with the figures estimated within this study. A possible explanation for these differences is that another evaporation method is used to determine the evaporation. The evaporation part of this study had shown that a factor two difference between two evaporation methods is not uncommon. Secondly, the mean climatological data is used for the location for a period of 30 years, while the most available evaporation studies focus only on a single year.

Some of the results presented in figures 3.2., 3.6. and 3.7 are based on a single reservoir, or are largely influenced by a single reservoir. For example, the reservoir of the Kariba dam accounts for 95% of the water footprint related to reservoir evaporation of Zimbabwe. Results based on a single reservoir can influence the general picture outlined in the figure.

If the production of a product by a reservoir is relatively low compared to its size, then this will result in a water footprint per unit of production that is approaching infinity. Results that are approaching infinity, will affect the presented mean water footprint of production. This is shown in table 3.7. because the water footprint per unit production for hydropower generation is not located within the 66% range.

It is complex to present the water footprint per unit of production per reservoir purpose. If the production of a product or service by a reservoir is relatively low of high, compared to its size, this will result in a water footprint per unit of production that is approaching zero or infinity. The water footprints that are approaching infinity, are influencing the global mean water footprint per unit of production. Therefore, the global mean water footprint per unit of production is in most cases not applicable on induvial reservoirs. It is better to present the water footprint per unit of production as a range, something what is done in this study.

5. Conclusion and recommendations

In this chapter, the conclusions of this study are drawn. Secondly, recommendations are given to improve further research and to reduce the water footprint related to reservoirs operation.

5.1. Conclusions

In this study, the water footprint is determined for the products and services provided by 2335 reservoirs globally. The sub question where answered for each reservoir individually, but due the large number of reservoirs it is not possible to draw conclusions for each reservoir. Therefore, conclusions are drawn in the same manner as the results are presented.

It can be concluded that all reservoir purposes treated in this study have a water footprint. The total annual water footprint from the reservoirs in this study is 1,04 x 10^{11} m^3 and the total annual economic value of the reservoirs purposes in this study is $ 311 billion, in 2014 U.S. Dollars. The total annual water footprint related to reservoir construction is 3,96 x 10^7 m^3. The global water footprint related to: hydropower generation by reservoirs is 7,18 x 10^{10} m^3y^{-1}, for irrigation water supply by reservoirs is 8,28 x 10^9 m^3y^{-1}, for flood prevention by reservoirs is 8,7 x 10^9 m^3y^{-1}, for open water recreation on reservoirs is 2,01 x 10^9 m^3y^{-1}, for residential and industrial water supply by reservoirs is 1,32 x 10^{10} m^3y^{-1} and for commercial fishing on reservoirs is 2,08 x 10^8 m^3y^{-1}.

The productivity per cubic meter evaporation per purpose is for all reservoir purposes high except for reservoir recreation, compared to the prices of residential and industrial water supply. This means that the products and services provided by reservoir are important from a social point of view.

Of all countries in this study, Brazil has the largest annual water footprint related to reservoir operation. This is mainly caused by a number of large reservoirs in combination with an equatorial climate. Some very large reservoirs, for example lake Nasser, lake Volta, the reservoir of the Kariba dam and the Brokopondo reservoir, have water footprints that are higher than water footprints related to reservoir operation for complete countries. The differences in water footprint can be partly explained by the location of the reservoir. Reservoirs located in equatorial and arid climates have in general a higher evaporation figure then reservoirs located in other climates.

Within this study, 4 evaporation methods are used to determine the evaporation from reservoirs. For most reservoirs, the method of Hamon is underestimation the evaporation and the method of Penman is overestimating the evaporation. The method of Jensen and Haise tends to overestimate the evaporation in equatorial climates.

The largest part of annual water footprint related to reservoir operation, is located in river basins with a low water scarcity level and the main reservoir purpose in these reservoirs is hydropower generation. A smaller part, 44%, of the water footprint related to reservoir operation is located in river basins with 1 to 11 months of water scarcity and the importance of hydropower as reservoir purpose decreases as the number of months with moderate to severe water scarcity increases. Only 1% of the water footprint of the reservoirs in this study is located in river basins with 12 months moderate to severe water scarcity. For these reservoirs, residential and industrial water supply is the main purpose.

In river basins with a high water scarcity level, residential and industrial water supply, irrigation water supply and flood prevention by reservoirs are the main reservoir purposes. Reservoirs constructed for these purposes are considered as needed. Only a very small part of the water footprint related to reservoir operation is allocated to reservoir purposes that are considered as not needed.

5.2. Recommendations for further research

To improve the quality and the accuracy of this study, the following further research is recommended:

This study only includes 6 reservoirs purposes and there are still some purposes missing. Of the missing purposes navigation is the most imported. Including these purposes would result in a more accurate study. Also is recommended to determine the economic value of flood prevention by reservoirs and recreation on reservoirs from multiple countries.

Recommended is to expand the WRD database with spatial data for at least the location of the dam and with the water abstraction from reservoirs for residential and industrial water supply. Expected is that both the location of the dam and the water abstraction for residential and industrial water supply is known by the government agencies that compose the ICOLD database. Also is recommended to improve the quality of the ICOLD database. There are still multiple reservoirs within the database where the purposes and the production figures contradict each other.

Multiple evaporation methods are used in this study, to estimate the evaporation from reservoirs. This because there is no standardised open water evaporation method available, to estimate the evaporation from multiple water bodies on a global scale. Secondly, there no study available that compares different open water evaporation methods for different locations or different climates. Standardised methods are available to estimate the evapotranspiration from vegetation, an example is the method provided by Allen, et al. (1998). So, recommended is to develop a standardized method, that includes the energy storage in water bodies and that is usable with data on different times scales, to determine the evaporation from open water bodies.

The results of this study are influenced by an assumed factor that is used the estimate the annual average reservoir area. If there was a factor available that describes the relation between the reservoir area and the reservoir volume, then the reservoir area could be estimated in a more accurate way. This would give a more accurate evaporation volume per reservoir. Recommended is to determine such a factor in the used databases.

5.3. Recommendations to reduce the water footprint related to reservoir operation

This study has showed that the location of the reservoir is influencing the water footprint of reservoir operation. Reservoirs located in colder climates have in general a lower water footprint than reservoirs located in warmer climates. So, if reservoirs are constructed to manage the water level in the river and prevent flooding, it is better to construct these in the colder parts of the river basin. The results of this study can also be used the benchmark the water footprint of reservoirs per climate class.

This study has shown that each reservoir purpose is a water user. For reservoirs that are located in river basins with a low water scarcity level, this will in general not result in problems. However, if reservoirs are located in water scare river basins, it is possible that reservoirs contribute to a higher water scarcity level. Recommended is to decrease the number of reservoirs with hydropower production, recreation and commercial fishing as main purposes, because these reservoirs purposes are considered as not needed. This will contribute to the reduction of the water scarcity level in river basins with a high water scarcity level.

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Appendix A. Exchange rates and inflation correction

During this research project, the 2014 U.S. Dollar is used as currency. The main reason to use the U.S. Dollar is that data provided by global institutions like the FAO and the World Bank are mainly in U.S. Dollar. The year 2014 is used as reference year because this is the most recent year with complete data availability. To convert other currencies in the U.S. Dollar, annual average exchange rates are used. These exchange rates are provided by the World Bank (2015).

To convert the historic U.S. Dollar value to the 2014 U.S. Dollar value, conversion factor based on the consumer price index are used. These conversion factors are provided by Williamson (2015). Table 1 shows the annual average exchange rates from U.S. dollar to Euro and table 2 presents the inflation correction factors.

Table A.1. Exchange rates from U.S. Dollar to Euro, between 2000 and 2015 (World Bank 2015).

Year	*$ to €*	*Year*	*$ to €*
2015	0,75	2007	0,73
2014	0,75	2006	0,80
2013	0,75	2005	0,80
2012	0,78	2004	0,81
2011	0,72	2003	0,89
2010	0,76	2002	1,06
2009	0,72	2001	1,12
2008	0,68	2000	1,09

Table A.2. Inflation correction factors for the U.S. Dollar between 1990 and 2015 (Williamson, 2015).

Year	Correction to 2014	Year	Correction to 2014
2015	1	2002	1,32
2014	1	2001	1,34
2013	1,02	2000	1,37
2012	1,03	1999	1,42
2011	1,05	1998	1,45
2010	1,09	1997	1,47
2009	1,1	1996	1,51
2008	1,1	1995	1,55
2007	1,14	1994	1,6
2006	1,17	1993	1,64
2005	1,21	1992	1,69
2004	1,25	1991	1,74
2003	1,29	1990	1,81

Appendix B. Electricity prices

The prices for electrical energy per country, with reservoirs is this study, are shown in table B.1. These prices are provided by: Eurostat (2015), the IEA (2012), the RCREEE (2015) or local sources. As the data was not available by these official sources, then data from Wikipedia or Statista was used. If the prices are not available for a certain nation, then the water price was determined by interpolating values of surrounding countries. Or, when there are large economic and cultural differences between neighbouring countries, the electricity price was based on one or several neighbouring nations with a comparable economic and cultural situation. Data was only available for a few sub Saharan African nations, so, for all these nations one average is determined. The prices are used inclusive taxes.

Table B.1. Electricity prices per country.

Country	*Price*	*Currency*	*Year*	*Price 2014$*	*Ref.*	*Comment*
Albania	0,08	€	2015	$ 0,06	1	Average medium industrial and household prices, without taxes.
Algeria	0,03	$	2013	$ 0,03	3	
Angola	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Argentina	0,11	$	2006	$ 0,13	6	Buenos Aires Only
Australia	0,05	$	2000	$ 0,06	2	
Austria	0,14	€	2015	$ 0,10	1	Average medium industrial and household prices, without taxes.
Belgium	0,15	€	2015	$ 0,11	1	Average medium industrial and household prices, without taxes.
Bolivia	0,16	$		$ 0,16		Interpolated average based on neighbouring countries.
Bosnia and Herzegovina	0,07	€	2015	$ 0,05	1	Average medium industrial and household prices, without taxes.
Botswana	0,02	€	2015	$ 0,02	10	Average households and Business prices. Inclusive 12% VAT
Brazil	0,37	$	2015	$ 0,37	4	Inclusive taxes
Brunei Darussalam	0,11	$		$ 0,11		Based on Malaysia
Bulgaria	0,08	€	2015	$ 0,06	1	Average medium industrial and household prices, without taxes.
Burkina Faso	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Cameroon	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Canada	0,07	$	2010	$ 0,08	2	
Central African Republic	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
China	0,04	$	2015	$ 0,04	23	
Colombia	0,18	$	2013	$ 0,18	11	Bogota only
Croatia	0,11	€	2015	$ 0,08	1	Average medium industrial and household prices, without taxes.
Cuba	0,13	$		$ 0,13		Average value of neighbouring countries.
Cyprus	0,16	€	2015	$ 0,12	1	Average medium industrial and household prices, without taxes.
Czech Republic	0,10	€	2015	$ 0,08	1	Average medium industrial and household prices, without taxes.

