Water scarcity footprint of selected hydropower reservoirs

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Introduction

After agriculture, hydropower is considered to be the next largest water consuming sector, largely due to evaporation (EV) from the reservoir surface. However, previous assessments of water footprints of hydropower were mostly based on a gross evaporation method that assigns all of the potential evaporation (PEV) of the reservoir to the water footprint of hydropower. This method does not take into account 1) that there was natural EV and transpiration before the construction of the dam, 2) how water scarce the watershed is and 3) that water scarcity is counteracted in many cases by water storage during the wet season and water release in the dry season (Buxmann et al. submitted). Additionally, the question of allocation between power production, irrigation and other reservoir purposes remains open. All this means that the water footprint of hydropower reported in previous scientific literature might be overestimating the real water consumption and the resulting impacts on water resource availability and the environment.

Research objective

The goal of the project is to assess the water footprint of hydropower plants with a significant contribution to the electricity supply of aluminium smelters. The dams considered in this study are compiled in Table 1 and displayed in Figure 1. In order to account for seasonal variations, the impact of the dam in terms of water scarcity footprint is calculated based on monthly water stress indices and storage effects of the reservoir. The net EV (NEV) is also calculated and multipurpose reservoirs are analysed with regards to impact allocation to purposes other than hydropower.

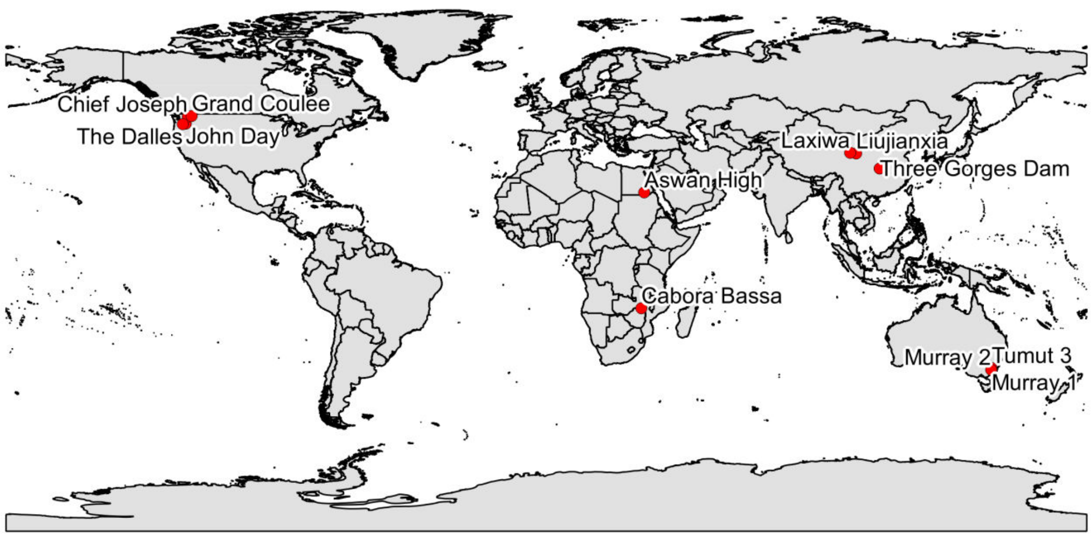

Figure 1: Dam locations

Methodology

Dam locations, purposes and hydroelectricity generation

Dam locations were mainly obtained from the global GRanD database (Lehner et al. 2011). If the dams were not contained in there, the global GLWD database (Lehner and Döll 2004) and the national databases for Australia (ANCOLD 2010) and the United States (USGS 2006) were consulted. With regards to locations, preference was given to the GLWD database as their coordinates represent reservoir centres, while in GRanD they represent reservoir outlets. Annual electricity generation of each dam was provided by CARMA (2015) for the year 2009. Consequently, the water scarcity footprints were also calculated for the same year. Each dam's database source, main purpose, and yearly hydroelectricity generation are compiled in Table 1. The Snowy Mountains scheme in Australia was analysed in addition to individual dams and hydropower plants comprising this scheme (Tumut 3, Murray 1 and 2). The scheme consists of 16 reservoirs, but only 8 hydropower plants operated in 2009. The main purpose of the scheme is the generation of hydroelectricity. Some reservoirs are not directly connected to a plant, but to one of the other reservoirs, which are in turn connected to plants. For the final results, the consumption of all 16 reservoirs was summed and related to the electricity generation of the 8 hydropower plants.

