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M.M. Mekonnen

A.Y. Hoekstra

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THE WATER FOOTPRINT OF ELECTRICITY FROM HYDROPOWER

M.M. MEKONNEN[1]
A.Y. HOEKSTRA[1,2]

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[1] Twente Water Centre, University of Twente, Enschede, The Netherlands
[2] Contact author: Arjen Y. Hoekstra, a.y.hoekstra@utwente.nl

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Summary

Hydropower accounts for about 16% of the world's electricity supply. Although dams often have big environmental and social impacts, proponents of hydropower regard it as a comparatively clean, low-cost and renewable form of energy. It has been debated whether hydroelectric generation is merely an in-stream water user or whether it also consumes water, in the sense of effectively taking away water from the river. In this report we provide scientific support for the argument that hydroelectric generation is in most cases a significant water consumer.

The study assesses the blue water footprint of hydroelectricity – the water evaporated from manmade reservoirs to produce electric energy – for 35 selected sites. The aggregated blue water footprint of the selected hydropower plants is 90 Gm^3/yr, which is equivalent to 10% of the blue water footprint of global crop production in the year 2000. The total blue water footprint of hydroelectric generation in the world must be considerably larger if one considers the fact that this study covers only 8% of the global installed hydroelectric capacity. Hydroelectric generation is thus a significant water consumer.

The average water footprint of the selected hydropower plants is 68 m^3/GJ. Great differences in water footprint among hydropower plants exist, due to differences in climate in the places where the plants are situated, but more importantly as a result of large differences in the area flooded per unit of installed hydroelectric capacity.

We recommend that water footprint assessment is added as a component in evaluations of newly proposed hydropower plants as well as in the evaluation of existing hydroelectric dams, so that the consequences of the water footprint of hydroelectric generation on downstream environmental flows and other water users can be evaluated. Sustainable development of hydropower requires the accounting and internalization of all external costs including water consumption. Internalization means that the economic and environmental costs of the water consumed are charged to the operator of a hydropower plant and included in the price of hydroelectricity. It should thereby be acknowledged that water consumption costs vary within the year and across river basins, since the degree of water scarcity and competition over water depend on the period within the year and local circumstances.

1. Introduction

The need to supply a growing population with sufficient fresh water in the context of increasing water scarcity and declining water quality has brought sustainable water resources management to the forefront of the global development agenda. For centuries, dams have played a key role in human development, bringing about significant social and economic improvements. About 30-40% of irrigated land worldwide relies on water stored behind dams (World Commission on Dams, 2000) and hydropower accounted for 16% of world electricity in 2008 (IEA, 2010).

Large hydropower dams have both positive and negative effects (Sternberg, 2008, 2010). Dams have been built to regulate river flows, store water to guarantee adequate supply of water in dry periods, control floods, irrigate agricultural lands, provide for navigation and to generate electricity. Negative impacts associated with the building of large dams include displacement of people, loss of land and alteration of river flows and water quality affecting downstream people and ecosystems (Gleick, 1993; Rosenberg et al., 1995; Poff et al., 1997; Scudder, 1997; Lerer and Scudder, 1999; Tilt et al., 2009). Worldwide, many countries are likely to continue depending on hydroelectric dams as their source of electricity. But such development should be in a manner which addresses environmental concerns and the question how water resources can best be allocated.

It has been debated whether hydroelectric generation is merely an in-stream water user or whether it also consumes water, in the sense of effectively taking away water from the river. In the upcoming World Congress organised by the International Hydropower Association, 14-17 June in Brazil, a special session is even devoted to the question: Does hydropower consume water? The session aims to explore different interpretations of water 'consumption' in an attempt to recognise the energy impacts on water. In this report we provide scientific support for the argument that the production of hydroelectricity is in most cases a significant water consumer.

As an indicator of water consumption of hydroelectricity we use the concept of the water footprint, which measures the volume of freshwater consumed and polluted to produce the product along its supply chain. The water footprint of a product is equal to the sum of freshwater consumed or polluted divided by the quantity of production of the product (Hoekstra and Chapagain, 2008; Hoekstra et al., 2011). The water footprint consists of three components: the green water footprint (consumptive use of rainwater), the blue water footprint (consumptive use of ground or surface water) and the grey water footprint (the volume of water polluted). The analysis in this report is restricted to the quantification of the blue water footprint of hydroelectricity and focuses on the consumptive use of water that relates to the evaporation from the artificial reservoirs that are created behind hydroelectric dams.

Storage of water behind large hydropower dams leads to consumptive water use through evaporation from the open water surface of the artificial lake. Gleick (1993) has shown that on average 1.5 m^3 of water per GJ of electricity produced is evaporated from hydroelectric facilities in California. By combining the estimate of global evaporation from artificial water reservoirs in the world from Shiklomanov (2000) with data on global hydroelectric generation from Gleick (1993), Gerbens-Leenes et al. (2009a) estimated that the global average blue water footprint of electricity from hydropower is 22 m^3/GJ.

The objective of the current study is to estimate the blue water footprint of hydroelectricity for 35 selected reservoirs. First we estimate the evaporation throughout the year for the selected reservoirs. Next, we calculate the water footprint of hydropower based on the annual evaporation rate and energy generated. We have considered both the theoretical maximum and the actual hydroelectric generation of the plant. The theoretical maximum hydroelectric generation refers to the energy that could be generated with 100% hydropower availability. Since this theoretical maximum is not realistically attainable, comparisons among the hydropower plants and further discussion of the water footprint will be based on the actual energy generation.

The selection of the hydropower plants has been largely arbitrary and mostly based on the availability of data. All plants selected have been primarily built for the purpose of hydroelectric generation, although some serve other purposes as well. With the exception of the largest hydropower plants such as Itaipu, Tucurui, Sayano Shushenskaya, Robert-Bourossa, Yacyreta and Cahora Bassa all hydropower plants selected are the ones included in World Bank (1996). The 35 hydropower plants have a total capacity of about 73 GW and represent 8% of the global installed hydroelectric capacity of 924 GW in 2007 (IEA, 2010).