Country	*Price*	*Currency*	*Year*	*Price 2014$*	*Ref.*	*Comment*
Congo (Democratic Republic of the)	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Egypt	0,05	$	2014	$ 0,05	5	Average of different tarrifs.
El Salvador	0,12	$		$ 0,12		Based on Mexico
Eritrea	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Ethiopia	0,06	$	2012	$ 0,07	5	Average of different tarrifs.
Finland	0,11	€	2015	$ 0,08	1	Average medium industrial and household prices, without taxes.
France	0,12	€	2015	$ 0,09	1	Average medium industrial and household prices, without taxes.
Gabon	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Germany	0,19	€	2015	$ 0,14	1	Average medium industrial and household prices, without taxes.
Ghana	0,11	€	2015	$ 0,08	12	Average of different tarrifs.
Greece	0,14	€	2015	$ 0,11	1	Average medium industrial and household prices, without taxes.
Guinea	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Hungary	0,10	€	2015	$ 0,07	1	Average medium industrial and household prices, without taxes.
Iceland	0,12	€	2015	$ 0,09	1	Average medium industrial and household prices, without taxes.
India	0,12	$	2015	$ 0,12	4	
Indonesia	0,11	$	2015	$ 0,11	5	
Iran (Islamic Republic of)	0,11	$	2011	$ 0,11	5	
Ireland	0,19	€	2015	$ 0,14	1	Average medium industrial and household prices, without taxes.
Italy	0,17	€	2015	$ 0,13	1	Average medium industrial and household prices, without taxes.
Côte d'Ivoire	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Japan	0,18	$	2011	$ 0,19	2	
Kazakhstan	0,07	€		$ 0,05		Based on Russia
Kenya	0,18	€	2015	$ 0,14	13	Including VAT
Lao People's Democratic Republic	0,07	$	2014	$ 0,07	5	
Latvia	0,13	€	2015	$ 0,10	1	Average medium industrial and household prices, without taxes.
Lesotho	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Liberia	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Libya	0,02	$	2013	$ 0,02	3	
Lithuania	0,10	€	2015	$ 0,08	1	Average medium industrial and household prices, without taxes.

Country	*Price*	*Currency*	*Year*	*Price 2014$*	*Ref.*	*Comment*
Macedonia (the former Yugoslav Republic of)	0,06	€	2015	$ 0,05	1	Average medium industrial and household prices, without taxes.
Malaysia	0,11	$	2013	$ 0,11	5	Average of different tarrifs.
Mali	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Mexico	0,12	$	2011	$ 0,12	2	
Montenegro	0,09	€	2015	$ 0,07	1	Average medium industrial and household prices, without taxes.
Morocco	0,12	$	2013	$ 0,13	3	Average of different tarrifs.
Mozambique	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Namibia	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Nepal	0,09	$	2012	$ 0,09	5	Average of different tarrifs.
New Zealand	0,07	$	2011	$ 0,08	2	
Nigeria	0,10	$	2013	$ 0,10	5	Average of different tarrifs.
Norway	0,11	€	2015	$ 0,08	1	Average medium industrial and household prices, without taxes.
Pakistan	0,09	$	2011	$ 0,09	5	Average of different tarrifs.
Panama	0,12	$		$ 0,12		Based on Mexico
Paraguay	0,08	$	2011	$ 0,08	5	
Philippines	0,34	$	2015	$ 0,34	4	
Poland	0,11	€	2015	$ 0,09	1	Average medium industrial and household prices, without taxes.
Portugal	0,16	€	2015	$ 0,12	1	Average medium industrial and household prices, without taxes.
Romania	0,10	€	2015	$ 0,08	1	Average medium industrial and household prices, without taxes.
Russian Federation	0,07	€	2012	$ 0,06	15	
Serbia	0,06	€	2015	$ 0,04	1	Average medium industrial and household prices, without taxes.
Singapore	0,14	€	2015	$ 0,11	16	Average tariff 2015 for households
Slovakia	0,13	€	2015	$ 0,10	1	Average medium industrial and household prices, without taxes.
Slovenia	0,12	€	2015	$ 0,09	1	Average medium industrial and household prices, without taxes.
South Africa	0,09	$	2014	$ 0,09	4	
Korea (Republic of)	0,06	$	2009	$ 0,06	2	
Spain	0,17	€	2015	$ 0,13	1	Average medium industrial and household prices, without taxes.
Sri Lanka	0,02	€	2014	$ 0,02	17	Average houshold tarrifs
Suriname	0,04	$	2013	$ 0,04	18	Average, Taxes included.
Sweden	0,12	€	2015	$ 0,09	1	Average medium industrial and household prices, without taxes.
Switzerland	0,13	$	2011	$ 0,14	2	
Tanzania, United Republic of	0,08	€	2015	$ 0,06	18	Standardized Small Power Purchase Tariff

Country	*Price*	*Currency*	*Year*	*Price 2014$*	*Ref.*	*Comment*
Taiwan, Province of China	0,12	$	2012	$ 0,12	5	Average
Thailand	0,11	$	2015	$ 0,11	4	
Togo	0,12	€		$ 0,09		Interpolated value for sub-sahara countries
Tunisia	0,03	€		$ 0,02		Interpolated average based on neighbouring countries.
Turkey	0,11	€	2015	$ 0,08	1	Average medium industrial and household prices, without taxes.
Ukraine	0,07	$	2015	$ 0,07	5	Average of diferent tarrifs
United Kingdom of Great Britain and Northern Ireland	0,18	€	2015	$ 0,13	1	Average medium industrial and household prices, without taxes.
United States of America	0,16	$	2015	$ 0,16	20	August 2015, All sectors
Uruguay	0,22	$	2012	$ 0,22	21	Inclusive taxes
Uzbekistan	0,05	$	2011	$ 0,05	5	
Venezuela (Bolivarian Republic of)	0,03	$	2015	$ 0,03	5	Using the official exchange rate
Viet Nam	0,06	$	2011	$ 0,07	22	
Zambia	0,34	€	2011	$ 0,26	5	Average of residental tarrifs.
Zimbabwe	0,12	€		$ 0,09		Interpolated value for sub-sahara countries

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Appendix C. Economic value of agricultural area by country

The averaged economic value of agricultural area by country is determined using the harvested area per crop per country and the value of agricultural production per crop per country (FAOSTAT, 2015. gross production value, current million US$). FAOstat defines the value of agricultural production as follow: *“Value of gross production has been compiled by multiplying gross production in physical terms by output prices at farm gate. Thus, value of production measures production in monetary terms at the farm gate level. Since intermediate uses within the agricultural sector (seed and feed) have not been subtracted from production data, this value of production aggregate refers to the notion of gross production".*

$$V_{aa;c} = \frac{\sum_{i=1}^{n}(V_{ap;cr;i})}{\sum_{i=1}^{n} A_{cr;c;i}} \quad \text{(C.1)}$$

The averaged economic value of agricultural area per country ($V_{aa;c}$), in 2014 U.S. dollar per ha, is the sum of the value of agricultural production for all crops ($V_{ap;cr;i}$) produced in a country divided by the sum of the area of production for all crops ($A_{cr;c;i}$). The equation is given by equation C.1. This is the same as the weighted average of the average value of agricultural production per crop per hectare per country and the harvested area per crop per country. Table C.1. shows the economic value per country for the countries with reservoirs in this study.

Table C.1. Economic value of agricultural area by country per ha.

Country	*Economic value in 2013*	*Corrected to 2014*
Albania	$ 3.874,71	$ 3.952,20
Algeria	$ 2.625,78	$ 2.678,30
Angola	$ 1.326,49	$ 1.353,02
Argentina	$ 991,59	$ 1.011,42
Australia	$ 897,96	$ 915,92
Austria	$ 2.036,36	$ 2.077,09
Belgium	$ 6.127,92	$ 6.250,48
Bolivia (Plurinational State of)	$ 703,86	$ 717,94
Bosnia and Herzegovina	$ 1.460,19	$ 1.489,40
Botswana	$ 169,84	$ 173,24
Brazil	$ 1.665,39	$ 1.698,70
Bulgaria	$ 993,19	$ 1.013,05
Burkina Faso	$ 358,76	$ 365,94
Cameroon	$ 1.329,43	$ 1.356,01
Canada	$ 1.087,38	$ 1.109,13
China, mainland	$ 4.204,76	$ 4.288,85
Colombia	$ 2.440,80	$ 2.489,61
Congo	$ 7.877,36	$ 8.034,91
Costa Rica	$ 7.806,17	$ 7.962,30
Côte d'Ivoire	$ 1.233,95	$ 1.258,63
Croatia	$ 1.367,40	$ 1.394,75
Cyprus	$ 3.279,07	$ 3.344,65

Country	*Economic value in 2013*	*Corrected to 2014*
Czech Republic	$ 1.580,18	$ 1.611,78
Egypt	$ 3.108,48	$ 3.170,65
El Salvador	$ 920,18	$ 938,59
Eritrea	$ 617,10	$ 629,45
Ethiopia	$ 813,88	$ 830,16
Finland	$ 1.120,77	$ 1.143,19
France	$ 2.365,61	$ 2.412,93
Germany	$ 2.191,76	$ 2.235,60
Ghana	$ 1.494,46	$ 1.524,34
Greece	$ 3.451,58	$ 3.520,61
Guinea	$ 401,69	$ 409,73
Hungary	$ 1.181,05	$ 1.204,67
Iceland	$ 28.799,25	$ 29.375,23
India	$ 1.012,27	$ 1.032,51
Indonesia	$ 2.842,21	$ 2.899,05
Iran (Islamic Republic of)	$ 3.118,91	$ 3.181,29
Ireland	$ 1.785,37	$ 1.821,07
Italy	$ 3.756,86	$ 3.832,00
Japan	$ 17.519,61	$ 17.870,00
Kazakhstan	$ 310,41	$ 316,62
Kenya	$ 1.025,45	$ 1.045,96
Lao People's Democratic Republic	$ 1.692,31	$ 1.726,16
Latvia	$ 885,51	$ 903,22
Malaysia	$ 2.577,61	$ 2.629,16
Mali	$ 587,56	$ 599,32
Mexico	$ 1.324,29	$ 1.350,78
Morocco	$ 917,48	$ 935,83
Mozambique	$ 1.143,08	$ 1.165,94
Namibia	$ 183,85	$ 187,52
Nepal	$ 982,35	$ 1.002,00
New Zealand	$ 6.878,27	$ 7.015,83
Nigeria	$ 1.095,21	$ 1.117,11
Norway	$ 2.193,70	$ 2.237,57
Pakistan	$ 951,25	$ 970,28
Panama	$ 2.071,20	$ 2.112,62
Paraguay	$ 1.218,07	$ 1.242,43
Philippines	$ 1.476,00	$ 1.505,52
Poland	$ 1.069,37	$ 1.090,75
Portugal	$ 3.424,74	$ 3.493,24
Republic of Korea	$ 14.369,42	$ 14.656,81
Romania	$ 1.501,36	$ 1.531,39

Country	*Economic value in 2013*	*Corrected to 2014*
Russian Federation	$ 698,70	$ 712,67
Serbia	$ 1.289,75	$ 1.315,54
Singapore	$ 18.673,99	$ 19.047,47
Slovakia	$ 1.224,64	$ 1.249,14
Slovenia	$ 2.127,39	$ 2.169,94
South Africa	$ 1.495,74	$ 1.525,66
Spain	$ 2.145,78	$ 2.188,70
Sri Lanka	$ 1.372,68	$ 1.400,14
Suriname	$ 2.144,11	$ 2.186,99
Sweden	$ 1.440,67	$ 1.469,48
Switzerland	$ 6.602,60	$ 6.734,65
Thailand	$ 1.313,84	$ 1.340,12
The former Yugoslav Republic of Macedonia	$ 2.207,99	$ 2.252,15
Togo	$ 464,77	$ 474,06
Tunisia	$ 772,15	$ 787,60
Turkey	$ 2.110,03	$ 2.152,23
Turkmenistan	$ 868,24	$ 885,60
Ukraine	$ 898,92	$ 916,89
United Kingdom	$ 2.509,99	$ 2.560,19
United Republic of Tanzania	$ 425,07	$ 433,57
United States of America	$ 1.789,12	$ 1.824,90
Uruguay	$ 1.608,17	$ 1.640,33
Vanuatu	$ 1.194,79	$ 1.218,69
Venezuela (Bolivarian Republic of)	$ 6.444,06	$ 6.572,95
Viet Nam	$ 1.946,13	$ 1.985,06
Yemen	$ 1.661,79	$ 1.695,02
Zambia	$ 1.009,98	$ 1.030,18
Zimbabwe	$ 225,25	$ 229,76

Appendix D. Economic value of flood storage in reservoirs

To estimate the economic value of flood prevention by reservoirs, the annually average economic value of flood storage in reservoirs is required. Zhoa and Liu (2015) provide an economic value of $ 0,16 for flood storage in the three Gorges reservoir, but no other examples are available in the literature to our knowledge.

