Water consumption from hydropower production: review of published estimates

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Abstract This paper presents an extensive review of all known published literature on water consumption from hydropower plants. The paper documents that the estimates show a large variation, from close to zero m^3/MWh to more than 3500 m^3/MWh, where the maximum values are far beyond the values published by IPCC (2011). The highest values are from irrigation reservoirs with very limited hydropower production. The review reveals that there is no consistent methodological approach in place, which is a major obstacle in making a fair comparison between hydropower projects, and ultimately between technologies.

Key words energy water nexus; hydropower; water consumption; water footprint; review of estimates

INTRODUCTION

Climate change and the needed reductions in the use of fossil fuels call for the development of renewable energy sources. Energy production is, however, recognised as potentially having an impact on the water resources and *vice versa*. This has led to a growing interest in assessing the "water footprint" of energy production, i.e. how much water is needed to produce one unit of energy (m^3/MWh). The recently published Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) compared renewable energy sources with respect to water consumption. This report revealed that the variation in water consumption per unit of electricity produced from hydropower projects was extremely large, ranging from close to 0 m^3/MWh up to 209 m^3/MWh, where the maximum value was far beyond other renewable energy sources. The high value of water consumption from hydropower is explained by the high evaporation rates from reservoirs located in subtropical and tropical regions, and that reservoir evaporation is assigned as losses of water to the hydropower plants. The report (ibid.) suffers from very few studies as the range of estimates for hydropower is based on only two sources/studies, reported in four publications. Due to the very limited number of studies, it is also very difficult to diversify the projects based on location, type of projects (reservoir *versus* run-of-the-river, large *versus* small) or other characteristics. A recent study (Macknick *et al.*, 2011, 2012a) provides an updated review of estimates of operational water withdrawal and water consumption factors for electricity generating technologies (but only including studies from the USA. These studies (IPCC, 2011; Macknick *et al.*, 2011, 2012a) all acknowledge that estimates of water consumption from hydropower production face methodological challenges.

The methodological approach of calculating the water footprint of hydropower projects has been questioned and debated (e.g. Pfister & Hellweg, 2009; IHA, 2011; Mekonnen & Hoekstra, 2011). The most well-known water footprint method is presented in Mekonnen & Hoekstra (2011) and defines the water footprint from hydropower to be the gross evaporation from the reservoir. This method misses several essential aspects. Firstly it does not take into account the evaporation from the reservoir areas prior to the hydropower project and provides therefore no information on net change in catchment water balance. Secondly, in the case of multi-purpose reservoirs, the water consumption is in most cases not shared between the various water uses, but is only assigned to the hydropower plant. Thirdly, the fact that reservoirs could improve the availability of water both in the reservoir area and the downstream areas due to their regulating effect is not accounted for, nor other services provided by the regulation, such as flood control, improved navigation, etc. Furthermore, Bates *et al.* (2008) emphasises the importance of reservoirs as measures against impacts on the water resources due to climate change.

This paper aims to provide a complete and updated review of all known and available studies/publications on estimates on water consumption from hydropower projects from all parts of the world. The paper clarifies terms, presents the estimates, unveils the primary sources, highlights the methodological differences used in the calculations and discusses possible reasons for the large variations.

REVIEW OF PUBLISHED ESTIMATES

Clarification of terms and limitations

A number of different terms related to the topic of this paper are used in the literature, including water use/usage, water consumption, water losses, water withdrawal and water footprint, sometimes having slightly different meaning, and applied in a non-consistent manner. The paper by USGS (Hutson *et al*., 2004), referred to by several authors (e.g. Kenny *et al*., 2009; Fthenakis & Kim, 2010; Macknick *et al*., 2012b), defines "*withdrawal as the amount of water removed from the ground or diverted from a water source for use*". Furthermore, consumptive use/water consumption is "*the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment*". Pfister *et al*. (2011) states that "*water consumption (consumptive use) denotes the part of the freshwater which is not released back to the original watershed; primarily due to evaporation and product integration*". Water withdrawal holds then both a consumptive and a non-consumptive component. Hoekstra *et al*. (2011) defines water footprint as "*the volume of water consumption that can be associated with a specific human purpose*" and by this argues (in the context of hydropower production) that "*the full reservoir evaporation can be attributed to the purpose of the reservoir*". According to the Water Footprint Network (WFN, 2012) the water footprint of a product (a commodity, good or service) "*is the total volume of freshwater used to produce the product, summed over the various steps of the production chain*". This definition clearly refers to a life-cycle perspective of the production of a commodity, good or service.