2. Method and data

2.1 Method

The water footprint of electricity (WF, m^3/GJ) generated from hydropower is calculated by dividing the amount of water evaporated from the reservoir annually (WE, m^3/yr) by the amount of energy generated (EG, GJ/yr):

$$WF = \frac{WE}{EG} \tag{1}$$

The total volume of evaporated water (WE, m^3/yr) from the hydropower reservoir over the year is:

$$WE = \left(10 \times \sum_{t=1}^{365} E\right) \times A \tag{2}$$

where E is the daily evaporation (mm/day) and A the area of the reservoir (ha).

There are a number of methods for the measurement or estimation of evaporation. These methods can be grouped into several categories including (Singh and Xu, 1997): (i) empirical, (ii) water budget, (iii) energy budget, (iv) mass transfer and (v) a combination of the previous methods.

Empirical methods relate pan evaporation, actual lake evaporation or lysimeter measurements to meteorological factors using regression analyses. The weakness of these empirical methods is that they have a limited range of applicability. The water budget methods are simple and can potentially provide a more reliable estimate of evaporation, as long as each water budget component is accurately measured. However, owing to difficulties in measuring some of the variables such as the seepage rate in a water system the water budget methods rarely produce reliable results in practice (Lenters et al., 2005, Singh and Xu, 1997). In the energy budget method, the evaporation from a water body is estimated as the difference between energy inputs and outputs measured at a site. Energy budget methods are considered to be the most reliable in theory (Lenters et al., 2005, Singh and Xu, 1997), but require costly instrumentation and a large commitment of personnel for field work and data processing (Winter et al., 1995). The mass-transfer (aerodynamic) based methods utilize the concept of eddy motion transfer of water vapour from an evaporating surface to the atmosphere. The mass-transfer methods normally use easily measurable variables and give satisfactory results in many cases. However, measurement of wind speed and air temperature at inconsistent heights, have resulted in a large number of equations with similar or identical structure (Singh and Xu, 1997). The combination methods combine the mass transfer and energy budget principles in a single equation. Two of the most commonly known combination methods are the Penman equation and the Penman-Monteith equation.

Owing to its limited empirical basis, the Penman-Monteith equation is more readily applicable to a variety of water bodies. In addition, the model takes into account heat storage within water bodies. Therefore, for the purpose of the current study the Penman-Monteith equation with heat storage is considered suitable for the estimation of evaporation from the selected hydropower reservoirs.

The evaporation from the water surface (*E*, mm/day) is estimated using the Penman-Monteith equation with an inclusion of water body heat storage. This equation is written as (McJannet et al., 2008):

$$E = \frac{1}{\lambda} \times \left(\frac{\Delta_w \times (R_n - G) + \gamma \times f(u) \times (e_w - e_a)}{\Delta_w + \gamma} \right) \tag{3}$$

where E is open water evaporation (mm/day); λ the latent heat of vaporization (MJ/kg); Δ_w the slope of the temperature saturation water vapour curve at water temperature (kPa/°C); R_n net radiation (MJ $m^{-2}day^{-1}$); G the change in heat storage in the water body (MJ/m^2/day); $f(u)$ the wind function (MJ/m^2/day/kPa); e_w the saturated vapour pressure at water temperature (kPa); e_a the vapour pressure at air temperature (kPa); and γ the psychometric constant (kPa/°C).

The latent heat of vaporisation (λ, MJ/kg) at air temperature (T_a, °C) is calculated as (McJannet et al., 2008):

$$\lambda = 2.501 - 2.361 \times 10^{-3} T_a \tag{4}$$

The psychometric constant (γ, kPa/°C) is calculated from (Allen et al., 1998):

$$\gamma = \frac{c_p \times P}{\varepsilon \times \lambda} = \frac{1.63 \times 10^{-3} P}{\lambda} \tag{5}$$

in which P is the atmospheric pressure (kPa); c_p the specific heat of air at constant pressure (which is equal to 1.013×10^{-3} MJ/kg/°C) and ε the ratio of molecular weight of water vapour to dry air and is equal to 0.622 (dimensionless).

The atmospheric pressure (P, kPa) varies with elevation above sea level (ψ, m) and is expressed as (Allen et al., 1998):

$$P = 101.3 \times \left(\frac{293 - 0.0065\psi}{293} \right)^{5.26} \tag{6}$$

The wind function $f(u)$ (MJ/m^2/day/kPa) is calculated from wind speed at 10 m (u_{10}, m/s) and the so-called equivalent area (A_e, km^2) (Sweers, 1976):

$$f(u) = \left(\frac{5}{A_e} \right)^{0.05} \times (3.80 + 1.57 u_{10}) \tag{7}$$

The equivalent area (A_e, km^2) is equal to the total surface area for regularly shaped reservoirs, but for irregularly shaped reservoirs, it can be taken equal to the square of the mean width.

Saturated vapour pressure at air temperature (e_a, kPa) is calculated from:

$$e_a = 0.6108 \times \exp\left(\frac{17.27 T_a}{(T_a + 237.3)}\right) \tag{8}$$

Net radiation (R_n, MJ m^{-2} d^{-1}) is the difference between the net incoming short-wave radiation (R_{ns}, MJ m^{-2} d^{-1}) and the net outgoing long-wave radiation (R_{nl}, MJ/m^2/day) (Allen et al., 1998):

$$R_n = R_{ns} - R_{nl} \tag{9}$$

The net incoming short-wave radiation (R_{ns}, MJ/m^2/day) resulting from the balance between incoming and reflected solar radiation is given by (Allen et al., 1998):

$$R_{ns} = (1-\alpha) \times R_s \tag{10}$$

where α is the albedo coefficient for open water (dimensionless), which has a value of 0.07 (Lenters et al., 2005), and R_s the incoming solar radiation (MJ/m^2/day).

Solar radiation (R_s, MJ m^{-2} day^{-1}) can be calculated with the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = (a_s + b_s \times \frac{n}{N}) \times R_a \tag{11}$$

where n is the actual duration of sunshine (hours); N the maximum possible duration of sunshine or daylight hours (hours); n/N the relative sunshine duration (which is equal to one minus the cloud cover fraction, dimensionless); R_a extraterrestrial radiation (MJ/m^2 /day); a_s a regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0) and a_s+b_s the fraction of extraterrestrial radiation reaching the earth on clear days (when n = N).

Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values a_s = 0.25 and b_s = 0.50 are taken as recommended by Allen et al. (1998).