The U.S. Army Corps of Engineers (USACE) reports the yearly prevented flood damage by all kinds of it's projects to the U.S. congress. This reports are publicly available but provide only the prevented damage per fiscal year per project. However, some USACE districts, especially the New England district, provides for each of their flood prevention projects, the prevented damage since the year of completion. This information in combination with the flood storage volume per reservoir, which is also provided by the USACE, gives the economic value of flood protection per flood storage volume.

Table D.1. Flood storage volumes, year of construction, prevented damage until 2011 and the EC for the 24 reservoirs in the New England district.

Reservoir name	*Flood storage volume* *(10^3 m^3)*	*Year of completion*	*Prevented damage until 2011*	*Corrected to 2014*	*Economic value of flood storage* *($\$m^{-3}$)*
Black rock dam	10713	1971	$ 217.100.000	$ 227.955.000	$ 0,53
Hall Meadow Brook dam	10637	1962	$ 105.700.000	$ 110.985.000	$ 0,21
Hop Brook dam	8820	1968	$ 108.400.000	$ 113.820.000	$ 0,30
Mad river dam	11735	1963	$ 16.000.000	$ 16.800.000	$ 0,03
Mansfield Hollow dam	31419	1952	$ 108.400.000	$ 113.820.000	$ 0,06
Sucker brook dam	1825	1971	$ 1.600.000	$ 1.680.000	$ 0,02
West Thompson lake	31570	1965	$ 56.400.000	$ 59.220.000	$ 0,04
Barre Falls dam	29602	1958	$ 53.200.000	$ 55.860.000	$ 0,04
Birch Hill dam	61551	1942	$ 78.100.000	$ 82.005.000	$ 0,02
Buffumville lake	19684	1958	$ 128.600.000	$ 135.030.000	$ 0,13
Conant Brook dam	4618	1966	$ 3.300.000	$ 3.465.000	$ 0,02
Knighville dam	60453	1941	$ 335.900.000	$ 352.695.000	$ 0,08
West Hill dam	15293	1961	$ 96.600.000	$ 101.430.000	$ 0,13
Edward MacDowell lake	190028	1950	$ 20.800.000	$ 21.840.000	$ 0,002
Otter Brook lake	40125	1958	$ 41.500.000	$ 43.575.000	$ 0,02
Surry Mountain lake	67380	1941	$ 101.300.000	$ 106.365.000	$ 0,02
North Hartland lake	87822	1961	$ 151.600.000	$ 159.180.000	$ 0,04
North Springfield lake	63216	1960	$ 134.800.000	$ 141.540.000	$ 0,04
Townshend lake	41640	1961	$ 137.100.000	$ 143.955.000	$ 0,07
Ball mountain dam	67380	1961	$ 162.200.000	$ 170.310.000	$ 0,05
Franklin falls dam	190028	1943	$ 178.300.000	$ 187.215.000	$ 0,01
Blackwater dam	56781	1941	$ 77.400.000	$ 81.270.000	$ 0,02
Thomaston dam	51822	1960	$ 828.900.000	$ 870.345.000	$ 0,33
Northfield Brook Dam	2998	1965	$ 75.800.000	$ 79.590.000	$ 0,58

Twenty-four reservoirs with useful information where found on the site of the USACE New England district (table D.1.). Prevented damage is given from the year of dam completion until 2011 and all these reservoirs are operational for at least 40 years. The annually averaged economic value of flood storage (EC) is determined with equation D.1.

$$EC = \frac{PD}{(2011 - y_c)V} \tag{D.1.}$$

Where PD is the prevented damage in U.S. dollar, y_c is the year of completion and V is the flood storage volume. The prevented damage is in 2011 U.S. dollar and this is corrected to 2014 prices using a factor 1,05 (appendix A). The average value of flood storage of these 24 reservoirs is \$0,117, which is of the same order of magnitude as the \$ 0,16 provided by Zhoa and Liu (2015) for the Three Gorges reservoir. The minimum e is \$0,002 and the maximal value is \$0,58.

The prevented damage for another 8 reservoirs located elsewhere in the U.S. are also available but without the flood storage volume (Table D.2). The reservoirs capacities provided by the WRD are generally larger than these provided by the USACE, with means that the EC is underestimated using these reservoir volumes. The EC of these reservoirs ranged between \$0,01 and \$0,09. For two relatively new reservoirs in the U.S., the Seven Oaks dam and the Portugues dam, the expected damage prevention is given. This, in combination with in an expected service life of 100 year gives for both reservoirs, an EC in the same order of magnitude as for the 24 reservoirs in the New England district.

Table D.2. Flood storage volumes, year of construction, prevented damage until 2011 and the EC for the 8 other reservoirs.

Reservoir name	*Flood storage volume* *(10^3 m^3)*	*Year of completion*	*Prevented damage until 2011*	*Corrected to 2014*	*Economic value of flood storage* *(\$/m^3)*
Pompton Dam	89797	1961	\$ 25.000.000	\$ 25.000.000	\$ 0,01
General Edwin Jadwin dam	58344	1960	\$ 32.000.000	\$ 32.000.000	\$ 0,01
Franklin Falls dam	30590	1943	\$ 178.300.000	\$ 187.215.000	\$ 0,09
Loyalhanna dam	157338	1951	\$ 529.000.000	\$ 529.000.000	\$ 0,05
Mahoning creek dam	115947	1941	\$ 686.000.000	\$ 720.300.000	\$ 0,09
Francis E Walter dam	197715	1961	\$ 180.000.000	\$ 189.000.000	\$ 0,02
Seven Oaks dam	179595	2000	\$ 4.000.000.000	\$ 5.480.000.000	\$ 0,22
Portugues dam	39471	2013	\$ 352.000.000	\$ 359.040.000	\$ 0,09

Reference

Black rock dam	USACE (2016) Black rock dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/BlackRock.aspx
Hall Meadow Brook dam	USACE (2016) Hall Meadow Brook dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/HallMeadow.aspx
Hop Brook dam	USACE (2016) Hop Brook dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/HopBrook.aspx
Mad river dam	USACE (2016) Mad river dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/MadRiver.aspx
Mansfield Hollow dam	USACE (2016) Mansfield Hollow dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/MansfieldHollow.aspx

Sucker brook dam	USACE (2016) Sucker brook dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/SuckerBrook.aspx
West Thompson lake	USACE (2016) West Thompson lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/WestThompson.aspx
Barre Falls dam	USACE (2016) Barre Falls dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Massachusetts/BarreFalls.aspx
Birch Hill dam	USACE (2016) Birch Hill dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Massachusetts/BirchHill.aspx
Buffumville lake	USACE (2016) Buffumville lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Massachusetts/Buffumville.aspx
Conant Brook dam	USACE (2016) Conant Brook dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Massachusetts/ConantBrook.aspx
Knighville dam	USACE (2016) Knighville dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Massachusetts/Knightville.aspx
West Hill dam	USACE (2016) West Hill dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Massachusetts/WestHill.aspx
Edward MacDowell lake	USACE (2016) Edward MacDowell lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/NewHampshire/EdwardMac.aspx
Otter Brook lake	USACE (2016) Otter Brook lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/NewHampshire/OtterBrook.aspx
Surry Mountain lake	USACE (2016) Surry Mountain lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/NewHampshire/Surry.aspx
North Hartland lake	USACE (2016) North Hartland lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Vermont/NorthHartland.aspx
North Springfield lake	USACE (2016) North Springfield lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Vermont/NorthSpringfield.aspx
Townshend lake	USACE (2016) Townshend lake. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Vermont/Townshend.aspx
Ball mountain dam	USACE (2016) Ball mountain dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Vermont/BallMtn.aspx
Franklin falls dam	USACE (2016) Franklin falls dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/NewHampshire/FranklinFalls.aspx
Blackwater dam	USACE (2016) Blackwater dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/NewHampshire/Blackwater.aspx
Thomaston dam	USACE (2016) Thomaston dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/ThomastonDam.aspx
Northfield Brook Dam	USACE (2016) Northfield Brook Dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/Connecticut/NorthfieldBrook.aspx
Pompton Dam	USACE (2016) Pompton Dam. Retrieved from www.nap.usace.army.mil/Missions/Factsheets/FactSheetArticleView/tabid/4694/Article/490856/prompton-lake.aspx
General Edwin Jadwin dam	USACE (2016) General Edwin Jadwin dam. Retrieved from www.nap.usace.army.mil/Missions/Factsheets/FactSheetArticleView/tabid/4694/Article/490855/general-edgar-jadwin-dam.aspx
Franklin Falls dam	USACE (2016) Franklin Falls dam. Retrieved from www.nae.usace.army.mil/Missions/CivilWorks/FloodRiskManagement/NewHampshire/FranklinFalls.aspx
Loyalhanna dam	USACE (2016) Loyalhanna dam. Retrieved from www.lrp.usace.army.mil/Missions/Recreation/Lakes/LoyalhannaLake.aspx
Mahoning creek dam	USACE (2016) Mahoning creek dam. Retrieved from http://www.lrp.usace.army.mil/Missions/Recreation/Lakes/MahoningCreekLake.aspx
Francis E Walter dam	USACE (2016) Francis E Walter dam. Retrieved from www.nap.usace.army.mil/Missions/CivilWorks/FrancisEWalterDam.aspx
Seven Oaks dam	USACE (2016) Seven Oaks dam. Retrieved from www.sbcounty.gov/dpw/floodcontrol/sevenOaks.asp
Portugues dam	USACE (2016) Portugues dam. Retrieved from www.saj.usace.army.mil/Portals/44/docs/Portugues_Dam/PortuguesDam_FS_Fall2012_508.pdf

Appendix E. Prices of residential and industrial water supply

Table E.1. presents the used water prices per country, for countries with reservoirs in this study. These prices are provided by: Dalilenko et al. (2014), IWA (2012) and OECD (2008). There are however differences how these figures are determined. Dalilenko et al. (2014) used the average revenue per m^3 water in U.S. dollar, per cubic meter water sold as water price. IWA (2012) determined the price of 100 m3 based on taxes, fixed tariffs and variable tariffs. The prices provided by the OECD (2008) are based on the water prices in $\$/m^3$ for households. For OECD countries, the figures provided by the OECD are used. For other countries the prices are provided by Dalilenko et al. (2014) and if these were not available, by IWA (2012).