Table 1: Consulted databases and characteristics of selected reservoirs for the year 2009

Dam	Countries	Database	Main purpose	Multi-purpose	Electricity (TWh)	Area/Electricity (km^2/TWh)
Cahora Bassa	Mozambique, Zimbabwe	GRanD	Irrigation	Yes	15.8	129.8
Aswan High	Egypt, Sudan	GRanD	Irrigation	Yes	7.4	728.5
Three Gorges	China	GRanD	Hydropower	Yes	79.9	10.7
Liujianxia	China	GRanD	Hydropower	Yes	6.3	18.3
Laxiwa	China	GRanD	Hydropower	No	2.1	2.1
Snowy Mountains	Australia	ANCOLD	Hydropower	Yes	3.9	16.5
Tumut 3	Australia	GRanD	Hydropower	No*	1.9	9.6
Murray 1	Australia	GRanD	Hydropower	No*	0.7	0.4
Murray 2	Australia	ANCOLD	Hydropower	No*	0.5	0.4
John Day	United States	GLWD	Hydropower	Yes	8.4	7.4
Chief Joseph	United States	USGS	Hydropower	No**	9.8	3.5
Grand Coulee	United States	GRanD	Irrigation	Yes	21.0	12.8
The Dalles	United States	USGS	Hydropower	Yes	6.1	7.9

**The reservoir belongs to the Snowy Mountains scheme. It does not serve multiple purposes, but the entire scheme does.*

***except for recreational purpose which is excluded from allocation*

Gross and net evaporation method

For comparison, we calculated the water consumption (WC_{gross}) of hydropower per unit of electricity generated (e.g. GJ or MWh) according to the commonly used gross evaporation method:

$$WC_{gross} = PEV_a * SA / HG_a$$

where PEV_a is the annual potential evaporation, SA is the reservoir surface area and HG_a is the annual hydroelectricity generation. The SA of the Laxiwa dam was not given and therefore estimated by dividing the reservoir capacity by the dam height.

Net water consumption (WC_{net}) is calculated according to the net evaporation method where PEV is replaced by net evaporation (NEV) as the difference between PEV and actual EV and transpiration of the surrounding land cover:

$$WC_{net} = NEV_a * SA / HG_a$$

The annual water scarcity footprints ($WSFP_a$) are subsequently calculated by applying the annual water stress index (WSI_a) to WC_{net}:

$$WSFP_a = WC_{net} * WSI_a$$

Monthly reservoir water balance

Only NEV was considered in the monthly approach. When determining the outflow of the reservoir PEV was used, but actual EV and transpiration (AET) was subtracted from the consumption. The annual water balance of the reservoir was calculated in order to determine the annual outflow (OF_a) of the reservoir:

$$OF_a = IF_a + P_a - PEV_a - SP_a$$

where IF is the inflow, P is precipitation and SP is seepage. The reservoir inflow was obtained from the global hydrological model WaterGAP 3 whose simulation results are provided within the Earth2Observe project (E2O 2015) on monthly level. The river discharge of the upstream cell of a dam was considered as inflow to the reservoir.

Precipitation data on monthly level were also taken from the Earth2Observe project and is based on ECMWF (E2O 2015).