In this paper we define water consumption in hydropower production as the quantity of water that leaves the analysed system due to the reservoirs, and can hence be considered lost for hydropower production or the downstream water users/ecosystem. It appears from the reviewed studies (see overview in Table 1) that the system boundaries for the analysis ("analysed system") are in most cases the reservoir(s) established for power production. The fact that the evaporated water might return as precipitation to the river basin is hence neglected. The temporal span of the analyses are in most cases the operational phase of the power production.

The publications reviewed in this paper are all focused on the quantities of water that are consumed, and to a very little extent how a regulation/reservoir affects the quality of the water. Changing the river system from running to standing water due to damming and changing the natural hydrological conditions in the affected rivers might also change the water quality. Referring to Hoekstra *et al*. (2011), the water footprint methodology consists of three components: blue, green and grey, where the grey represents the polluted part, but in all the reviewed cases (including the case by Mekonnen & Hoekstra, 2012), only the impacts on the blue component (surface water and groundwater) are estimated.

It is assumed in the reviewed studies that the major water consumption from hydropower projects are by far dominated by evaporation losses from the reservoir surface. The issue is raised by e.g. Gleick (1994) by discussing the possible contribution of losses due to seepage, which might be present in hydropower projects sited in areas with porous geological formations. Gleick (1994) argues that seepage should not be considered as "consumed water" even though it is not available for electricity production, as it is assumed returning to the river/river basin downstream of the hydropower plant and hence not "lost" into the atmosphere or embedded in a product or service.

Table 1 Published estimates for water consumption from hydropower projects.

Study	Given estimate	Estimate in (m^3/MWh)	Climatic region	Calculat. method(1)	Data source
Gleick (1992) / Gleick (1993)	Range: 0.01–58 $km^3/10^{18}$ J Median: 1.5	0.04 (min) 5.4 (median) 209 (max)	California, US (a diverse set of 100 plants)	Gross E	Primary source
Gleick (1994)	California: Mean: 5.4 $m^3/10^3$ KWh Median: 26 $m^3/10^3$ KWh US average: 17 $m^3/10^3$ KWh	California: Mean: 5.4 m^3/MWh Median: 26 m^3/MWh US average: 17 m^3/MWh	California and US averages	Gross E	Gleick (1992)
Torcellini *et al*. (2003)	18 gal/KWh	68 (average)	US average – 120 largest plants, providing ~65% of prod. in 1999	Gross E(2)	Primary source
US Dept. of Energy (2006)	4500 gal/MWh	17	US average	Gross E	Gleick (1994)
Pasqualetti & Kelly (2008)	30078 gal/MWh	113.9	Arizona, US	Gross E(3)	Primary source
Gerbens-Leenes *et al*. (2009)	22 m^3/GJ	80	Global average(4)	Gross E	Primary source
Mielke *et al*. (2010)	4500 gal/MWh	17	US average	Gross E	Gleick (1994) & US Dept. of Energy (2006)
Fthenakis & Kim (2010)	California – range: 38–210000 L/MWh Median: 5300 L/MWh US average: 17 000 L/MWh	0.04 (min) 5.4 (median) 209 (max) 17 (US average)	California and US	Gross E	Gleick (1993)(5)
Herath *et al*. (2010)	Gross average: 6.05 m^3/GJ Net average: 2.72 m^3/GJ Water balance: 1.55 m^3/GJ	21.8 (Gross average) 9.8 (Net average) 5.6 (Water balance)	"All plants" Northern and Southern New Zealand	Gross E, Net E & WB(6)	Primary source
IPCC (2011)	Range: 38 L/MWh – 209 m^3/MWh	0.038 (min) 209 (max)	US only	Gross E	Gleick (1993), Torcellini *et al*. (2003), Mielke *et al*. (2010), Fthenakis & Kim (2010)(7)
Macknick *et al*. (2011) / Macknick *et al*. (2012a) /	Range: 1425 gal/MWh – 18 000 gal/MWh Median: 4491 gal/MWh	5.4 (min) 17.0 (median) 68.1 (max)	US	Gross E	Gleick (1994), Torcellini *et al*. (2003)(8)
Pfister *et al*. (2011)	Low estimate: 1.0 m^3/MWh Average: 25 m^3/MWh High estimate: 600 m^3/MWh	Low: 1 Average: 25 High: 600	Mainly US, but probably also Tanzania and the Alps	Gross E	Gleick (1994), Torcellini *et al*. (2003), Kadigi *et al*. (2008), SN Energie Gruppe (2008)(9)
Mekonnen & Hoekstra (2012)	Range: 0.3 m^3/GJ – 846 m^3/GJ Average: 68 m^3/GJ	1.08 (min) 244.8 (average) 3045.6 (max)	World-wide, 35 plants, ~ 8% of global installed capacity	Gross E	Primary source
Yesuf (2012)	Gross estimate – range: 34 – 82 L/KWh Net estimate – range: 10 – 26 L/KWh	34 (Gross min) 82 (Gross max) 10 (Net min) 26 (Net max)	Ethiopia (Omo-Ghibe River)	Gross E & Net E	Primary source
Tefferi (2012)(10)	Range: 11 – 137 L/KWh 4 hydropower reservoirs Range 1371-3521 L/kWh 2 irrigation reservoirs	11 (min) 136.9 (max) 99 (w. average) 1371 (min) 3521 (max) 1480 (w. average)	Ethiopia (Blue Nile) Sudan (Blue Nile) Roseires & Sennar Irrigation reservoirs	Gross E	Primary source