If the prices are not available for a certain nation, then the water price was determined by interpolating surrounding values. Or, when there are large economic and cultural differences between neighbouring countries, the water price was based on one or several neighbouring nations with a comparable economic and cultural situation. Data was only available for a few central American nations, so, for all these nations one average is determined. To correct the inflation, all prices are corrected to 2014 price level. All correction factors are presented in Appendix A.

Table E.1. The economic value of residential and industrial water supply.

Country	*Price/m^3*	*Year*	*Price 2014*	*Ref.*	*Comment*
Afghanistan	$ 0,03		$ 0,03		Interpolated, average of Pakistan and Tajikistan
Albania	$ 0,54	2011	$ 0,57	1	
Algeria	$ 0,32	2010	$ 0,35	1	
Angola	$ 1,07		$ 1,09		Interpolated, average of Namibia, Zambia and DR Congo
Argentina	$ 0,45	2011	$ 0,47	2	For Buenos Aires only
Armenia	$ 0,47	2010	$ 0,51	1	
Australia	$ 5,37	2011	$ 5,64	1	
Austria	$ 4,40	2008	$ 4,84	3	
Azerbaijan	$ 0,41	2009	$ 0,45	1	
Bahrain	$ 0,29	2010	$ 0,32	1	
Bangladesh	$ 0,16	2013	$ 0,16	1	
Belarus	$ 1,05	2012	$ 1,08	1	
Belgium	$ 4,03	2008	$ 4,43	3	Average of Walloon and Flemish water prices
Belize	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Benin	$ 1,37	2009	$ 1,51	1	
Bhutan	$ 0,06	2004	$ 0,08	1	
Bolivia	$ 0,40	2006	$ 0,47	1	
Bosnia and Herzegovina	$ 0,82	2007	$ 0,93	1	
Botswana	$ 1,73		$ 1,76		Average of Namibia and South Africa
Brazil	$ 2,03	2011	$ 2,13	1	
Brunei Darussalam	$ 0,40		$ 0,41		Based on Malaysia
Bulgaria	$ 1,01	2008	$ 1,11	1	

Country	*Price/m^3*	*Year*	*Price 2014*	*Ref.*	*Comment*
Burkina Faso	$ 1,67	2009	$ 1,84	1	
Burundi	$ 0,24	2006	$ 0,28	1	
Cambodia	$ 0,28	2007	$ 0,32	1	
Cameroon	$ 0,88	2009	$ 0,97	1	
Canada	$ 1,58	2008	$ 1,74	3	
Central African Republic	$ 0,71	2009	$ 0,78	1	
Chile	$ 1,25	2008	$ 1,38	1	
China	$ 0,32	2012	$ 0,33	1	
Colombia	$ 1,78	2010	$ 1,94	1	
Costa rica	$ 1,05	2010	$ 1,14	1	
Croatia	$ 0,68	2004	$ 0,85	1	
Cuba	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Cyprus	$ 0,51	2011	$ 0,54	2	
Czech Republic	$ 2,31	2010	$ 2,52	1	
Congo (Democratic Republic of the)	$ 0,49	2005	$ 0,59	1	
Denmark	$ 6,70	2008	$ 7,37	3	
Djibouti	$ 0,31		$ 0,32		Based on Ethopia
Dominican republic	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Timor-Leste	$ 0,20		$ 0,20		Based on Indonesia
Ecuador	$ 0,59	2010	$ 0,64	1	
Egypt	$ 0,19	2010	$ 0,21	1	
El Salvador	$ 0,04	2006	$ 0,05	1	
Equatorial Guinea	$ 0,81		$ 0,83		Interpolated, average of Cameroon and Gabon
Eritrea	$ 0,31		$ 0,32		Based on Ethopia
Estonia	$ 2,15		$ 2,19		Based on Lithuania
Ethiopia	$ 0,31	2009	$ 0,34	1	
Fiji	$ 0,27	2013	$ 0,28	1	
Finland	$ 4,41	2008	$ 4,85	3	
France	$ 3,74	2008	$ 4,11	3	
Gabon	$ 0,73	2013	$ 0,74	1	
Gambia	$ 0,26	2005	$ 0,31	1	
Georgia	$ 0,14	2008	$ 0,15	1	
Germany	$ 0,50	2008	$ 0,55	3	
Ghana	$ 0,63	2009	$ 0,69	1	
Greece	$ 0,79		$ 0,81		Interpolated, average of Bulgaria, Macedonia and Albania
Guatemala	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].

Guinea	$ 0,65	2009	$ 0,72	1	

Country	*Price/m^3*	*Year*	*Price 2014*	*Ref.*	*Comment*
Guinea-Bissau	$ 0,95		$ 0,97		Interpolated, average of Senegal and Guinee
Guyana	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Haiti	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Honduras	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Hungary	$ 2,02	2008	$ 2,22	3	
Iceland	$ 3,50		$ 3,57		Based on Norway
India	$ 0,15	2009	$ 0,17	1	
Indonesia	$ 0,20	2004	$ 0,25	1	
Iran (Islamic Republic of)	$ 0,22	2011	$ 0,23	2	
Iraq	$ 0,46		$ 0,47		Interpolated, average of Iran and Jordan
Ireland	$ 4,77		$ 4,87		Based on the United Kingdom
Israel	$ 2,26	2011	$ 2,37	2	
Italy	$ 1,45	2008	$ 1,60	3	
Côte d'Ivoire	$ 0,65	2004	$ 0,81	1	
Jamaica	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Japan	$ 1,85	2008	$ 2,04	3	
Jordan	$ 0,69	2010	$ 0,75	1	
Kazakhstan	$ 0,34	2010	$ 0,37	1	
Kenya	$ 0,72	2010	$ 0,78	1	
Kuwait	$ 0,30	2010	$ 0,33	1	
Kyrgyzstan	$ 0,15	2011	$ 0,16	1	
Lao People's Democratic Republic	$ 0,15	2008	$ 0,17	1	
Latvia	$ 2,15		$ 2,19		Based on Lithuania
Lebanon	$ 0,46		$ 0,47		Average of Iran and Jordan
Lesotho	$ 0,88	2008	$ 0,97	1	
Liberia	$ 1,22	2006	$ 1,43	1	
Libya	$ 0,30		$ 0,31		Interpolated, average of Egypt and Tunisia
Lithuania	$ 2,15	2011	$ 2,26	2	
Luxembourg	$ 5,70	2008	$ 6,27	3	
Macedonia (the former Yugoslav Republic of)	$ 0,82	2012	$ 0,84	1	

Madagascar	$ 0,69		$ 0,70		Based on Mozambique
Malawi	$ 0,78	2011	$ 0,82	2	

Country	*Price/m^3*	*Year*	*Price 2014*	*Ref.*	*Comment*
Malaysia	$ 0,40	2007	$ 0,46	1	
Mali	$ 0,65	2009	$ 0,72	1	
Malta	$ 1,45		$ 1,48		Based on Italy
Mauritania	$ 0,36	2008	$ 0,40	1	
Mauritius	$ 0,63	2011	$ 0,66	2	
Mexico	$ 0,49	2008	$ 0,54	3	
Micronesia (Federated States of)	$ 0,55	2013	$ 0,56	1	
Moldova (Republic of)	$ 1,06	2012	$ 1,09	1	
Mongolia	$ 0,63		$ 0,64		Interpolated, average of China and Russia
Montenegro	$ 0,68		$ 0,69		Interpolated, average of Albania and Bosnia Hercegovina
Morocco	$ 0,72	2011	$ 0,76	1	
Mozambique	$ 0,69	2007	$ 0,79	1	
Myanmar	$ 0,24		$ 0,24		Interpolated, average of China and Bangladesh
Namibia	$ 2,20	2009	$ 2,42	1	
Nepal	$ 0,24		$ 0,24		Interpolated, average of China and India
Netherlands	$ 2,65	2008	$ 2,92	3	
New Zealand	$ 1,98	2008	$ 2,18	3	
Nicaragua	$ 0,42	2005	$ 0,51	1	
Niger	$ 0,58	2009	$ 0,64	1	
Nigeria	$ 1,13		$ 1,15		Average of Benin and Cameroon
Korea (Democratic People's Republic of)	$ 0,63		$ 0,64		Average of China and Russia
Norway	$ 3,50	2008	$ 3,85	3	
Oman	$ 0,56		$ 0,57		Based on Oman
Pakistan	$ 0,02	2012	$ 0,02	1	
Panama	$ 0,25	2006	$ 0,29	1	
Papua New Guinea	$ 2,03	2013	$ 2,07	1	
Paraguay	$ 0,36	2005	$ 0,44	1	
Peru	$ 0,68	2008	$ 0,75	1	
Philippines	$ 0,54	2009	$ 0,59	1	
Poland	$ 1,92	2010	$ 2,09	1	
Portugal	$ 1,23	2008	$ 1,35	3	
Qatar	$ 0,29		$ 0,30		Based on Bahrain

Congo	$ 0,49		$ 0,50		Based on DR Congo
Romania	$ 1,02	2010	$ 1,11	1	

Country	*Price/m^3*	*Year*	*Price 2014*	*Ref.*	*Comment*
Russian Federation	$ 0,93	2012	$ 0,96	1	
Rwanda	$ 0,42	2005	$ 0,51	1	
Saudi Arabia	$ 0,29		$ 0,30		Based on Bahrain
Senegal	$ 1,25	2009	$ 1,38	1	
Serbia	$ 0,84		$ 0,86		Interpolated, average of Albania, Macedonia, Bulgaria, Romenia, Hungary and Bosnia Hercegovina
Sierra Leone	$ 0,65		$ 0,66		Interpolated, average of Ivory Coast and Guinee
Singapore	$ 2,04	2011	$ 2,14	2	
Slovakia	$ 2,70		$ 2,97	3	Average of residential and industrial water supply
Slovenia	$ 1,35		$ 1,38		Interpolated, average of Croatia and Hungary
Somalia	$ 0,31		$ 0,32		Based on Ethopia
South Africa	$ 1,26	2009	$ 1,39	1	
Korea (Republic of)	$ 0,77	2008	$ 0,85	3	
South Sudan	$ 0,36		$ 0,37		Based on Sudan
Spain	$ 1,92	2008	$ 2,11	3	
Sri Lanka	$ 0,32	2009	$ 0,35	1	
Sudan	$ 0,36	2009	$ 0,40	1	
Suriname	$ 0,45		$ 0,46		Interpolated, average value for Central America[1].
Swaziland	$ 1,56	2009	$ 1,72	1	
Sweden	$ 3,59	2008	$ 3,95	3	
Switzerland	$ 3,13	2008	$ 3,44	3	
Syrian Arab Republic	$ 0,46		$ 0,47		Interpolated, average of Iran and Jordan
Tajikistan	$ 0,03	2005	$ 0,04	1	
Tanzania, United Republic of	$ 0,39	2009	$ 0,43	1	
Taiwan, Province of China[a]	$ 0,62	2011	$ 0,65	2	
Thailand	$ 0,26		$ 0,27		Interpolated, average of Malaysia, Cambodja and Laos
Togo	$ 0,71	2009	$ 0,78	1	
Tunisia	$ 0,40	2010	$ 0,44	1	
Turkey	$ 1,21	2008	$ 1,33	1	
Turkmenistan	$ 0,16		$ 0,16		Interpolated, average of Uzbekistan and Iran
Uganda	$ 1,22	2011	$ 1,28	2	