PEV and actual EV and transpiration were obtained from Mu et al. (2011). In case of data gaps in the dam area, the mean value of a buffer zone around the dam was calculated. This concerns the Aswan High dam and the Liujianxia dam for which buffer radiuses of 180 and 4 km, respectively, were applied.

SP is treated similar to the reservoir outflow as seepage contributes to groundwater recharge and is therefore released as runoff. Its velocity was derived from hydraulic conductivity (K) by the following equation (Watson and Burnett 1993):

$$SP = K * i / n$$

Hydraulic conductivity was estimated based on Saxton and Rawls (2006). The required soil parameters were given in the Harmonized World Soil Database of the FAO (Nachtergaele et al. 2012). The additional required parameters hydraulic gradient (i) and porosity (n) were assumed to be 0.01 (Morrison 1999) and 0.4 (McWhorter and Sunada 1977), respectively.

Reservoir operation

The monthly reservoir outflow depends on the reservoir operation. We distinguished two different operations based on the main purpose of the reservoir which is either hydropower or irrigation.

For each country, we compared the monthly fluctuations of hydropower as provided in the OECD library (IEA 2014) with the monthly fluctuations of river discharge in WaterGAP3 aggregated to the country level. The mean reduction factor of the hydrological fluctuations by hydropower production was 1.62 for the years 2000 to 2012 (for all countries where the correlation between discharge and hydroelectricity generation was at least 0.5) and this factor was applied for all outflows of reservoirs where hydropower is the primary purpose, i.e. the monthly variation in mean annual runoff was decreased by a factor of 1.62.

When irrigation was the main purpose, we assumed the fluctuations of water consumption (Pfister et al. 2011a, WATCH 2010) to be reflected in the reservoir outflow as suggested by Hanasaki et al. (2006). Water consumption other than irrigation was assumed to be constant throughout the year. Although this might not be realistic, fluctuations are minor compared to irrigation and it is a common assumption used in global models. Therefore, the fluctuations were only derived from variations in irrigation water consumption, but consumption from other sectors was also taken into account in order to avoid zero flows in months without any irrigation. The irrigation rasters were resampled to 0.5°, thereby matching the resolution of the WATCH data. We only considered the fluctuation in the next five downstream cells of the dam as suggested by Döll et al. (2009).

Water scarcity footprint

The monthly consumption (CS(t)) of the reservoir was determined by its monthly water balance:

$$CS(t) = IF(t) + P(t) - OF(t) - SP(t) - AET(t)$$

The resulting consumption was then multiplied with the monthly water stress index (WSI, Pfister and Bayer 2014) to obtain the water scarcity impact (WS):

$$WS(t) = CS(t) * WSI(t)$$

The annual WSFP based on a monthly water balance ($WSFP_m$) is derived from the sum of all monthly WSs over the year:

$$\mathrm{WSFP_m} = \frac{\sum_{i=1}^{12} \mathrm{WS_i}}{\mathrm{HG}_a}$$

If the resulting $WSFP_m$ assigned to hydropower is negative, it is set to zero.

Allocation

Where reservoirs serve multiple purposes, an allocation of impacts between the different purposes should be undertaken. Allocation was based on the ranks of the purposes of a reservoir with ratios of 2:1 or 3:2:1 depending on how many purposes a reservoir fulfils. When hydropower is the only purpose of a reservoir, 100% of the impacts are allocated to hydropower; if it is the main purpose 67% or 50% of the impacts are allocated to it depending on the total number of purposes and if it is the second or tertiary purpose only 33% or 17% of the impacts are allocated to it.

Avoided floodplain evaporation by Aswan High dam

The Aswan High dam has the largest water footprint according to the gross evaporation method. However, besides the actual EV and transpiration at the location of the reservoir, when assuming the land cover of its surroundings, downstream inundation areas resulted in additional natural EV and transpiration that was reduced due to the flood control by the dam. This avoided evaporation of flooded areas needs to be deducted from the NEV.