The extraterrestrial radiation, R_a, for each day of the year and for different latitudes, can be estimated from the solar constant, the solar declination and the time of the year.

$$R_a = \frac{24 \times 60}{\pi} G_{sc} \times d_r \left[\omega_s \times \sin(\varphi) \times \sin(\delta) + \cos(\varphi) \times \cos(\delta) \times \sin(\omega_s) \right] \quad (12)$$

where G_{sc} is the solar constant (which is equal to 0.0820 MJ/m^2/day); d_r the inverse relative distance Earth-Sun; ω_s the sunset hour angle (rad); φ the latitude (rad) and δ the solar decimation (rad).

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} \times J \right) \quad (13)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} \times J - 1.39 \right) \quad (14)$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The latitude φ, expressed in radians, is positive for the northern hemisphere and negative for the southern hemisphere.

The sunset hour angle, ω_s, is given by:

$$\omega_s = arccos[-tan(\varphi) \times tan(\delta)] \quad (15)$$

The net outgoing long-wave radiation (R_{nl}, MJ/m^2/day) is the difference between the outgoing long-wave radiation ($R_l\uparrow$, MJ/m^2/day) and the incoming long-wave radiation ($R_l\downarrow$, MJ m^{-2} d^{-1}):

$$R_{nl} = R_l \uparrow - R_l \downarrow \quad (16)$$

The incoming long-wave radiation ($R_l\downarrow$, MJ/m^2/day) is calculated from (Fischer et al., 1979; Henderson-Sellers, 1986):

$$R_l \downarrow = \varepsilon_a \times \sigma \times (T_a + 273.15)^4 \left(1 + 0.17 C_f^2\right)(1 - r_{lw}) \quad (17)$$

where ε_a is the emissivity of air (dimensionless); σ the Stefan-Boltzmann constant (4.903x10^{-9} MJ/K^4/m^2/day); C_f the fractional cloud cover (dimensionless); and r_{lw} the total reflectivity of the water surface for long wave radiation, taken as a constant with a value of 0.03 (Henderson-Sellers, 1986).

The emissivity of air is calculated as (Swinbank, 1963):

$$\varepsilon_a = C_\varepsilon \times (T_a + 273.15)^2 \qquad (18)$$

where $C_\varepsilon = 9.37\times10^{-6}$ K^{-2}.

The outgoing long-wave radiation at water temperature ($R_l\uparrow$, MJ/m^2/day) is calculated as (Henderson-Sellers, 1986):

$$R_l\uparrow = \varepsilon_w \times \sigma \times (T_w + 273.15)^4 \qquad (19)$$

where σ is the Stefan-Boltzmann constant (MJ/m^2/K^4/day); T_w the water surface temperature (^{o}C); and ε_w the emissivity of water, equal to 0.97.

The water temperature at day i (T_{wi}, ^{o}C) is calculated from the following equation (De Bruin, 1982):

$$T_{w,i} = T_e + (T_{w,i-1} - T_e) \times exp(-1/\tau) \qquad (20)$$

where $T_{w,i-1}$ is the water temperature at day i-1 (^{o}C); T_e the equilibrium temperature (^{o}C); and τ the time constant (day).

The equilibrium temperature (T_e, ^{o}C) is calculated as follows (De Bruin, 1982):

$$T_e = T_n + \frac{R_n^*}{4\sigma \times (T_n + 273.15)^3 + f(u) \times (\Delta_n + \gamma)} \qquad (21)$$

Wet-bulb temperature (T_n, ^{o}C) is calculated using vapour pressure (e_a, kPa) and dew point temperature (T_d, ^{o}C) as follows (McJannet et al., 2008):

$$T_n = \frac{0.00066 \times 100 T_a + \left(4098 e_a / (T_d + 237.3)^2\right) \times T_d}{0.00066 \times 100 + \left(4098 e_a / (T_d + 237.3)^2\right)} \qquad (22)$$

The slope of the temperature saturation water vapour curve at wet bulb temperature (Δ_n, kPa/K) is:

$$\Delta_n = \frac{4098 \times \left[0.6108 \times exp\left(\frac{17.27 T_n}{(T_n + 237.3)}\right)\right]}{(T_n + 237.3)^2} \qquad (23)$$

Net radiation at wet-bulb temperature (R_n^*, MJ/m^2/day) is calculated using albedo (α) as follows:

$$R_n^* = (1-\alpha)\times R_s + (R_l \downarrow - R_l \uparrow_n) \tag{24}$$

Outgoing long-wave radiation at wet-bulb temperature ($R_l\uparrow_n$, MJ/m^2/day) is calculated, based on Finch and Gash (2002):

$$R_l \uparrow_n = C_f \times \left(\sigma \times (T_a + 273.15)^4 + 4\sigma \times (T_a + 273.15)^3 \times (T_n - T_a)\right) \tag{25}$$

where C_f is fractional cloud cover.

The time constant (τ, day) is given as (De Bruin, 1982):

$$\tau = \frac{\rho_w \times c_w \times h}{4\sigma \times (T_n + 273.15)^3 + f(u)\times(\Delta_n + \gamma)} \tag{26}$$

where ρ_w is the density of water (= 1000 kg/m^3); c_w the specific heat of water (= 0.0042 MJ/kg/K); and h the depth of water (m), estimated from reservoir volume capacity and area.

Change in the heat storage in the water body (G, MJ/m^2/day) is calculated from Finch (2001):

$$G = \rho_w \times c_w \times h \times (T_{w,i} - T_{w,i-1}) \tag{27}$$

Saturated vapour pressure at water temperature (e_w, kPa) is calculated from:

$$e_w = 0.6108 \times \exp\left(\frac{17.27T_w}{(T_w + 237.3)}\right) \tag{28}$$

Finally, the slope of the temperature saturation water vapour curve at water temperature (Δ_w, kPa $^{o}C^{-1}$) is:

$$\Delta_w = \frac{4098 \times \left[0.6108 \times \exp\left(\frac{17.27T_w}{(T_w + 237.3)}\right)\right]}{(T_w + 237.3)^2} \tag{29}$$

The water footprint of electricity from hydropower is compared with the water footprint of electricity from combustion of primary crops. The latter has been calculated per type of crop by first multiplying the water footprint of the primary crop in m^3/ton from Mekonnen and Hoekstra (2011) by the harvest index for that crop to get the water footprint in m^3 per ton of total biomass harvested. Harvest indices were taken from Gerbens-

Leenes et al. (2009a,b). Next, the water footprint of total biomass was divided by the bio-electricity output per unit of crop (GJ/ton) as reported by Gerbens-Leenes et al. (2008).