Ukraine	$ 0,44	2007	$ 0,50	1	
United Arab Emirates	$ 0,29		$ 0,30		Based on Bahrain

Country	*Price/m^3*	*Year*	*Price 2014*	*Ref.*	*Comment*
United Kingdom of Great Britain and Northern Ireland	$ 4,77	2008	$ 5,25	3	Average for Scotland, England and Wales.
United States of America	$ 1,36	2011	$ 1,43	1	
Uruguay	$ 1,94	2011	$ 2,04	1	
Uzbekistan	$ 0,10	2010	$ 0,11	1	
Venezuela (Bolivarian Republic of)	$ 0,25	2006	$ 0,29	1	
Viet Nam	$ 0,26	2009	$ 0,29	1	
Yemen	$ 0,56	2010	$ 0,61	1	
Zambia	$ 0,52	2013	$ 0,53	1	
Zimbabwe	$ 0,82		$ 0,84		Interpolated, average of Mozambique, South Africa and Zambia

Appendix F. Estimating water abstraction based on reservoir volume

Information about the volume of abstracted water from reservoirs with residential or industrial water supply as function, are not available. Based on 132 reservoirs with a water supply function operated by the USACE (table F.1.) and data from several Australian drink water companies (table F.2.), estimation functions are made to estimate the abstraction volume based on reservoir volume. The data for the Australian drink water companies are not based on individual reservoirs, but on the abstracted volume and storage capacity of those drinking water companies.

For both the U.S. reservoirs and the Australian drinking water companies, abstraction and reservoir volume ratios are determined. These ratios are plotted as scatterplot with trend line as function of the reservoir volume in figures F.1., F.2. and F.3. Trend lines with power functions gave the best fit, although the coefficient of determination is still low for reservoirs in arid regions. A distinction is made between humid and arid areas because the abstraction/volume ratios in humid river basins are higher. Generally, small reservoirs, located in humid river basins have a high ratio, while large reservoirs located in ared river basins have a low ratio.

The trend line equations are used to estimate the abstraction volume from reservoirs. For reservoirs located in countries with a generally humid climate, the humid trend line equation is used and vice versa for arid climates. For countries with different climate zones, the function based on all reservoirs is used.

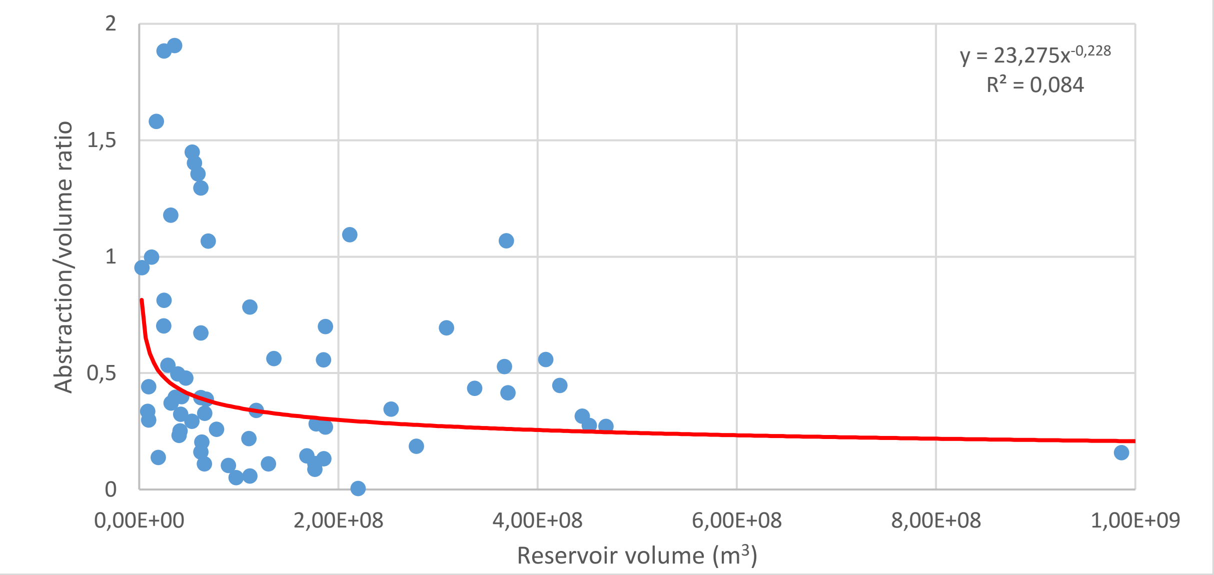

Figure F.1. The scatterplot for reservoirs located in arid river basins, with trend line, equation and coefficient of determination.

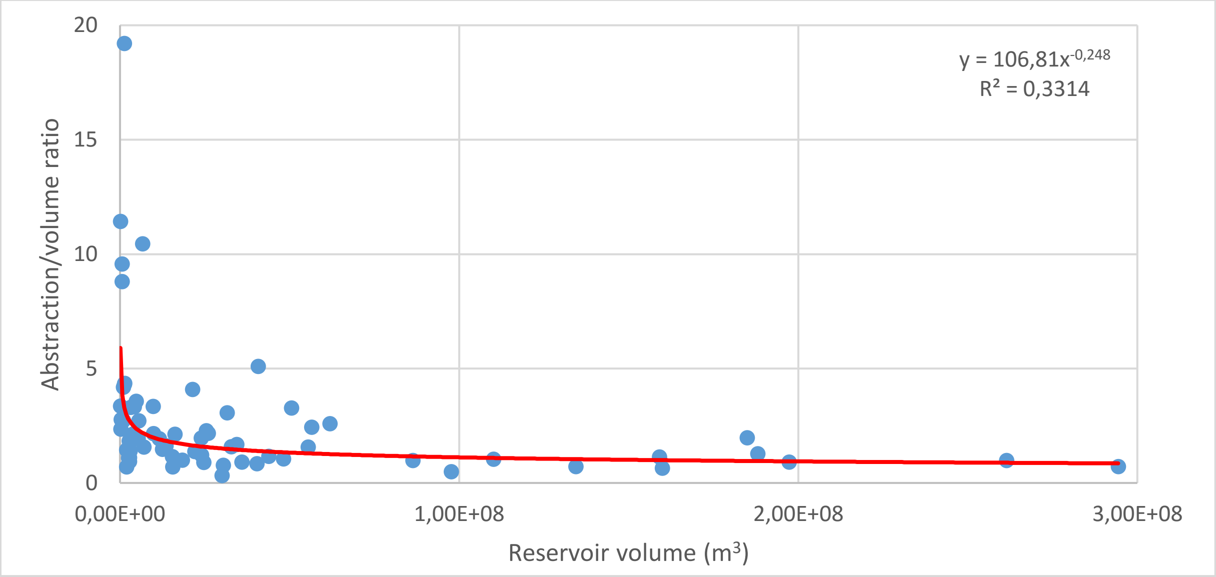

Figure F.2. The scatterplot for reservoirs located in humid river basins, with trend line, equation and coefficient of determination.

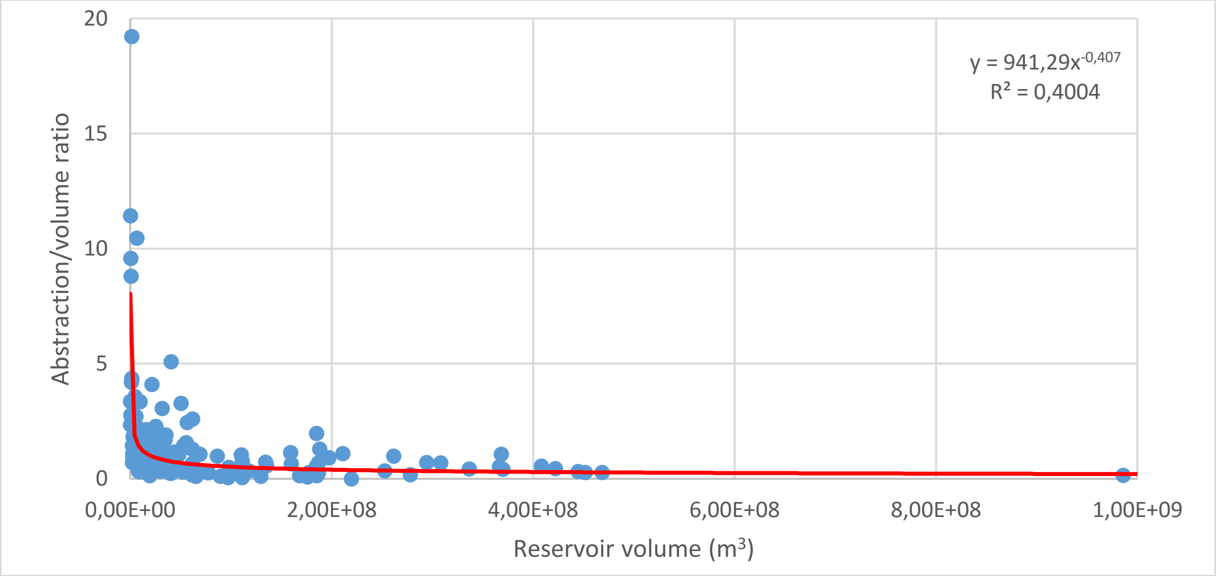

Figure F.3. The scatterplot for all reservoirs, with trend line, equation and coefficient of determination.

Table F.1. Abstraction and reservoirs volumes for reservoirs operated by the USACE (IWR, 2012).