First, the drainage capacity of the Nile River downstream of the dam was estimated. We assumed a river width of 1250 m, a bank height of 6.2 m, a rectangular cross section (Yamazaki et al. 2011) and a universal flow velocity of 1 m/s (Döll et al. 2003):

$$Q_c = w * h * q$$

where Q_c is the drainage capacity (m^3/s), w is the river width (m), h is the bank height (m) and q is the flow velocity (m/s).

Then, the discharge exceeding the drainage capacity was determined for each month:

$$Q_e = Q - Q_c$$

where Q_e is the discharge exceedance (m^3/s) and Q is the river discharge (m^3/s).

Next, the inundation area was estimated assuming a river length of 1100 km to the river mouth (WWF 2015) and a floodplain depth of 1 m (Hassan et al. 2006):

$$A = Q_e / q / d_{fp} * l$$

where A is the inundation area (m^2), d_{fp} is the floodplain depth (m) and l is the river length (m).

The net evaporation was then determined along the flow path of the Nile downstream of the dam.

Sensitivity analysis

We investigated the effects of modifying various input parameters on the resulting $WSFP_m$ by the following actions: i) We performed the same calculations for the year 2004 instead of 2009, which affects the potential and actual evaporation and transpiration, the discharge, the precipitation and the hydroelectricity generation. ii) We used a country specific flow reduction factor for the operation of reservoirs having hydropower as their main purpose, as long as the data was available and the correlation between discharge and hydroelectricity generation was at least 0.5. This was only valid for the United States and therefore affects 3 out of the 12 reservoirs. iii), We considered two alternative approaches to derive the reservoir operation for reservoirs with irrigation as their main purpose. First, we derived the operation by reducing the variability of irrigation by 50% instead of using a minimum flow based on the water consumption of other sectors. Second, we looked at the monthly irrigation requirements of the whole watershed instead of only the next five downstream cells. In this case, water consumption of other sectors was not considered. iv) Monthly water scarcity assessments rather overestimate fluctuations, since they are mainly based on surface runoff and neglect potential dampening effects of groundwater-surface water interactions as well as residence times of >1 month in large watersheds (Pfister and Bayer 2014). Therefore, we reduced these fluctuations by taking the mean of the monthly and annual WSI:

$$WSI_{mean}(t) = (WSI(t) + WSI_a) / 2$$

Results and discussion

Water scarcity footprint

The water footprints of hydropower and the ranking between plants largely depend on the method used for their derivation. Consequently, the conclusions that can be drawn from the results using this novel approach for water footprint assessment of hydropower differ considerably from the conclusions that could be drawn from the results of previous assessments. If the water consumption of the reservoir is considered using only the gross evaporation method, the Aswan High dam appears to have the largest impacts with over 500 Mio. m^3/GJ. However, if monthly water stress and water storage are accounted for, it provides the highest benefits in terms of alleviating water scarcity. Another relevant insight from this study is that the Snowy Mountains scheme has a much higher water consumption than its most important individual dams because of the large reservoir Eucumbene, which is part of the scheme even though it is not directly connected to any hydropower plant.

Mekonnen and Hoekstra (2012) calculated the water consumption per unit electricity generated for 35 globally distributed hydropower plants. Among their selected plants was the Cahora Bassa dam, which was also investigated in this study. They estimated the water consumption to be 186 m^3/GJ, which is almost twice our own estimate. The difference can be explained by their assumption of a higher PEV (8140 Mio. m^3/a, compared to 5382 Mio. m^3/a) and a lower annual hydroelectricity generation (12.2 TWh, cf. Table 1). On the other hand, Zhao and Liu (2015) calculated the water consumption of the Three Gorges dam in 2009 to be 2.5 m^3/GJ, which is lower than our own estimate. They assumed a lower PEV of only 716 Mio. m^3/a (compared to 1242 Mio. m^3/a).