2.2 Data

Data on installed hydroelectric capacity, actual hydroelectric generation and reservoir area were obtained from the World Bank (1996). For some hydropower plants data were obtained from Dorcey et al. (1997) and other sources. Data on reservoir water holding capacity were obtained mainly from Chao et al. (2008). Appendix I provides data on installed capacity, hydroelectric generation, reservoir capacity and reservoir area for the selected hydropower plants.

Daily values of mean air temperature, dew point temperature and wind speed for the selected meteorological stations were obtained from NCDC (2009). The daily data for the years 1996-2005 were averaged in order to fill missing values and smooth out some inconsistencies in the data. Monthly values of cloud cover and percentage of maximum possible sunshine with a spatial resolution of 10 arc minute were obtained from the CRU CL-2.0 database (New et al., 2002). The cloud cover and sunshine duration were available only as monthly averages for the period 1961-1990. Therefore the monthly average values were used as daily values for each month of the year.

3. Results: the water footprint of hydroelectricity

The aggregated blue water footprint of the 35 selected hydropower plants is 90 Gm^3/yr, which is equivalent to 10% of the blue water footprint of global crop production in the year 2000 (Mekonnen and Hoekstra, 2011; Fader et al., 2011). The total blue water footprint of hydroelectric generation in the world must be considerably larger if one considers the fact that this study covers only 8% of the global installed hydroelectric capacity. Appendix II provides a map of the locations of the hydropower sites included in this study and the total water footprint associated per plant. The annual evaporation from hydropower reservoirs depends on both climate (which determines the evaporation from the water surface in mm/yr) and reservoir area.

The water footprint of electricity from hydropower for the 35 selected hydropower plants is presented in Table 1. The average water footprint of electricity from hydropower for the selected plants is 68 m^3/GJ. There is a large variation in water footprint among the different power plants, ranging from 0.3 m^3/GJ for San Carlos in Colombia to 846 m^3/GJ for Akosombo-Kpong in Ghana.

Most of the reservoirs show an evaporation rate between 2000 and 3000 mm/yr. Reservoirs in the tropics have generally a higher evaporation rate than reservoirs in temperate and sub-tropic climatic regions. The surface water evaporation varies from no more than 486 mm/yr from the Sayano Shushenskaya reservoir in Russia to 3059 mm/yr from the Cahora Bassa reservoir in the Zambezi River in Mozambique (Table 1). Minimum and maximum evaporation rates thus differ by a factor of six, which partially explains the differences between the water footprints of different hydropower reservoirs. The size of the reservoir surface in relation to the installed hydroelectric capacity, however, has a much bigger impact on the ultimate water footprint of hydroelectricity. While the average reservoir area per unit of installed capacity in the reservoirs studied is 83 ha/MW, the minimum is 0.26 ha/MW (San Carlos reservoir, Colombia) and the maximum 720 ha/MW (Akosombo-Kpong in the Volta River, Ghana). The total evaporation from a hydropower reservoir thus depends more on its size than on climate. This is illustrated in Figure 1, which shows a more or less linear relationship between the water footprint of the power plants and ha/MW. Hydropower plants that inundate a large area per unit of installed capacity have in general a larger water footprint per unit of electricity generated than those that flood a small area per unit of installed capacity.

The largest hydropower plant in terms of installed hydroelectric capacity in this study, the Itaipu dam in the Paraná River at the border of Brazil and Paraguay, has a water footprint of 7.6 m^3/GJ. The second-largest studied hydropower plant in terms of MW, the Guri reservoir in Venezuela, has a water footprint that is close to the global average of 68 m^3/GJ found in this study. The largest plant in terms of MW that has a water footprint far beyond the average found in this study is the Cahora Bassa dam in the Zambezi River in Mozambique, with a water footprint of 186 m^3/GJ.

Table 1. Water footprint of electricity for selected hydropower plants.

Power plant	Reservoir area [ha]	Installed capacity [MW]	Evaporation [mm/yr]	Evaporation [Gm^3/yr]	Water footprint [m^3/GJ] for theoretical maximum energy production	Water footprint [m^3/GJ] for actual energy production
Akosombo-Kpong*	850200	1180	2185	18.58	499	846
Bayano	35000	150	2156	0.75	160	381
Cahora Bassa	266000	2075	3059	8.14	124	186
Cerron Grande (Silencio)	13500	135	2267	0.31	71.9	152
Chivor (La Esmerelda)	1200	1008	1607	0.02	0.6	1.7
Chixoy	1300	300	2393	0.03	3.3	6.4
Cirata	6100	500	2626	0.16	10.2	31.1
El Chocon	81600	1200	2089	1.70	45.0	131
Estreito	45600	1050	2285	1.04	31.5	70.6
Fortuna	1000	300	2251	0.02	2.4	4.3
Guri	426000	10300	2787	11.87	36.6	71.7
Itaipu	135000	14000	1808	2.44	5.5	7.6
Itezhi Tezhi	37000	600	2572	0.95	50.3	94.4
Itumbiara	76000	2082	2239	1.70	26	52.5
Jaguari	7001	460	1782	0.12	8.6	14.4
Karakaya	29800	1800	1920	0.57	10.1	21.8
Kariba	510000	1320	2860	14.59	350	633
Kiambere	2500	150	2356	0.06	12.5	18.0
Kulekhani	2000	60	1574	0.03	16.6	47.0
Lubuge	400	600	1040	0.00	0.2	0.5
Marimbondo	43800	1400	2330	1.02	23.1	38.3
Morazan (El Cajo)	9400	300	2622	0.25	26.1	52.2
Nam Ngum	37000	150	2411	0.89	189	252
Pehuenche	200	500	1884	0.00	0.2	0.4
Playas	1100	204	1663	0.02	2.8	3.6
Robert-Bourossa-La Grande-2A**	281500	7722	586	1.65	6.8	8.3
Saguling	5600	700	2422	0.14	6.1	17.5
San Carlos	300	1145	1726	0.01	0.1	0.3
Sao Simao	67400	1635	2229	1.50	29.1	40.8
Sayano Shushenskaya	62100	6400	486	0.30	1.5	3.6
Sir	4100	315	1973	0.08	8.1	31.0
Sobradinho	421400	1050	2841	11.97	362	399
Tucurui (Raul G. Lhano)	243000	8400	2378	5.78	21.8	49.5
Yacyreta	172000	2700	1907	3.28	47.8	79.6
Yantan	10800	1210	1646	0.18	4.7	7.7
Average			2320	90	39	68

* The data are for the combined Akosombo-Kpong system. Kpong is a runoff power plant using Akosombo dam. Akosombo and Kpong generate 1020 MW and 160 MW respectively.