Reservoirs in the U.S.	*U.S.-state*	*Abstracted volume (10^6 m^3)*	*Reservoir volume (10^6 m^3)*	*Ratio*	*River basin climate*
Colebrook	CT	160,69	61,90	2,60	Humid
Littleville	MA	22,38	11,59	1,93	Humid
Beltzville	PA	58,03	34,38	1,69	Humid
Blue Marsh	PA	21,28	9,86	2,16	Humid
Cowanesque	PA	96,72	31,56	3,06	Humid
Curwensville	PA	69,08	6,61	10,45	Humid

Reservoirs in the U.S.	*U.S.-state*	*Abstracted volume (10^6 m^3)*	*Reservoir volume (10^6 m^3)*	*Ratio*	*River basin climate*
Jennings Randolph	MD/ WV	165,80	50,55	3,28	Humid
B. Evert Jordan	NC	138,17	56,47	2,45	Humid
Falls Lake	NC	87,05	55,49	1,57	Humid
John H. Kerr	VA	56,65	26,03	2,18	Humid
W. Kerr Scott	NC	207,25	40,69	5,09	Humid
Hartwell	GA & SC	52,23	32,77	1,59	Humid
J. Strom Thurmond	GA & SC	16,86	4,73	3,57	Humid
Richard B. Russell	GA & SC	21,97	1,08	20,43	Humid
Allatoona	GA	29,57	24,06	1,23	Humid
Carters	GA	2,76	1,01	2,74	Humid
Okatibbee	MS	34,54	16,15	2,14	Humid
Alum Creek Lake	OH	48,36	97,65	0,50	Humid
Grayson Lake	KY	10,36	3,13	3,31	Humid
John W. Flannagan	VA	13,82	4,14	3,34	Humid
North Fork of Pound Lake	VA	0,41	0,12	3,36	Humid
Paint Creek	OH	5,53	1,28	4,31	Humid
Paintsville	KY	8,29	3,86	2,15	Humid
Summersville	WV	5,53	0,58	9,58	Humid
Tom Jenkins Dam	OH	11,05	7,02	1,58	Humid
Barren River Lake	KY	24,87	1,29	19,21	Humid
Brookville Lake	IN	113,99	110,11	1,04	Humid
Caesar Creek Lake	OH	51,12	48,21	1,06	Humid
Carr Creek Lake	KY	2,76	2,53	1,09	Humid
Cave Run Lake	KY	4,15	0,99	4,19	Humid
Green River Lake	KY	10,36	5,32	1,95	Humid
Monroe Lake	IN	179,62	197,28	0,91	Humid
Nolin Lake	KY	1,38	0,12	11,43	Humid
Patoka Lake	IN	103,63	159,87	0,65	Humid
Rough River Lake	KY	5,66	0,64	8,80	Humid
William H. Harsha Lake	OH	51,12	43,81	1,17	Humid
Center Hill Lake	TN	32,61	9,72	3,36	Humid
Dale Hollow Lake	TN & KY	3,04	2,73	1,12	Humid
J Percy Priest Dam & Reservoir	TN	87,46	21,34	4,10	Humid
Laurel River Lake	KY	5,94	1,36	4,36	Humid
Berlin Lake	OH	46,98	23,92	1,96	Humid
Mosquito Creek Lake	OH	22,11	13,56	1,63	Humid
Stonewall Jackson Lake	WV	4,97	2,71	1,83	Humid
Tygart	WV	2,63	2,76	0,95	Humid
Youghiogheny	PA	6,91	3,64	1,90	Humid
Saylorville	IA	18,38	18,37	1,00	Humid
Carlyle Lake	IL	33,85	40,31	0,84	Humid
Clarence Cannon Dam / Mark Twain Lake	MO	22,11	24,66	0,90	Humid

Reservoirs in the U.S.	*U.S.-state*	*Abstracted volume (10^6 m^3)*	*Reservoir volume (10^6 m^3)*	*Ratio*	*River basin climate*
Lake Shelbyville	IL	23,49	30,47	0,77	Humid
Rend Lake	IL	96,72	134,40	0,72	Humid
Blakey M. Dam / Lake Ouachita	AR	1,38	1,94	0,71	Humid
DeGray	AR	210,01	294,35	0,71	Humid
Enid	MS	15,06	5,55	2,71	Humid
Bowman Haley	ND	2,63	19,11	0,14	Arid
Garrison Dam / Lake Sakakawea	ND	25,98	67,06	0,39	Arid
Howard Hanson	WA	46,42	24,66	1,88	Arid
Lost Creek. OR	OR	12,30	12,33	1,00	Arid
Clinton Lake	KS	24,04	109,98	0,22	Arid
Harry S. Truman Dam & Res.	MO	0,97	0,35	2,77	
Hillsdale	KS	7,18	65,35	0,11	Arid
Kanopolis Lake	KS	17,82	15,41	1,16	
Long Branch Lake	MO	9,81	30,09	0,33	Arid
Melvern Lake	KS	9,95	61,65	0,16	Arid
Milford Lake	KS	153,50	369,90	0,41	Arid
Perry Lake	KS	103,07	184,95	0,56	Arid
Pomona Lake	KS	10,22	40,69	0,25	Arid
Rathbun Lake	IA	2,76	8,24	0,34	Arid
Smithville Lake	MO	39,79	117,38	0,34	Arid
Stockton Lake	MO	41,45	61,65	0,67	Arid
Tuttle Creek Lake	KS	79,86	61,65	1,30	Arid
Abiquiu	NM	0,97	219,47	0,00	Arid
Coyote Valley Dam / Lake Mendocino	CA	85,66	86,31	0,99	Humid
Dry Creek Warm Springs Dam / Lake Sonoma	CA	257,54	261,40	0,99	Humid
New Hogan	CA	14,23	129,47	0,11	Arid
Beaver	AR	181,28	159,05	1,14	Humid
Blue Mountain Lake	AR	2,76	1,91	1,45	Humid
Bull Shoals Lake	AR	11,05	15,55	0,71	Humid
DeQueen Lake	AR	30,40	22,05	1,38	Humid
Dierks Lake	AR	18,38	12,45	1,48	Humid
Gillham Lake	AR	58,03	25,40	2,28	Humid
Greers Ferry Lake	AR	33,02	35,92	0,92	Humid
Millwood Lake	AR	366,14	184,95	1,98	Humid
Nimrod Lake	AR	0,41	0,18	2,35	Humid
Norfork Lake	AR	4,15	2,96	1,40	Humid
Aquilla Lake	TX	13,40	41,43	0,32	Arid
Bardwell Lake	TX	15,47	52,77	0,29	Arid
Belton Lake	TX	139,96	444,74	0,31	Arid
Benbrook Lake	TX	9,26	89,39	0,10	Arid

Reservoirs in the U.S.	*U.S.-state*	*Abstracted volume (10^6 m^3)*	*Reservoir volume (10^6 m^3)*	*Ratio*	*River basin climate*
Canyon Lake	TX	124,21	451,77	0,27	Arid
Cooper Dam Jim Chapman Lake	TX	146,32	336,61	0,43	Arid
Ferrell’s Bridge Dam Lake O’The Pines	TX	214,16	308,25	0,69	Arid
Granger Dam & Lake	TX	22,38	46,73	0,48	Arid
Grapevine Lake	TX	24,18	168,00	0,14	Arid
Joe Pool Lake	TX	19,62	176,20	0,11	Arid
Lavon Lake	TX	127,11	468,54	0,27	Arid
Lewisville Dam	TX	227,98	408,12	0,56	Arid
Navarro Mills Lake	TX	21,42	65,60	0,33	Arid
N. San Gabriel D&L (Georgetown)	TX	14,23	36,00	0,40	Arid
O. C. Fisher	TX	4,97	97,15	0,05	Arid
Proctor Lake	TX	19,21	38,72	0,50	Arid
Ray Roberts Lake	TX	155,44	985,91	0,16	Arid
Sam Rayburn Dan & Reservoir	TX	76,82	53,02	1,45	Arid
Somerville Lake	TX	50,02	177,43	0,28	Arid
Stillhouse Hollow Dam	TX	87,32	252,64	0,35	Arid
Waco Lake	TX	130,71	186,95	0,70	Arid
Whitney Lake	TX	24,32	61,65	0,39	Arid
Wightman Patman Dam & Lake	TX	87,05	111,05	0,78	Arid
Arcadia Lake	OK	15,20	28,47	0,53	Arid
Birch Lake	OK	4,15	9,41	0,44	Arid
Broken Bow Lake	OK	241,65	188,03	1,29	Humid
Canton Lake	OK	6,36	110,97	0,06	Arid
Copan Lake	OK	2,76	9,25	0,30	Arid
Council Grove Lake	KS	9,26	39,95	0,23	Arid
Denison Dam Lake Texoma	OK & TX	393,36	368,29	1,07	Arid
El Dorado Lake	KS	15,20	176,06	0,09	Arid
Elk City	KS	16,86	42,29	0,40	Arid
Eufaula Lake	OK	73,92	69,29	1,07	Arid
Heyburn	OK	2,35	2,47	0,95	Arid
Hugh Lake	OK	79,58	58,69	1,36	Arid
Hula	OK	17,13	24,41	0,70	Arid
John Redmond	KS	77,65	55,36	1,40	Arid
Kaw Lake	OK	230,88	211,09	1,09	Arid
Keystone Lake	OK	20,03	24,66	0,81	Arid
Marion	KS	12,71	62,64	0,20	Arid
Oologah Lake	OK	188,74	422,14	0,45	Arid
Pat Mayse Lake	TX	75,99	135,14	0,56	Arid
Pearson – Skubitz Big Hill Lake	KS	11,74	31,69	0,37	Arid
Pine Creek Lake	OK	67,70	35,51	1,91	Arid
Sardis Lake	OK	193,43	366,45	0,53	Arid

Reservoirs in the U.S.	*U.S.-state*	*Abstracted volume (10^{6} m^{3})*	*Reservoir volume (10^{6} m^{3})*	*Ratio*	*River basin climate*
Skiatook Lake	OK	20,03	77,56	0,26	Arid
Tenkiller Ferry Alake	OK	37,03	31,42	1,18	Arid
Waurika Lake	OK	50,02	186,68	0,27	Arid
Wister Lake	OK	26,94	17,04	1,58	Arid

Table F.2. Abstraction and reservoirs volumes for Australian drink water companies. All reservoirs are located in arid areas.

Drink water company	*Abstracted volume (10^{6} m^{3})*	*Reservoir volume (10^{6} m^{3})*	*Ratio*	*Ref.*
Melborne	401	1812,18	0,22	1
West Australia	143,9	185,31	0,78	2
Canberra	51,42	278	0,18	3
Sydney	511	2027	0,25	4

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Appendix G. Commercial reservoir fishing

Table G.1. gives for all countries with commercial fishing as reservoir purpose the fishing yield in $kgha^{-1}y^{-1}$. Fishing yields depends on the volume of the water body, food supply and the climate (Marmulla, 2001). However, only average yields per country are used, because this is the only available information. The fish prices are provided by table G.2. If no information was available for fishing yields or fish prices, then the yield or the price was based on neighbouring countries.

Table G.1. Annual fishing yields for reservoirs per country.

Country	*Fishing yield ($kgha^{-1}y^{-1}$)*	*Comment*	*Ref.*
Burkina Faso	168	Hypothetical yield for a sub-Saharan reservoir.	1
China	500		7
France	26	Average inland open water fishing yield.	2
Germany	16	Average inland open water fishing yield.	2
Nigeria	168	Hypothetical yield for a sub-Saharan reservoir.	1
United States of America	24		3

Table G.2. Fishing prices for fresh water fish per country.