As in the fictitious example provided by Kurt Buxmann, most reservoirs have a negative WSFP when seasonality is taken into account, which implies that they alleviate water scarcity and benefit the affected water consumers as shown in the fourth column of Table 2 (see also Table 4 to Table 15, Table 17). The fifth column shows the $WSFP_m$ values allocated to the electricity production. It is proposed to select an allocation factor of zero for negative values of $WSFP_{m,unallocated}$. Some of the impacts might, however, be underestimated, as some of the storage changes might exceed storage capacity. Storage capacity could not be taken into account because initial storage is unknown.

The US dams Chief Joseph, John Day and The Dalles are run-of-river types (BPA et al. 2001), meaning that the increase in reservoir surface area might be negligible and that the WSFPs are likely to be overestimated. In this case, they could be assumed to equal zero.

The water consumption per unit of electricity generated is closely correlated to the ratio of reservoir surface area to annual electricity production ($R \approx 1$, cf. Table 1). The potential evaporation has a lower influence ($R = 0.68$). For the $WSFP_m$, the main influence cannot be easily identified, as it is a complex system with many interactions.

Table 2: Summed monthly water scarcity footprints (m^3 H_2O_e / GJ) of selected reservoirs

Dam	WC_{gross}	$WSFP_a$	$WSFP_{m,unallocated}$	$WSFP_{m,allocated}$
Cahora Bassa	94.81	0.82	0.38	0.13
Aswan High	558.03	513.74	-707.79	0
Three Gorges Dam	4.32	0.05	-1.59	0
Liujianxia	9.02	7.59	4.05	2.03

Laxiwa	0.92	0.71	-6.28	0
Snow Mountains	27.42	3.41	-28.63	0
Tumut 3 / Talbingo	4.61	2.14	-6.15	0
Murray 1 / Geehi	0.19	0.09	-8.15	0
Murray 2	0.19	0.08	-12.75	0
John Day*	3.29	0.07	-89.53	0
Chief Joseph*	1.39	0.03	-20.38	0
Grand Coulee	4.51	0.09	-22.97	0
The Dalles*	2.76	0.06	-137.38	0

**run-of-river dams where WSFP might be assumed to equal zero*

Allocation

The resulting parameters for $WSFP_{m,allocated}$, i.e. the WSFP allocated to one unit of generated hydropower (e.g. 1 GJ), are shown in the last column of Table 2. In case of negative $WSPF_{m,unallocated}$, an allocation factor of zero has been selected for the purpose of this study with a resulting $WSFP_{m,allocated}$ of zero. We have chosen this conservative approach because we hesitated to assign negative WSFP values to hydropower. This approach does not preclude other considerations which might lead to negative WSFPs for hydropower.

Five out of twelve reservoirs provide hydropower as their only purpose. The remaining seven reservoirs fulfil multiple purposes, thereby sharing their responsibility for impacts or benefits. The dam with the highest impacts is Liujianxia, which provides hydropower, irrigation and flood control. Because of this, only 50% of the total impacts were allocated to hydropower, as this functions as the dam's main purpose (Table 2). The only other dam with net impacts is Cahora Bassa, whose primary purpose is irrigation. Hydropower is its secondary purpose, with flood control services being its tertiary function. Therefore, only one third of the impacts were allocated to hydropower.

Zhao and Liu (2015) studied the allocation of impacts of the Three Gorges dam in detail and allocated 63% to hydropower, which is close to our own assumption of 50% (Table 2). However, we could not conduct such detailed allocation analyses, as the required data was unavailable. Also the data from the study of Zhao and Liu (2015) was obtained from Chinese documents and therefore not available to us. However, deviations of +/- 25% are not considered critical in an LCA context.