(1) Abbreviations used: Gross E = gross evaporation divided on production; Net E = net evaporation divided on production and WB = Water Balance-approach

(2) The study also includes an assessment of the evaporation prior to damming, assuming a free-flowing river. Estimates of evaporation before are only 3.2% of the evaporation after damming, giving a negligible difference between gross and net evaporation.

(3) This study takes into account the multi-purpose functions of the reservoirs, and the water consumption is assigned to the various water users based on the economic valuation of water to each sector/user. In this study, 55% of the losses were assigned to hydropower.

Notes continued overleaf

(4) This study combines global hydropower production (Gleick, 1993) with global evaporation estimates from reservoirs (Shiklomanov, 2000).

(5) The study introduces LCA-concepts to assessment of water consumption, but as this is limited documented/described and hence not presented in our paper.

(6) The net water balance method is defined as the evaporation from the reservoir surface minus the direct rainfall on the reservoir, divided on production.

(7) IPCC (2011) also refers to LeCornu (1998), but we do not see that this reference provides useful information to the discussion of water consumption estimates.

(8) The max value in Macknick *et al*. (2011) seems to be the same as the average value in Torcellini *et al*. (2003). It could be speculated if this is because Torcellini *et al*. (2003) includes only large (most reservoir-based) plants, while Macknick *et al*. (2011) also includes in-stream plants (run-of-the-river plants).

(9) The latter reference appears to be not available from the web-site given in Pfister *et al*. (2011).

(10) This study includes a large lake/reservoir where irrigation is the (by far) dominant water use, and also a large lake where hydropower is just a minor add-on, giving extremely low estimates as all the evaporation losses are assigned to the hydropower production.

Comments on the published estimates (Table 1)

– The presented estimates are based on different methodological approaches and only figures based on the same methodologies should be compared. The approach using the gross evaporation divided by production is dominant.
– There is an extensive re-use of data in publications, especially data originating from Gleick (1992).
– Some of the newly published estimates are far beyond the maximum values published earlier by IPCC (2011).
– Some of the high estimates are from reservoirs, with the irrigation as the primary purpose and limited hydropower production.
– Only two studies report both gross and net evaporation. In these cases the net evaporation was 30–45% of gross evaporation.
– Some studies are single-plant studies, while others have a very large geographical extent (up to world-wide averages presented), “smoothing out” large spatial variations in water consumption values.
– There is probably large uncertainties related to the quality/precision of the evaporation rates used in many studies, due to limited observations and the reason given in the preceding bullet point.
– The studies/publications range from technical reports, master theses to peer-reviewed scientific articles, representing differences in quality.

DISCUSSION

The literature study has shown that there are at least four different approaches for estimating the water consumption from a hydropower project, where three of them include only the water consumption in the operational phase of the project. Most studies (see Table 1, column 5) seem to base the water consumption estimates on gross evaporation rates, i.e. they do not adjust the gross evaporation rates with the evaporation from the areas prior to the damming/construction of the plant. Herath *et al*. (2011) and Yesuf (2012) estimate the water consumption based on both the gross and the net evaporation rates and Herath *et al*. (2011) also introduce a third calculation method called the “water balance”-approach. In addition to these three calculation methods, a Life-Cycle Assessment (LCA) is an alternative approach that also includes the water consumption in processes upstream of/prior to the operational phase (i.e. planning and construction phase of a hydropower project). This approach is briefly described in some of the reviewed papers (Inhaber, 2004; Ridoutt & Pfister, 2010; Fthenakis & Kim, 2010), but a full LCA has not been performed for hydropower in any of the published studies, as far as the authors know. Pfister *et al*. (2011) argues that the operational phase with evaporation from the reservoir by far dominates the water consumption from the other life-stages of a project, making a full LCA too comprehensive and inappropriate for the purpose. The selection of approach might have large effects on the results, as shown in Herath *et al*. (2010) and Yesuf (2012) that compare the gross- and net evaporation. IPCC (2011) therefore emphasised the need for a consistent calculation framework, and stressed especially the need for research to determine the net effect of reservoir construction on evaporation in a specific watershed.

