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The water footprint of electricity from hydropower

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Abstract

Hydropower accounts for about 16% of the world's electricity supply. It has been debated whether hydroelectric generation is merely an in-stream water user or whether it also consumes water. In this paper 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 man-made reservoirs to produce electric energy – for 35 selected sites. The aggregated blue water footprint of the selected hydropower plants is $90 \text{ Gm}^3 \text{ yr}^{-1}$, 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 $68 \text{ m}^3 \text{ GJ}^{-1}$. 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.

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

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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 World Congress organized by the International Hydropower Association, 14–17 June 2011 in Brazil, a special session was even devoted to the question: Does hydropower consume water? The session explored different interpretations of water ‘consumption’ in an attempt to recognize the energy impacts on water. In this paper 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 paper is restricted

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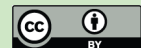
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to the quantification of the blue water footprint of hydroelectricity and focuses on the consumptive use of water that relates to the evaporation from the artificial reservoirs that are created behind hydroelectric dams.

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 $22 \text{ m}^3 \text{ GJ}^{-1}$.

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, Yacireta 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).

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2 Method and data

The water footprint of electricity (WF, m³ GJ⁻¹) generated from hydropower is calculated by dividing the amount of water evaporated from the reservoir annually (WE, m³ yr⁻¹) by the amount of energy generated (EG, GJ yr⁻¹):

$$WF = \frac{WE}{EG} \quad (1)$$

The total volume of evaporated water (WE, m³ yr⁻¹) from the hydropower reservoir over the year is:

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

where E is the daily evaporation (mm day⁻¹) 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

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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^{-1}) is estimated using the Penman-Monteith equation with an inclusion of water body heat storage. This equation is written as (McJannet et al., 2008):

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

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

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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 $\text{m}^3 \text{ton}^{-1}$ 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^{-1}) as reported by Gerbens-Leenes et al. (2008).

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 Goodland (1997) and other sources. Data on reservoir water holding capacity were obtained mainly from Chao et al. (2008).

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 min 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 $90 \text{ Gm}^3 \text{yr}^{-1}$, 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. The annual evaporation from hydropower reservoirs depends

on both climate (which determines the evaporation from the water surface in mm yr^{-1}) 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 $68 \text{ m}^3 \text{ GJ}^{-1}$. There is a large variation in water footprint among the different power plants, ranging from $0.3 \text{ m}^3 \text{ GJ}^{-1}$ for San Carlos in Colombia to $846 \text{ m}^3 \text{ GJ}^{-1}$ for Akosombo-Kpong in Ghana.

Most of the reservoirs show an evaporation rate between 2000 and 3000 mm yr^{-1} . 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^{-1} from the Sayano Shushenskaya reservoir in Russia to 3059 mm yr^{-1} 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^{-1} , the minimum is 0.26 ha MW^{-1} (San Carlos reservoir, Colombia) and the maximum 720 ha MW^{-1} (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 Fig. 1, which shows a more or less linear relationship between the water footprint of the power plants and ha MW^{-1} . 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 $7.6 \text{ m}^3 \text{ GJ}^{-1}$. The second-largest studied hydropower plant in terms of MW, the Guri reservoir in Brazil, has a water footprint that is close to the global av-

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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, fibers or biofuel or to let the blue water in the river to maintain environmental flows.

4 Discussion

The water footprints of the artificial reservoirs analyzed 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. Due to the uncertainties in the input data, the data presented should be seen as indicative. The order of magnitude

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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.

5 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 (1996) and Goodland (1997). Since reported areas generally refer to the
10 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
15 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),
20 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
25 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.

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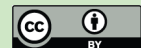
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The current study does not claim to be exhaustive in terms of showing both the beneficial and negative effects of hydropower. The study has been restricted to the estimation of the water footprint of different hydropower plants. Environmental issues 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 Conclusions

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.

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Gerbens-Leenes, P. W., Hoekstra, A. Y., and Van der Meer, Th. H.: water footprint of bioenergy and other primary energy carriers, Value of Water Research Report Series No. 29, UNESCO-IHE, Delft, The Netherlands, 2008.

Gerbens-Leenes, P. W., Hoekstra, A. Y., and Van der Meer, T. H.: The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bioenergy in energy supply, *Ecol. Econ.*, 68, 1052–1060, 2009a.

Gerbens-Leenes, W., Hoekstra, A. Y., and Van der Meer, T. H.: The water footprint of bioenergy, *Proc. of Natl. Acad. Sci. U.S.A.*, 106, 10219–10223, 2009b.

Gleick, P. H. (Ed.): *Water in crisis, A guide to the world's freshwater resources*, Oxford University Press, New York, 1993.

Goodland, R.: Environmental sustainability in the hydro industry, in: *Workshop Proceedings of IUCN-The World Conservation Union and The World Bank Group*, Gland, Switzerland, 69–102, 1997.