In the case of economic allocation, assumed prices of the various functions could be 9 cents/kWh for hydropower (Sims et al. 2003, IRENA 2012), 2 cents/m^3 (FAO 2004) for irrigation, 16 cents/m^3 (Zhao and Liu 2015) for flood control and 50 cents/km/day (Dierikx and van den Berg 2010) for navigation and the transport of commodities. While the annual hydroelectricity generation is known and the economic value can easily be calculated, the volumes used for irrigation or flood control and the amount of transported commodities are unknown. There are no objective ways of estimating these values and direct data from local authorities is required.

Avoided floodplain evaporation by Aswan High dam

The avoided net evaporation from floodplains downstream of the Aswan High dam amounts to 439 Mio. m^3 (Table 16). If this is subtracted from the net evaporation of the Aswan High reservoir, it reduces to 13493 Mio. m^3 (cf. Table 5) and results in a $WSFP_a$ of 498 m^3 H_2O_e / GJ (compared to 514 m^3 H_2O_e / GJ). While the derivation of the inundation area (peak of 8593 km^2 in September) entails uncertainties, it still matches reported historical irrigation areas well (8000 km^2, Postel 1999). Despite the large areas that are flooded, the overall effect on the $WSFP_a$ is small, as the evaporation from floodplains only occurs during a few months of the year and therefore justifies the negligence of this process. This is also valid for other dams.

Sensitivity analysis

The results from the sensitivity analysis are compiled in Table 3. The year under investigation had the largest influence on the resulting $WSFP_m$. The largest difference was obtained for the Three Gorges dam, which only started operating in 2003 (Lehner et al. 2011). The annual electricity generation in 2004 was 75% lower than in 2009 (CARMA 2015), but in both years no net impacts are caused. For the Laxiwa dam, no value is available for the year 2004 because operation began in 2009 (HydroWorld 2009). Its electricity generation is expected to increase in the future by a factor of 6 (CARMA 2015), so impacts or benefits per unit electricity generated will decrease. In the case of the Grand Coulee and Chief Joseph dams the differences in annual electricity production are small, but the change in impacts is caused by a change in the inflow pattern, which even leads to a switch from benefits in 2009 to impacts in 2004.

The attenuation factor for the three US dams whose main purpose is hydropower (all but Grand Coulee) was reduced compared to the universal attenuation factor otherwise applied. It only amounted to 1.44 instead of 1.62. The weaker attenuation led to lower benefits in terms of alleviating water scarcity.

The method of considering irrigation in the operation of reservoirs whose main purpose is irrigation can also play a large role. The area considered, whether it is the next five downstream cells or the entire watershed, affects the resulting $WSFP_m$.

The chosen monthly WSI largely influences the results and the smoothing of their fluctuations generally leads to an increase in the $WSFP_m$. As an example, the chosen WSI has a large influence on the results of the Aswan High dam as the dam with the highest water consumption, but also largest benefits in terms of alleviating water consumption. When considering the mean of monthly and annual WSI, the benefits are reduced by 86%. Nevertheless, the benefits remain high for that dam.

Table 3: Summed monthly allocated water scarcity footprints (m^3 H_2O_e / GJ) based on sensitivity analyses (dams with net impacts in some scenarios are bolded)

Dam	Original	Year 2004	Specific attenuation	Irrigation dampening	Watershed irrigation	WSI_{mean}
Cahora Bassa	0.13	0.02	NA*	0	0	0.20
Aswan High	0	0	NA	0	0	0
Three Gorges	0	0	NA	NA	NA	0
Liujianxia	2.03	0	NA	NA	NA	2.91
Laxiwa	0	NA	NA	NA	NA	0
Snowy Mountains	0	0	NA	NA	NA	0
Tumut 3	0	0	NA	NA	NA	0
Murray 1	0	0	NA	NA	NA	0
Murray 2	0	0	NA	NA	NA	0
John Day	0	0	0	NA	NA	0
Chief Joseph	0	6.14	0	NA	NA	0
Grand Coulee	0	1.71	NA	0	0	0
The Dalles	0	0	0	NA	NA	0
Mean**	0.09	0.97	0.09	0.08	0.08	0.13