** Robert-Bourossa together with La Grande-2A use the Robert-Bourossa reservoir and generate 5616 MW and 2106 MW respectively. Energy generation of La Grand-2-A is assumed to be half of that of Robert-Bourossa

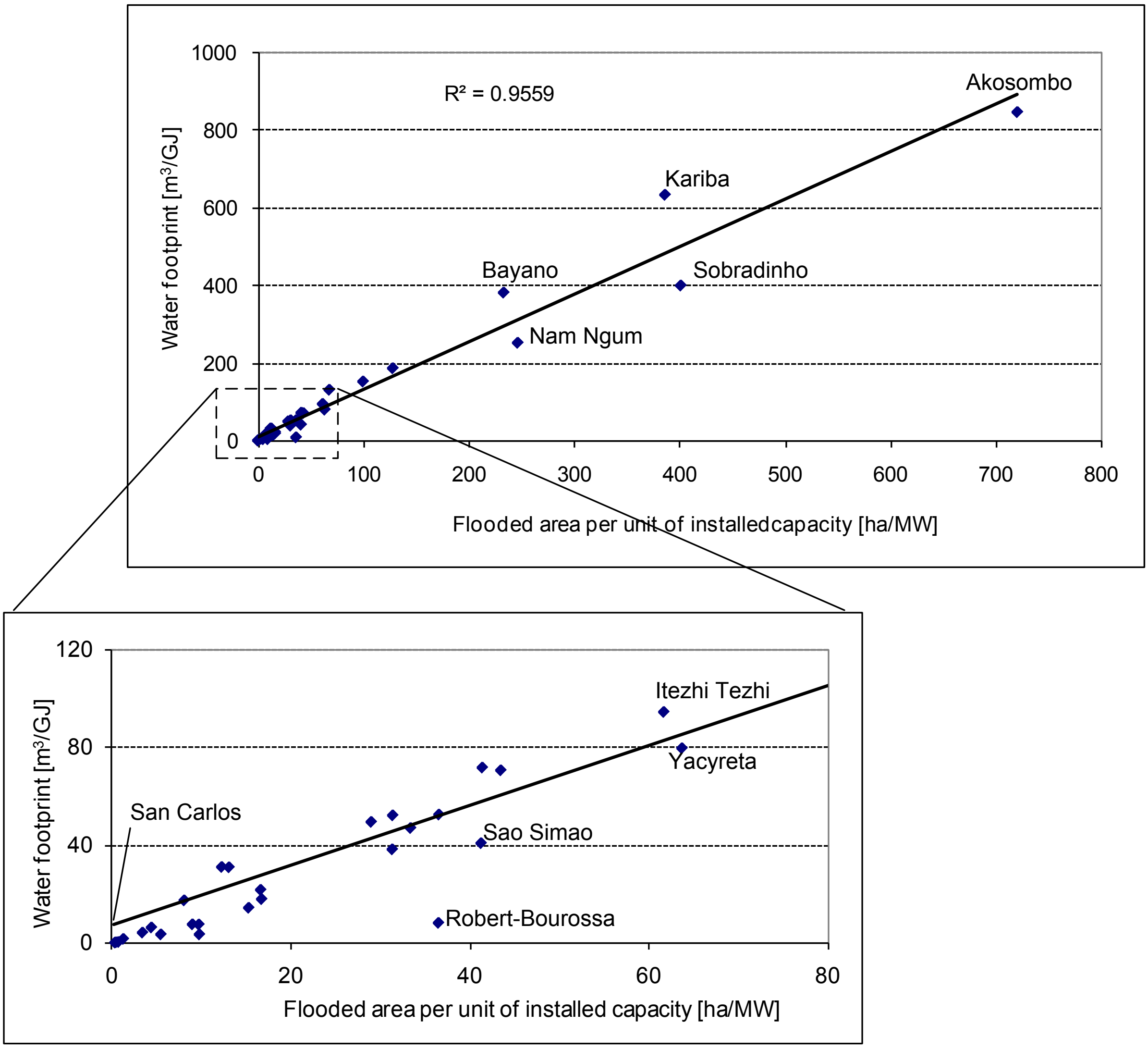

Figure 1. Relation between the water footprint of hydroelectricity and the flooded area per unit of installed hydroelectric capacity.

When we compare the water footprint of electricity from hydropower with the water footprint of electricity from other renewable sources, it appears that hydroelectricity has a relatively large water footprint per GJ. The blue water footprint of electricity from wind and solar energy is estimated to be well below 1 m^3/GJ (Gerbens-Leenes et al., 2009a). The blue water footprint of bio-electricity – when derived from combustion of the full biomass of primary crops – ranges from zero to 40 m^3/GJ, depending on which crop is used for comparison and to which extent it is irrigated. The 40 m^3/GJ refers to bio-electricity from combustion of cotton, which is a rather theoretical example, because cotton is in practice not used for the purpose of electricity generation. Also other crops are rarely used for that purpose. More common feedstock for the generation of bio-electricity are crop residues, animal manure, wood wastes from forestry and industry, residues from food and paper industries, municipal green wastes and sewage sludge. In all those cases, the water footprint of bio-electricity will be much lower than the water footprint of bio-electricity from combustion of primary crops, because the water footprint of biomass is largely attributed to the primary product and not to the residues and waste (Hoekstra et al., 2011).