Hoekstra, A. Y. and Chapagain, A. K.: *Globalization of water: Sharing the planet's freshwater resources*, Blackwell Publishing, Oxford, UK, 2008.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., and Mekonnen, M. M.: *The water footprint assessment manual: Setting the global standard*, Earthscan, London, UK, 2011.

IEA: *Key world energy statistics 2010*, International Energy Agency, Paris, France, 18–19, 2010.

Lenters, J. D., Kratz, T. K., and Bowser, C. J.: Effects of climate variability on lake evaporation: Results from a long-term energy budget study of sparkling lake, Northern Wisconsin, USA, *J. Hydrol.*, 308, 168–195, 2005.

Lerer, L. B. and Scudder, T.: Health impacts of large dams, *Environ. Impact Asses.*, 19, 113–123, 1999.

McJannet, D. L., Webster, I. T., Stenson, M. P., and Sherman, B. S.: *Estimating open water evaporation for the Murray Darling basin*, Report for CSIRO, Australia, 2008.

Mekonnen, M. M. and Hoekstra, A. Y.: The green, blue and grey water footprint of crops and derived crop products, *Hydrol. Earth Syst. Sci.*, 15, 1577–1600, doi:10.5194/hess-15-1577-2011, 2011.

NCDC, *Global surface summary of the day*, National Climatic Data Centre, <http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html>, last access: 5 February 2009.

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- New, M., Lister, D., Hulme, M., and Makin, I.: A high-resolution data set of surface climate over global land areas, *Climate Res.*, 21, 1–25, 2002.
- Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O’Keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E., and Warner, A.: The natural flow regime: a paradigm for river conservation and restoration, *BioScience*, 47, 769–784, 1997.
- Rosenberg, D. M., Bodaly, R. A., and Usher, P. J.: Environmental and social impacts of large scale hydroelectric development: who is listening?, *Global Environ. Chang.*, 5, 127–148, 1995.
- Scudder, T.: Social impacts of large dams, in: *Workshop Proceedings of IUCN-The World Conservation Union and The World Bank Group*, Gland, Switzerland, 41–68, 1997.
- Shiklomanov, I. A.: Appraisal and assessment of world water resources, *Water Int.*, 25, 11–32, 2000.
- Singh, V. P. and Xu, C.-Y.: Evaluation and generalization of 13 mass-transfer equations for determining free water evaporation, *Hydrol. Process.*, 11, 311–323, 1997.
- Sternberg, R.: Hydropower: dimensions of social and environmental coexistence, *Renew. Sust. Energ. Rev.*, 12, 1588–1621, 2008.
- Sternberg, R.: Hydropower’s future, the environment, and global electricity systems, *Renew. Sust. Energ. Rev.*, 14, 713–723, 2010.
- Tilt, B., Braun, Y., and He, D.: Social impacts of large dam projects: A comparison of international case studies and implications for best practice, *J. Environ. Manage.*, 90 (Supplement 3), S249–S257, 2009.
- Winter, T. C., Rosenberry, D. O., and Sturrock, A. M.: Evaluation of 11 equations for determining evaporation for a small lake in the north central United States, *Water Resour. Res.*, 31, 983–993, 1995.
- World Bank: *The World Bank’s experience with large dams: a preliminary review of impacts*, Operations Evaluation Department, World Bank, Washington, D.C., USA, 1996.
- World Commission on Dams: *Dams and development: a new framework for decision-making*, Earthscan, London, UK, 2000.

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

Power plant	Reservoir area [ha]	Installed capacity [MW]	Evaporation		Water footprint [m ³ GJ ⁻¹]	
			[mm yr ⁻¹]	[Gm ³ yr ⁻¹]	for theoretical maximum energy production	for actual energy production
Akosombo-Kpong*	850 200	1180	2185	18.58	499	846
Bayano	35 000	150	2156	0.75	160	381
Cahora Bassa	266 000	2075	3059	8.14	124	186
Cerron Grande (Silencio)	13 500	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	81 600	1200	2089	1.70	45.0	131
Estreito	45 600	1050	2285	1.04	31.5	70.6
Fortuna	1000	300	2251	0.02	2.4	4.3
Guri	426 000	10 300	2787	11.87	36.6	71.7
Itaipu	135 000	14 000	1808	2.44	5.5	7.6
Itezhi Tezhi	37 000	600	2572	0.95	50.3	94.4
Itumbiara	76 000	2082	2239	1.70	26	52.5
Jaguari	7001	460	1782	0.12	8.6	14.4
Karakaya	29 800	1800	1920	0.57	10.1	21.8
Kariba	510 000	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	43 800	1400	2330	1.02	23.1	38.3
Morazan (El Cajo)	9400	300	2622	0.25	26.1	52.2
Nam Ngum	37 000	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-Bouroussa-La Grande-2A**	281 500	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	67 400	1635	2229	1.50	29.1	40.8
Sayano Shushenskaya	62 100	6400	486	0.30	1.5	3.6
Sir	4100	315	1973	0.08	8.1	31.0
Sobradinho	421 400	1050	2841	11.97	362	399
Tucurui (Raul G. Lhano)	243 000	8400	2378	5.78	21.8	49.5
Yacyreta	172 000	2700	1907	3.28	47.8	79.6
Yantan	10 800	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-Bouroussa together with La Grande-2A use the Robert-Bouroussa 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-Bouroussa.