The water consumption estimates are very sensitive to the evaporation values that are used. Large uncertainties in the evaporation estimates will be transferred into large uncertainties in the water consumption estimates. The reviewed studies have very different geographical extent, ranging from studies of single plants, to regional and global studies. The precision/quality of the evaporation data will hence most likely vary a lot, possibly causing biased estimates, which means that comparisons should be made with great care.

It is timely to ask if large water consumption values are problematic or not, i.e. if the water consumption is sustainable. The reviewed papers discuss to a small extent the impacts on the water resources caused by high water consumption values. Ridoutt & Pfister (2010) argue for such a need and Pfister *et al*. (2011) proposes to bring in "aridity" as a possible proxy for potential impact on the water resources from an activity, e.g. power production. In the water footprint manual (Hoekstra *et al*., 2011) a very simplistic sustainability calculation is defined. The sustainability calculation is based on the estimates of the blue water availability and the water footprint, and sustainability concerns rise when the water footprint exceeds the blue water availability. We also refer to the application in Heihe River (Zeng *et al*., 2012) for further details on this.

CONCLUSION

This review has revealed that there are now a larger number of published studies on water consumption from hydropower plants available than during the review carried out by IPCC (2011). The newly published data partly falls within the range of estimates published by IPCC (ibid.), partly far beyond the earlier published maximum values (e.g. Pfister *et al*., 2011; Mekonnen & Hoekstra, 2012; Tefferi, 2012). The dominant method for estimating the water consumption is by using the gross evaporation (in contrast to net) divided by production, but it is problematic that this approach is controversial and no consistent, solid and agreed methodology is in place. Furthermore, the issue of assigning the water loss to the appropriate water user in a fair way in the case of multi-purpose reservoirs remains unsolved. Methodological inconsistencies and natural large variation possibly explain most of the large variation in the water consumption estimates.

An improved concept for calculating the water consumption/footprint should also address the possible impact an activity with high water consumption values might have on the local water resources. So far, this issue has only been raised by a few publications to a limited extent (e.g. Ridoutt & Pfister, 2010; Pfister *et al*., 2011; Hoekstra *et al*., 2011; Zeng *et al*., 2012). Such a concept should also take into account the possible positive effect a regulation could have on the availability of water.

REFERENCES

Bates, B. C., Kundzewicz, Z. W., Wu, S. & Palutikof, J. P. (eds) (2008) Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Berger M. & Finkbeiner M. (2010) Water footprinting: how to address water use in life cycle assessment? *Sustainability* 2 (4), 919–944.

Fthenakis, V. & Kim, H. C. (2010) Life-cycle uses of water in US electricity generation. *Renewable and Sustainable Energy Reviews* 14, 2039–2048.

Gerbens-Leenes, P. W., Hoekstra, A. Y. & van der Meer, Th. (2009) The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecological Economics* 68, 1052–1060.

Gleick, P. (1992) Environmental consequences of hydroelectric development: The role of facility size and type. *Energy: The Int. J.* 17(8), 735–747.

Gleick, P. (1993) *Water in Crisis: A Guide to the World's Fresh Water Resources*. Oxford University Press, New York, NY, USA.

Gleick, P. H. (1994) Water and energy. *Annual Review of Energy and Environment* 19, 267–299, Annual Reviews, Inc. Palo Alto, California.

Herath, I., Deurer, M., Horne, D., Singh, R. & Clothier, B. (2011) The water footprint of hydroelectricity: a methodological comparison from a case study in New Zealand. *Journal of Cleaner Production* 19, 1582–1589.

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

Hutson, S. S., Barber, N. L., Kenny, J. F., Linsey, K. S., Lumia, D. S. & Maupin, M. A. (2004) Estimated use of water in the United States in 2000. US Geological Survey; 2004. http://pubs.usgs.gov/circ/2004/circ1268/ (accessed 12 January 2013).