Figure 2 compares the blue water footprint of electricity from hydropower with the total (green+blue+grey) water footprint of electricity from combustion of primary crops. For a fair comparison one should compare the blue water footprints. But even when comparing the total water footprints, bioelectricity from a number of crops – including sugar beet, sugar cane and maize – will have a smaller water footprint than hydroelectricity. In other words, one drop of blue water allocated for consumption for hydroelectric generation generally yields much less energy than one drop of blue water allocated for consumption in crop production for generating feedstock for bioelectricity. This is not to suggest that in general it is advisable to allocate water to grow crops for producing bioelectricity rather than to generate a much lower amount of hydroelectricity at the cost of the same volume of water. In many cases this alternative allocation is not a reasonable choice, or even impossible (e.g. due to the unavailability of suitable land). Besides, for such broad decisions as investing in different sectors, one needs to take into account all relevant economic, social and environmental factors, not the factor of water productivity alone. Also one should account for the fact that many hydroelectric dams are designed to serve other purposes as well. What we do want to argue, however, is that hydroelectric generation is generally a large water consumer and that in allocating water to hydroelectric generation it is advisable to explore the foregone costs by not allocating the water to alternative uses, either upstream or downstream of the location of a planned hydropower reservoir. Alternative uses include crop growing for bioelectricity, but more common alternatives are to allocate the blue water to grow crops for food, feed, fibres or biofuel or to let the blue water in the river to maintain environmental flows.

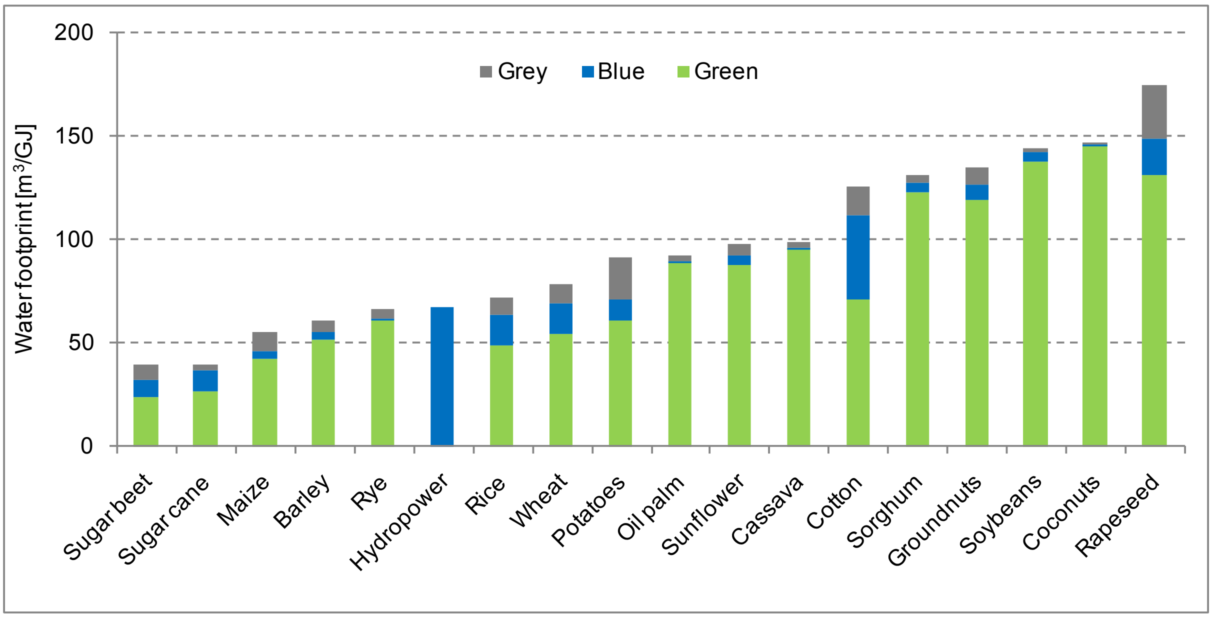

Figure 2. Global average water footprint of electricity from hydropower compared to the water footprint of electricity from combustion of primary crops.

4. Discussion

The water footprints of the artificial reservoirs analysed in this study were fully attributed to hydroelectric generation, even though some of the reservoirs serve other purposes as well, such as flood control and irrigation. We justify this choice by the fact that all selected hydropower dams and associated reservoirs were primarily created for hydroelectric generation. Future research could be directed towards the analysis of the water footprint of reservoirs created for storing water for irrigation or other purposes and on tackling the water footprint attribution issue when reservoirs are used for multiple purposes.

The model output is sensitive to a number of input parameters such as air temperature, wind speed and water body depth. Since climatic data at the dam site are available only for a few plants, data from the most nearby climatic stations have been used, some of which are a bit far from the reservoir (see Appendix I). Due to the uncertainties in the input data, the data presented should be seen as indicative. The order of magnitude of the results, however, will not change with better data, so that the results are good enough to compare the water footprint of hydroelectricity with the water footprint of other forms of electricity and to make rough comparisons between the water footprints of different hydropower sites.

Most reservoirs have a varying water surface area over time, as a result of changes in water volume during the year and between years. The difference between minimum and maximum area relative to the maximum area over a multi-year period differs greatly across reservoirs. In this study we have used a fixed reservoir area as provided by World Bank (1997) and Dorcey et al. (1997). Since reported areas generally refer to the maximum, this can lead to some overestimation of evaporation over the year. It is very difficult to find good data of area changes over the year; future studies devoted to particular sites could improve this.

We have estimated the water footprint per reservoir by considering the total evaporation from the reservoir, whereas one could argue that before the reservoir was created there was evaporation from the area as well, probably not so much from the original flowing river (since in most cases the reservoir area is much larger than the original river water area) but possibly significant from the inundated land. However, here it is relevant to recall the definition and meaning of the water footprint. The water footprint is not meant to refer to additional evaporation (compared to some reference situation), but for quantifying the volume of water consumption that can be associated with a specific human purpose (Hoekstra et al., 2011). From this perspective, the full reservoir evaporation can be attributed to the purpose of the reservoir.

The study has been limited to the estimation of the evaporation from reservoirs, i.e. the so-called operational water footprint of hydroelectric generation. The study does not include an assessment of the supply-chain water footprint of hydroelectric generation, which is expected to be much smaller than the operational water footprint. The supply-chain water footprint refers to the water footprint of producing the materials used in the construction and the operation and maintenance of the site.