Country	*Price* (LCUkg^{-1})*	*Year*	*Corrected price (\$kg^{-1})*	*Comment*	*Ref.*
Burkina Faso	1,16	2008	1,28		4
China	4,60	2015	4,6	Based on the price of Nile Tilapia, the most cached fresh water fish.	5
France	8,82	2009	13,48		2
Germany	3,10	2007	4,84		2
Nigeria	1,39	2008	1,53		7
United States of America	1,63	2003	2,1		6

**: LCU means local currency unit.*

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Appendix H. Evaporation equations

The solar radiation (R_s) and maximal number of daylight hours (N) are determined with the equations H1 to H6. These equations are provided by Allen, et al., (1998). The solar radiation and the maximal hours of daylight are used within the methods of Jensen and Haise, Penman and Hamon.

$$d_r = 1 + 0{,}033 \cos\left(\frac{2\pi}{365} J\right) \tag{H.1}$$

$$\delta = 0{,}409\, sin\left(\frac{2\pi}{365} J - 1{,}39\right) \tag{H.2}$$

$$\omega_s = \arccos(-\, tan(\varphi)\, tan(\delta)) \tag{H.3}$$

$$R_a = \frac{1440}{\pi} G_{sc} d_r (\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)) \tag{H.4}$$

$$N = \frac{24\, \omega_s}{\pi} \tag{H.5}$$

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \tag{H.6}$$

Where:
d_r is the inverse relative distance Earth-Sun.
J is the number of the day between 1 January and 31 December.
ω_s is the sunset hour angle in rad.
δ is the solar decimation in rad.
φ is the latitude in rad.
R_a is extra-terrestrial radiation in $MJm^{-2}d^{-1}$.
G_{sc} is the solar constant which is 0,0820 $MJm^{-2}min^{-1}$.
N is the maximal number of daylight hours.
R_s is solar radiation in MJm-2d-1.
a_s is regression constant, expressing the fraction of extra-terrestrial radiation reaching the earth on overcast days (n = 0).
a_s+b_s is fraction of extraterrestrial radiation reaching the earth on clear days (n=N).
n is the actual duration of sunshine in hours.

To determine the evaporation from reservoirs with the Hamon method, equation H.7. to H.9. are used. These equations are provided by Harwell (2012).

$$e_s = 0{,}6108\, exp\left(\frac{17{,}27\, T_a}{237{,}3 + T_a}\right) \tag{H.7}$$

$$SVD = 2166{,}74\, \frac{e_s}{T_a} \tag{H.8}$$

$$E = 13{,}97 \left(\frac{N}{12}\right)^2 \left(\frac{SVD}{100}\right) \tag{H.9}$$

Where:
e_s is the saturation vapour pressure in kPa.
T_a is the mean day temperature in °C or for equation H.8.in °K.
SVD is the saturation vapour density in gm^{-3}.
E is the evaporation in mmd^{-1}.

To determine the evaporation from reservoirs with the modified Penman method, equation H.10. to H.15. are used. These equations are provided by Harwell (2012).

$$\frac{\Delta}{\Delta + \gamma} = \left(1 + \frac{0{,}66}{(0{,}00815\, T_a + 0{,}8912)^7}\right)^{-1} \tag{H.10}$$

$$\frac{\gamma}{\Delta - \gamma} = 1 - \frac{\Delta}{\Delta + y} \tag{H.11}$$

$$R_n = 0{,}00714 R_s + 5{,}26 \times 10^{-6} R_s (T_a + 17{,}8)^{1{,}87} + 3{,}94 \times 10^{-6} {R_s}^2 - 2{,}39 \times 10^{-9} {R_s}^2\, (T_a - 7{,}2)^2 - 1{,}02 \tag{H.12}$$

$$e_s - e_a = 33{,}86((0{,}00738 T_a + 0{,}8072)^8 - (0{,}00738\, T_d + 0{,}8072)^8) \tag{H.13}$$

$$E_a = \ (e_s - e_a)^{0{,}88} (0{,}42 + 0{,}0029 U_{10}) \tag{H.14}$$

$$E = 0{,}7 \left(\frac{\Delta}{\Delta + \gamma}\, R_n + \frac{\gamma}{\Delta + \gamma}\, E_a\right) \tag{H.15}$$

Where:
Δ is the gradient of saturated vapour pressure.
γ is the psychrometric constant.
R_n is the effective net radiation in mmd^{-1}.
e_s is the saturation vapour pressure in mb
e_a is the vapour pressure at the temperature of the air in mb
T_d is the dew point temperature in °C
E_a is the amount of evaporation from a Class A pan in mmd^{-1}.
U_{10} is the average wind speed at a height of 10 m in kmd^{-1}.
E is the evaporation in mmd^{-1}.

Appendix I. Estimating the dam body volume based on dam height.

For some reservoirs, the dam body volume is not available in the WRD database (ICOLD, 2011). These dams, the dam body volume is estimated based on the dam height. For each type of dam (table I.1) another factor is determined, because the dam body volume differs per dam type. The dam types are provided by the WRD database (ICOLD, 2011). For embankment dams, the construction material is also provided by the WRD database. But, for the other dam types, the assumption is made that reinforced concrete is the main construction material.

The dam body volume is estimated using the dam type factor, which is the dam body volume divided by the dam height. This value is determined for all dams where both parameters are known and the dam type factor is the average of these ratios. Table (I.1) presents for all dam types the dam type factors and the number of dams were the dam types factors are based on. The length of the dam is not taken into account within the dam type factor, because for most dams with unknown dam body volumes, also the dam length is unknown.

Table I.1. Number of dams with data availability and the dam type factor per dam type.

Dam type	*Number of dams with dam body volume and height*	*Dam type factor*
Embankment dam, earth fill	1343	71038
Embankment dam, rock fill	449	35177
Gravity dam	881	18027
Buttress dam	85	6970
Arch dam	245	2874

Appendix J. Reservoir area factor.

Reservoirs are not completely filled through the whole year and using the maximal reservoirs areas provided by the reservoir databases, would result in an overestimation of the water footprint per reservoir purpose. Assumed is, that on average, the reservoir is half-filled through the year. A reservoir shape is assumed to determine the relationship between the reservoir area and the reservoir volume. This shape is considered as a reprehensive form for a general reservoir. A half-filled reservoir corresponds to an area percentage of 56,25% and this factor is used to determine the evaporation volume per reservoir.

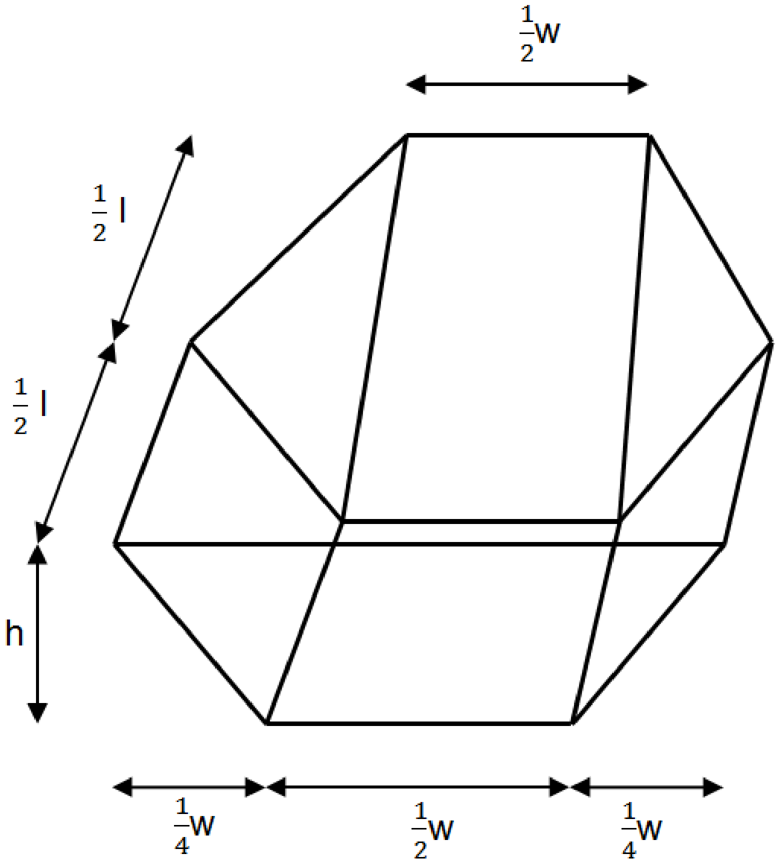

Figure J.1. The assumed shape of the reservoir.

Appendix K. Results for remaining purposes

Figures K.1. to K.5. show the average water footprints for selected countries for the purposes irrigation water supply, flood prevention, recreation, residential and industrial water supply and commercial fishing. No comparable results are available in the literature for these reservoir purposes. The average water footprint related to irrigation water supply is the highest in Ukraine and the lowest in Greece. The difference between both is approximately a factor 1000. Ukraine has the highest average annual water footprint related to flood control storage, while the Czech Republic has the lowest annual average water footprint related to flood prevention. The difference between the highest and the lowest annual average water footprint related to flood prevention is approximately a factor 1 billion.

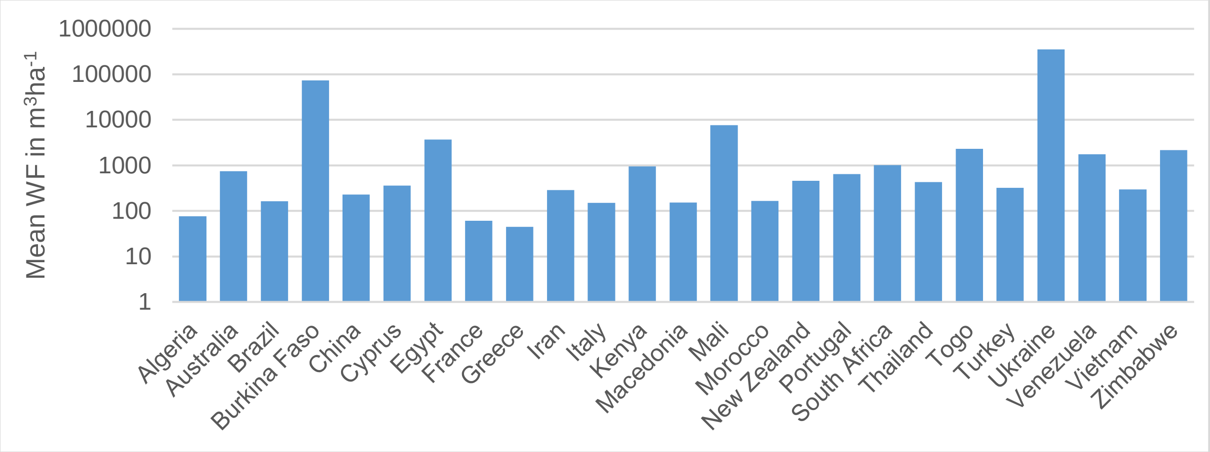

Figure K.1. The average water footprint of irrigation water supply for selected countries.