IHA (2011) World Congress Bulletin: Summary of the International Hydropower Association Paper presented at the World Congress on advancing sustainable hydropower, New York. http://www.iisd.ca/ymb/hydro/iha2011/html/ymbvol139num7e.html. (accessed 12 January 2013).

Inhaber, H. (2004) Water use in renewable and conventional electricity production. *Energy Sources* 26(3), 309–322.

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

Kadigi, R. M. J., Mdoe, N. S. Y., Ashimogo, G. C. & Morardet, S. (2008) Water for irrigation or hydropower generation? Complex questions regarding water allocation in Tanzania. *Agric. Water Manage.* 95(8), 984–992.

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K. & Maupin, M. A. (2009) Estimated use of water in the United States in 2005. *US Geological Survey Circular* vol 1344. USGS, Reston, VA.

LeCornu, J. (1998) Dams and water management. Report of the Secretary General, International Commission on Large Dams to the Conférence Internationale Eau et Développement Durable, Paris, France, 19–21 March 1998.

Macknick, J., Newmark, R, Heath, G. & Hallett, K. C. (2011) A review of operational water consumption and withdrawal factors for electricity generating technologies. Technical Report. NREL/TP-6A20-50900. March 2011.

Macknick, J., Newmark, R, Heath, G. & Hallett, K. C. (2012a) Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environ. Res. Lett.* 7 (2012) 045802 (10 pp).

Macknick, J., Sattler, S., Averyt, K., Clemmer, S. & Rogers, J. (2012b) The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. *Environ. Res. Lett*. 7 (2012) 045803 (10 pp).

Mekonnen, M. M. & Hoekstra, A. Y. (2011) The water footprint of electricity from hydropower. *Hydrol. Earth Syst. Sci. Discuss.* 8, 8355–8372. http://www.hydrol-earth-syst-sci-discuss.net/8/8355/2011/hessd-8-8355-2011-discussion.html. (accessed 12 January 2013).

Mekonnen, M. M. & Hoekstra, A.Y. (2012) The blue water footprint of electricity from hydropower. *Hydrol. Earth Syst. Sci*. 16, 179–187.

Mielke, E., Anadon, L. D. & Narayanamurti, V. (2010) Water Consumption of Energy Resource Extraction, Processing and Conversion. Discussion Paper no. 2010–15, Harvard Kennedy School, Cambridge, MA, USA.

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

Pfister, S. & Hellweg, S. (2009) The water "Shoesize" *vs*. Footprint of bioenergy. *Proceedings of the National Academy of Sciences* 106(35), E93–E94.

Pfister, S., Saner, D. & Koehler, A. (2011) The environmental relevance of water consumption in global power production. *International Journal of Life Cycle Assessment* 16(6).

Ridoutt, B. G. & Pfister, S. (2010) A revised approach to water foot printing to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environmental Change* 20(1), 113–120.

Shiklomanov, I. A. (2000) Appraisal and assessment of world water resources. *Water International* 25(1).

SN Energie Gruppe (2008) Aquapower Switzerland. http://www.aquapower.ch/uploads/media/aquapower-news_2_2008.pdf. (accessed 12 January 2013).

Tefferi, M-E. A. (2012) The effect of Ethiopian hydropower reservoirs on Blue Nile River flow regime. Master Thesis Norwegian University of Science and Technology, Dept. of Hydraulic and Environmental Engineering.

Torcellini, P., Long, N. & Judkoff, R. (2003) Consumptive Water Use for US Power Production. Technical Report-TP-550-33905, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Available at: www.nrel.gov/docs/fy04osti/33905.pdf. (accessed 12 January 2013).

US Department of Energy (2006). Energy demands on water resources. Report to Congress on the interdependency of energy and water. 80 pp.

WFN (Water Footprint Network) (2012) Glossary, Water Footprint. http://www.waterfootprint.org/?page=files/Glossary. (accessed 12 January 2013).

Yesuf, M. B. (2012) Impacts of cascade hydropower plants on the flow of the river system and water level in Lake Turkana in Omo-Ghibe Catchment, Ethiopia. Master Thesis Norwegian University of Science and Technology, Dept. of Hydraulic and Environmental Engineering.

Zeng, Z., Liu, J., Koeneman, P. H., Zarate, E. & Hoekstra, A. Y. (2012) Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China. *Hydrology and Earth System Sciences* 16(8), 2771–2781.