The current study does not claim to be exhaustive in terms of showing both the beneficial and negative effects of hydropower. The study has been restricted to the estimation of the water footprint of different hydropower plants. Environmental issues surrounding hydropower dams relate to, for example: physical, chemical, biological and geomorphological aspects of blocking a river; flooding of natural habitats and related loss of plants and animals; alteration of water flow regimes; and water quality problems due to the decay of submerged vegetations. On the other hand, hydropower is often perceived as a clean and cost-effective source of renewable energy. Many countries rely upon hydropower for a substantial portion of their electricity supply. Between 1973 and 2008, hydroelectric generation grew from 1295 TWh to 3288 TWh, which is a growth by a factor 2.5 (IEA, 2010). Further development of hydropower should take into account all the associated environmental and social costs. In this respect, the water footprint of hydroelectricity, i.e. the consumptive use of water, should be considered as one item in environmental impact assessment studies for newly proposed hydroelectric dams.

5. Conclusion

Hydroelectric generation has historically been considered as a non-consumptive water user; however, through the estimation of the blue water footprint of hydroelectricity at 35 sites, this study finds that hydropower is a large consumptive user of water. The amount of water lost through evaporation annually from the selected reservoirs is equivalent to 10% of the global blue water footprint related to crop production. The 35 sites represent only 8% of the global installed hydroelectric capacity. The study shows that the range of water footprint values for the different hydropower plants is very wide. Although local climate has an influence, the water footprint of hydroelectricity is largely influenced by the area flooded per unit of installed capacity. The water footprint linearly increases with the area flooded per unit of installed capacity.

The water evaporated from the reservoir is seldom taken into account in assessing the pros and cons of constructing dams for hydroelectric generation. This study demonstrates that accounting for water loss through evaporation is an additional consideration when evaluating the environmental, social and economic sustainability of a proposed dam or in the evaluation of hydropower as an energy source. We recommend that water footprint assessment is added as a component in evaluations of newly proposed hydropower plants as well as in the evaluation of existing hydroelectric dams, so that the consequences of the water footprint of hydroelectric generation on downstream environmental flows and other water users can be evaluated.

The water footprint of hydroelectric dams should be considered in the context of the river basin in which this water footprint occurs, because competition over water and possible alternative uses of water differ per basin. This study contributes new information that can be used in river basin planning and water allocation decisions.

Sustainable development of hydropower requires the accounting and internalization of all external costs including water consumption. Internalization means that the economic and environmental costs of the water consumed are charged to the operator of a hydropower plant and included in the price of hydroelectricity. It should thereby be acknowledged that water consumption costs vary within the year and across river basins, since the degree of water scarcity and competition over water depend on the period within the year and local circumstances.

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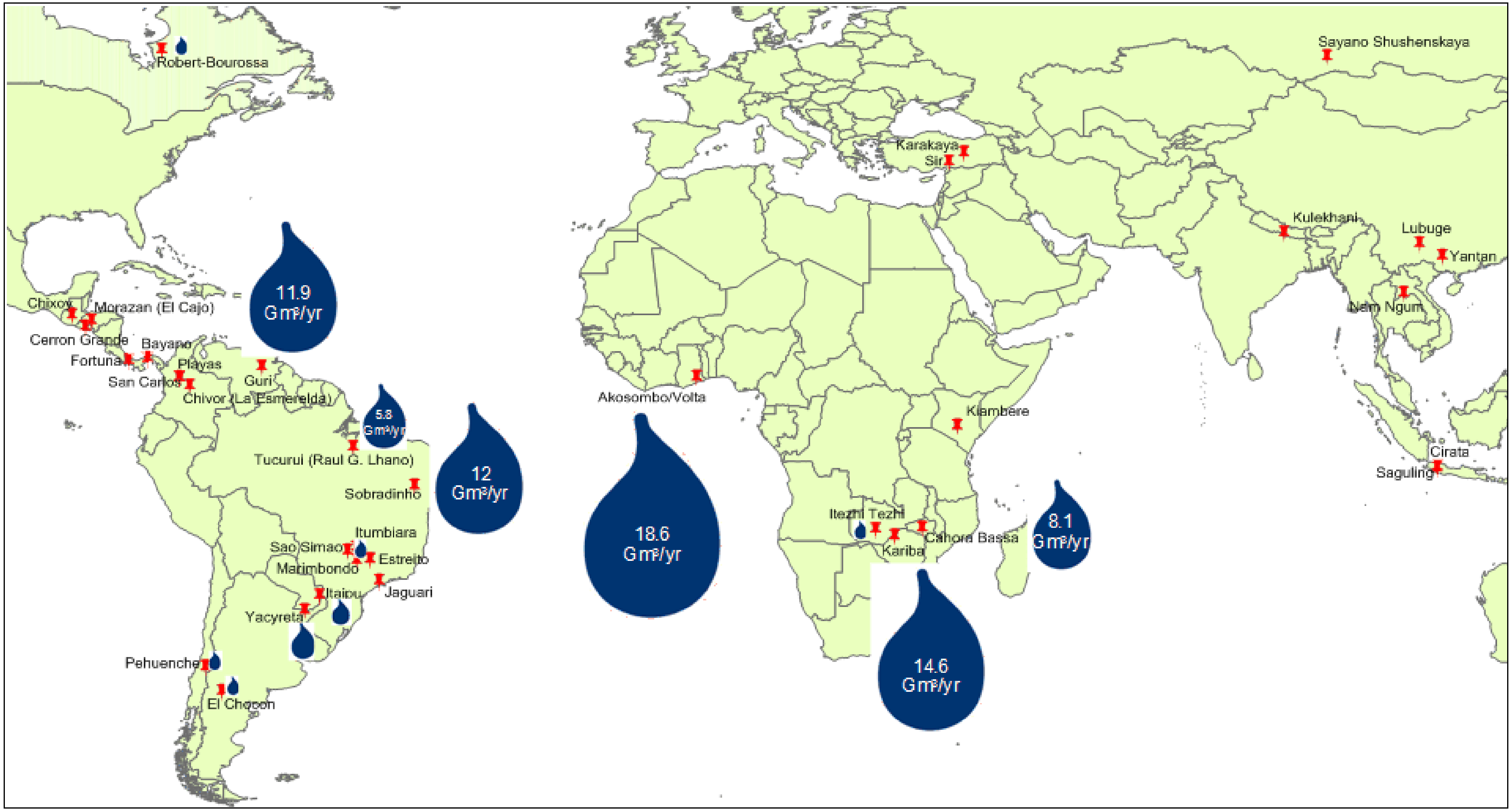
Appendix I: Data on the location, reservoir capacity and area, installed capacity and hydroelectric generation of selected hydropower plants