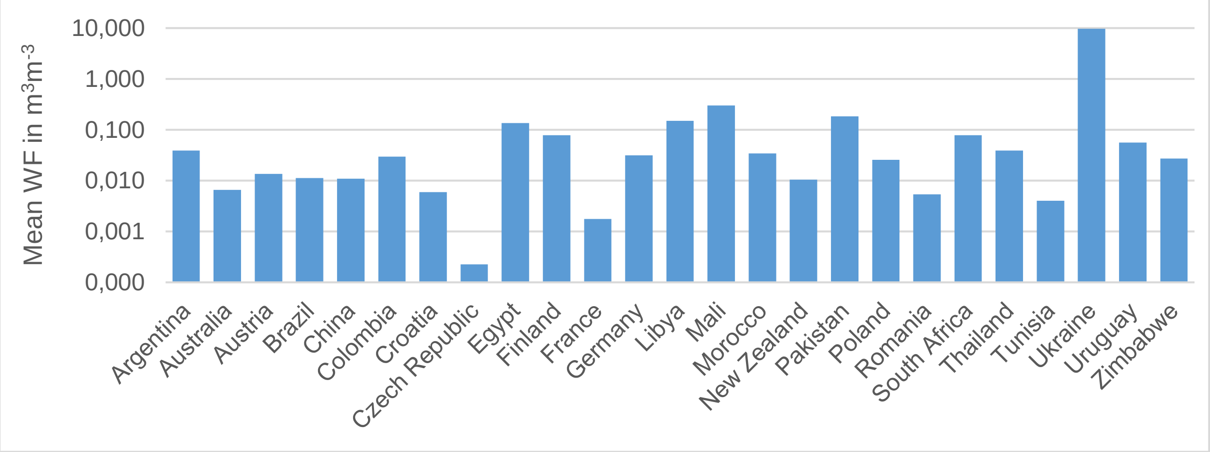

Figure K.2. The average water footprint of flood prevention by reservoirs for selected countries.

Recreation is mainly a reservoir purpose in developed countries. However, Burkina Faso has the highest average annual water footprint related to recreation, while this water footprint is the lowest in United Kingdom. Russia has the highest annual average water footprint related to residential and industrial water supply, the annual average water footprint is the lowest in the United Kingdom. Commercial fishing is a reservoir purpose in only in a few counties. Burkina Faso has the highest annual average water footprint while Nigeria has the lowest annual average water footprint.

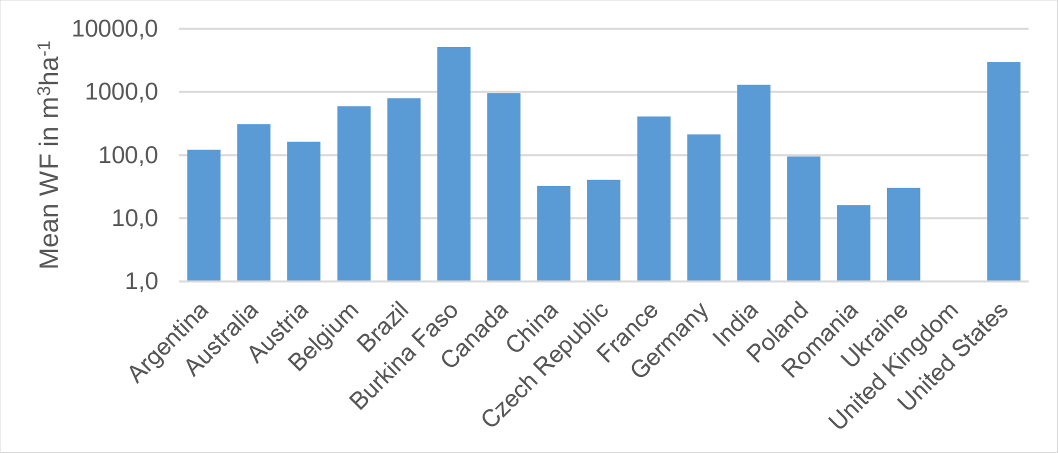

Figure K.3. The average water footprint of recreation on reservoirs for selected countries. The average water footprint of recreation in the United Kingdom is approximately 1.

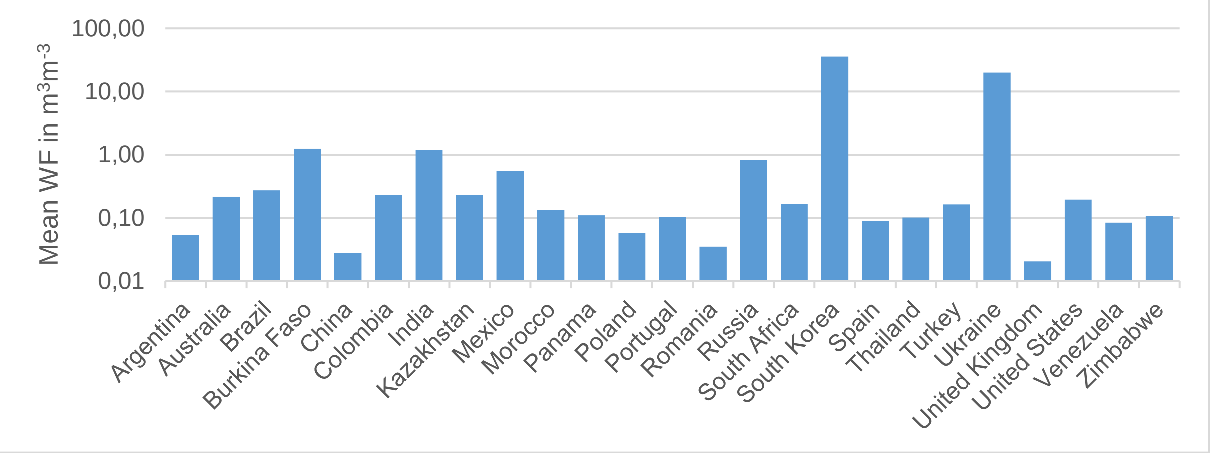

Figure K.4. The annual average water footprint of residential and industrial water supply for selected countries.

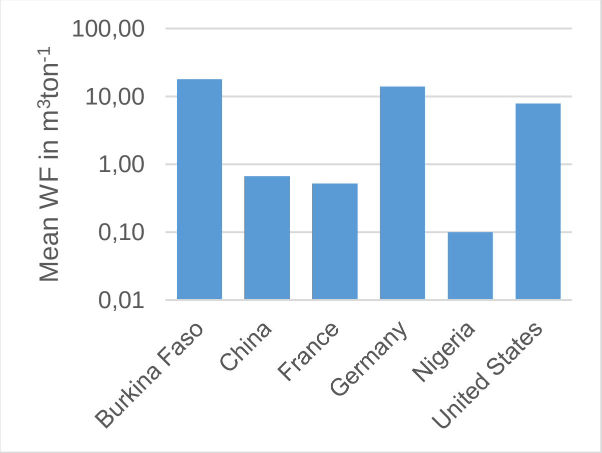

Figure K.5. The annual average water footprint of commercial fishing on reservoirs for selected countries.

Appendix L. Used climate classification.

In this study, the Köppen-Geiger climate classification is used to divide the reservoirs into different climate classes. The Köppen-Geiger climate classification provided by Kottek, et al. (2006) is used. This is presented in figure L.1. The climates classes are described in tables L.1 and L.2.

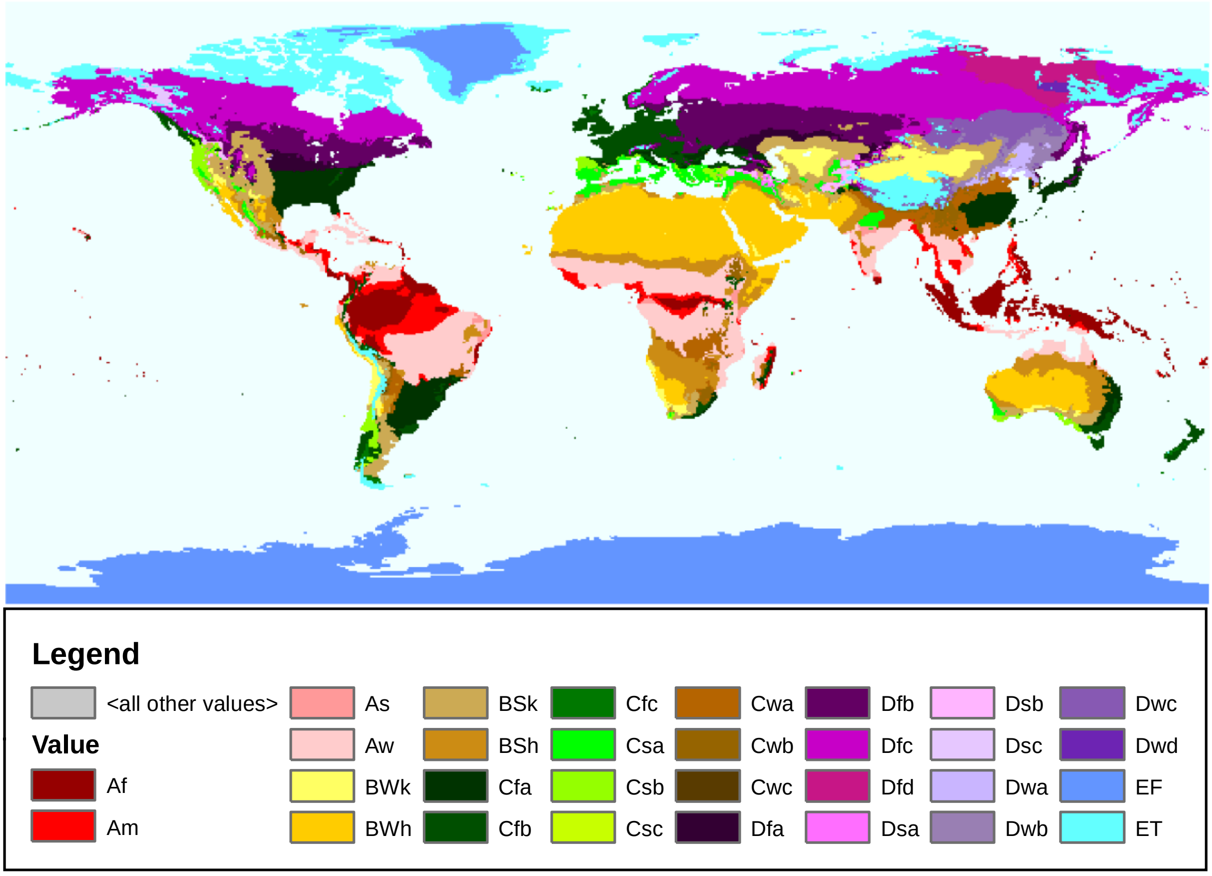

Figure L.1. The köppen-Geiger classification.

Table L.1. Description of the used Köppen-Geiger climate classification

Type	*Description*	*Criterion*
A	**Equatorial climates**	$T_{min} \geq +18°$ C
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25(100-P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climate**	$P_{ann} < 10P_{th}$
BS	Steppe climate	$P_{ann} > 5P_{th}$
BW	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	**Warm temperature climates**	$-3°C < T_{min} < +18°C$
Cs	Warm temperature climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperature climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Cf	Warm temperature climate, fully humid	Neither Cs or Cw
D	**Snow climates**	$T_{min} \leq -3°C$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climates with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Df	Snow climates, fully humid	Neither Ds or Dw
E	**Polar climates**	$T_{max} < +10°C$
ET	Tundra climate	$0°C \leq T_{max} < +10°C$
EF	Frost climate	$T_{max} < 0°C$

Table L.2. Description of the used Köppen-Geiger climate classification third letter temperature classification.

Type	*Description*	*Criterion*
h	Hot steppe/dessert	$T_{ann} \geq +18°C$
k	Cold steppe/dessert	$T_{ann} < +18°C$
a	Hot summer	$T_{max} \geq +22°C$
b	Warm summer	not a and at least 4 $T_{mon} \geq +10°C$
c	Cool summer and cold winter	not b and $T_{min} > -38°C$
d	Extremely continental	like c but $T_{min} \leq -38°C$