The water footprint of electricity from hydropower

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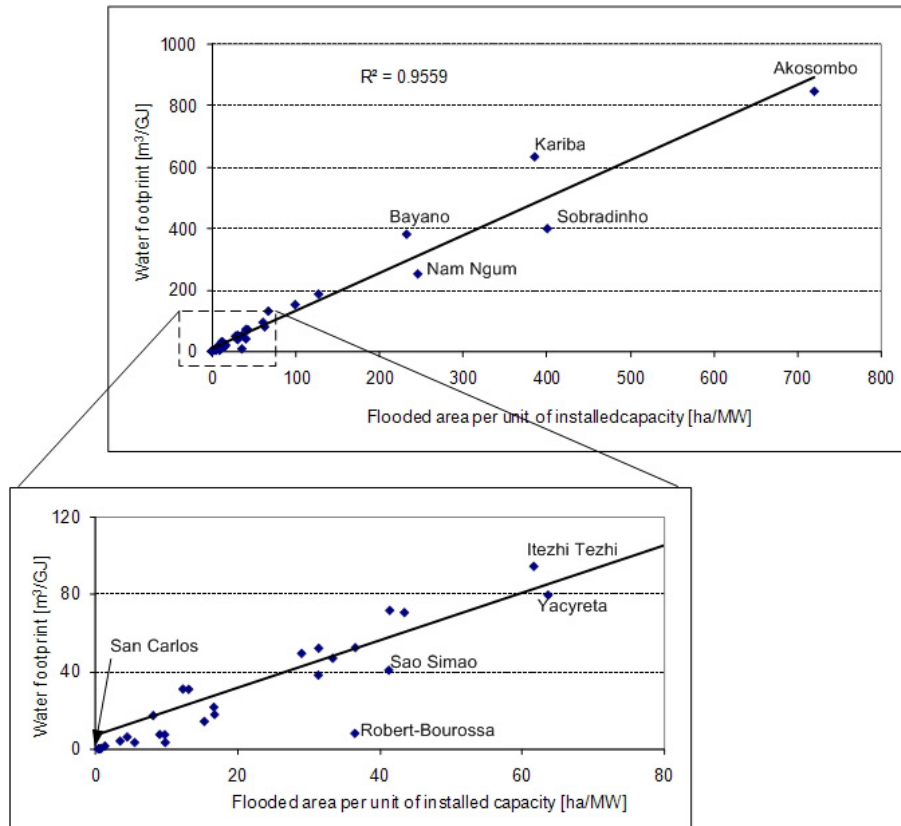


Fig. 1. Relation between the water footprint of hydroelectricity and the flooded area per unit of installed hydroelectric capacity.

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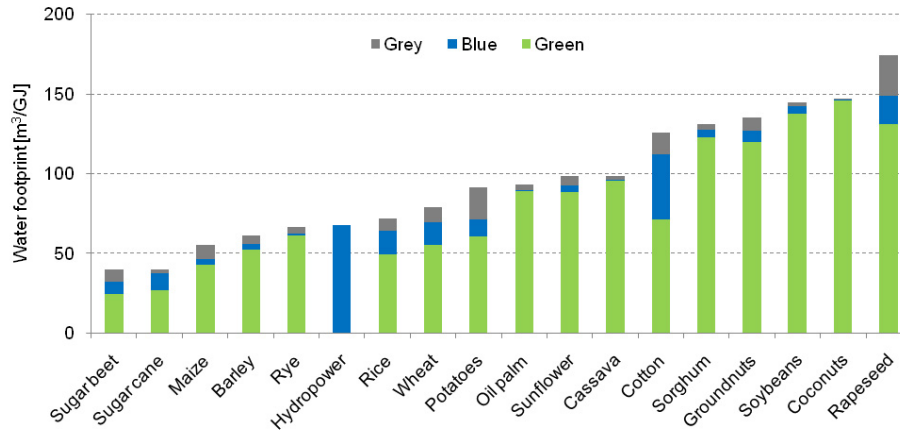


Fig. 2. Global average water footprint of electricity from hydropower compared to the water footprint of electricity from combustion of primary crops.

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