Reservoir	Country	Coordinate system at dam site		Dam height	Reservoir capacity*	Reservoir area**	Installed capacity**	Hydroelectric generation [GWh/yr]**		Nearest climatic station***	Coordinate system of station***	
		LAT	LON	[m]	[10^6 m^3]	[ha]	[MW]	theoretical maximum	actual production		LAT	LON
Itaipu	Brazil-Paraguay	-25.409	-54.589	196	29000	135000	14000	122640	88964	Foz Do Iguacu (Aero)	-25.517	-54.583
Guri	Venezuela	7.767	-63.000	162	135000	426000	10300	90228	46000	Ciudad Bolivar	8.150	-63.550
Tucurui	Brazil	-3.867	-49.733	93	36375	243000	8400	73584	32412	Tucurui	-3.717	-49.717
Sayano Shushenskaya	Russia	52.826	91.371	245	31300	62100	6400	56064	23500	Beja	53.050	90.917
Robert-Bourossa	Canada	53.795	-77.441	170	61700	281500	7722	67645	55346	La Grande Riviere	53.633	-77.700
Yacyreta	Argentina/ Paraguay	-27.567	-56.733	43	21000	172000	2700	19080	11448	Posadas Aero.	-27.367	-55.967
Cahora Bassa	Mozambique	-15.567	32.700	171	55800	266000	2075	18177	12133	Kanyemba	-15.633	30.417
Karakaya	Turkey	38.833	38.750	173	9580	29800	1800	15768	7300	Elazig	38.600	39.283
Sao Simao	Brazil	-18.933	-50.517	120	12540	67400	1635	14323	10223	Uberlandia	-18.883	-48.217
Marimbondo	Brazil	-20.303	-49.198	90	6150	43800	1400	12264	7400	Uberaba	-19.783	-47.967
Kariba	Zambia-Zimbabwe	-16.750	28.750	128	180600	510000	1320	11563	6400	Kariba	-16.517	28.883
Yantan	China	23.854	108.132	110	2430	10800	1210	10600	6420	Da-Wan	23.850	109.417
El Chocon	Argentina	-39.283	-68.767	86	20200	81600	1200	10512	3621	Neuquen Aero	-38.950	-68.133
San Carlos	Colombia	6.207	-74.839	77	72	300	1145	10030	5400	Rionegro/J.M. Cordov	6.133	-75.433
Estreito	Brazil	-20.155	-47.281	92	1418	45600	1050	9198	4100	Uberaba	-19.783	-47.967
Sobradinho	Brazil	-9.467	-40.834	33	34100	421400	1050	9198	8326	Petrolina (Aeroport)	-9.350	-40.550
Akosombo-Kpong	Ghana	6.300	0.059	134	150000	850200	1180	9461	6100	Atakpame	7.583	1.117
Chivor (La Esmerelda)	Colombia	5.033	-73.417	237	760	1200	1008	8830	3100	Bogota/Eldorad o	4.700	-74.133
Itumbiara	Brazil	-18.417	-49.250	106	17000	76000	2082	18238	9000	Uberlandia	-18.883	-48.217
Saguling	Indonesia	-6.913	107.367	99	875	5600	700	6132	2156	Bandung	-6.883	107.600
Itezhi Tezhi	Zambia	-15.765	26.018	65	5600	37000	600	5256	2800	Lusaka City Airport	-15.417	28.467
Lubuge	China	25.712	104.794	100	1110	400	600	5256	2400	Xingren	25.433	105.183
Cirata	Indonesia	-6.701	107.367	125	3165	6100	500	4380	1430	Bandung	-6.883	107.600

Reservoir	Country	Coordinate system at dam site		Dam height	Reservoir capacity*	Reservoir area**	Installed capacity**	Hydroelectric generation [GWh/yr]**		Nearest climatic station***	Coordinate system of station***	
		LAT	LON	[m]	[10^6 m^3]	[ha]	[MW]	theoretical maximum	actual production		LAT	LON
Pehuenche	Chile	-35.759	-71.087	90	40	200	500	4380	2871	Curico	-34.967	-71.233
Jaguari	Brazil	-23.283	-45.950	70	1396	7001	460	4030	2400	Sao Jose Dos Campos	-23.217	-45.850
Sir	Turkey	37.501	36.596	120	1120	4100	315	2759	725	Kahramanmara s	37.600	36.933
Chixoy	Guatemala	15.282	-90.491	133	424	1300	300	2628	1350	Huehuetenango	15.317	-91.467
Fortuna	Panama	8.742	-82.251	110	160	1000	300	2628	1450	David	8.400	-82.417
Morazan (El Cajo)	Honduras	14.500	-87.650	238	7085	9400	300	2628	1312	La Mesa (San Pedro)	15.450	-87.933
Playas	Colombia	6.290	-74.938	65	76.4	1100	204	1787	1422	Rionegro/J.M.C ordov	6.133	-75.433
Bayano	Panama	8.950	-79.500	75	4000	35000	150	1314	550	Tocumen	9.050	-79.367
Kiambere	Kenya	-0.817	37.817	112	585	2500	150	1314	910	Embu	-0.500	37.450
Nam Ngum	Laos	18.500	102.500	75	7030	37000	150	1314	984	Vientiane	17.950	102.567
Cerron Grande (Silencio)	El Salvador	13.600	-88.533	76	1430	13500	135	1183	559	San Salvador/Ilopan	13.700	-89.117
Kulekhani	Nepal	27.244	85.171	114	85.3	2000	60	526	186	Kathmandu Airport	27.700	85.367

Sources:
* Chao et al. (2008).
** World Bank (1997), Dorcey et al. (1997) and other sources.
*** NCDC (2009).

Appendix II: Water footprint of selected hydropower plants in the world



The map shows the location of the selected hydropower plants and the total water footprint for plants with total water footprint above 1Gm^3/yr.

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UNESCO-IHE
P.O. Box 3015
2601 DA Delft
The Netherlands

Website www.unesco-ihe.org
Phone +31 15 2151715

UNESCO-IHE
Institute for Water Education

University of Twente

UNIVERSITY OF TWENTE.

Delft University of Technology

TU Delft
Delft University of Technology