**Not available mostly because it only concerns reservoirs with specific main purposes or from specific countries.*

***Weighted by annual hydroelectricity generation considering all 12 selected dams but not the Snowy Mountains scheme*

The electricity weighted mean $WSFP_m$ for the 12 selected hydropower plants (Table 3) varies between 0.08 m^3 H_2O_e / GJ (using a different algorithm for the operation of irrigation reservoirs) and 0.13 m^3 H_2O_e / GJ (smoothed monthly WSIs). A higher value of 0.97 m^3 H_2O_e / GJ was obtained for the year 2004. The range of possible results indicates the uncertainty of the applied method. Nevertheless, it shows that current global estimates ranging from 7 m^3/GJ (Pfister et al. 2011b) to 68 m^3/GJ (Mekonnen and Hoekstra 2012) are overestimating the impacts.

Conclusions

A novel approach to water footprint assessment of hydropower was used and different conclusions can be drawn than those from previous studies. While according to the gross evaporation method, some hydropower plants had large adverse impacts on water availability by consuming a lot of water through lake evaporation, all plants investigated in this study have small water footprints, and most of them cause no net impact, but rather counteract water scarcity by storing water in the wet season and releasing it in the dry season. The electricity weighted mean $WSFP_m$ for the 12 selected hydropower plants is estimated at 0.1 m^3 H_2O_e / GJ. It shows that current global estimates ranging from 7 m^3/GJ (Pfister et al. 2011b) to 68 m^3/GJ (Mekonnen and Hoekstra 2012) are largely overestimating the impacts.

Sensitivity analysis did not affect the study's drawn conclusions; however, with different input data some plants switch from providing benefits to causing impacts and vice versa. Out of the twelve investigated plants, three plants in the US are of the run-of-river type and their water footprint can be assumed to be zero because they do not have reservoirs. These plants are Chief Joseph, John Day and The Dalles. Six plants, namely Aswan High, Three Gorges, Laxiwa and the three Australian plants Tumut 3 and Murray 1 and 2 (as well as the Snowy Mountains scheme as a whole), do not cause any impacts in any of the scenarios investigated in the sensitivity analysis. The remaining three plants, Cahora Bassa, Liujianxia, and Grand Coulee, cause adverse impacts in at least one of the scenarios, but none cause impacts in all of them.

When impacts occur, they should be allocated between the different purposes of the reservoirs. Among the three hydropower plants that cause adverse impacts under some of the scenarios, only the Laxiwa dam serves hydropower as single purpose. For both others, the impacts of hydropower should be reduced compared to the total impacts of the reservoir. The allocation is challenging and without data from local authorities, only a simple procedure based on the ranks of purposes could be applied. However, since the differences in results between the commonly used gross evaporation method and the novel approach are large and the impacts low, the allocation procedure is less relevant.

While the impacts of hydropower plants on local water availability do not seem to be as severe as previously thought, it has to be emphasised that freshwater consumption is only one of many impact categories. In order to avoid burden shifting, other impacts should be analysed. As an example, the homogenisation of river flows leads to reduced floodplain inundation, which threatens the rich biodiversity of these habitats (Tockner and Stanford 2002). Furthermore, changed river morphologies, temperature profiles, and land use changes caused by dams might be of environmental relevance.

Appendix

The appendix contains monthly water balances of the individual reservoirs (Tables 4 – 15), the derivation of net evaporation from floodplains downstream of the Aswan High dam (Table 16) and the results tables in the unit m^3 H_2O_e / MWh instead of m^3 H_2O_e / GJ (Tables 17 – 18).

Acknowledgements

We thank Kurt Buxmann for discussions and helpful comments and Christie Walker for proofreading the manuscript. This work was funded by the International Aluminium Institute.

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Appendix

Table 4: Water balance of Cahora Bassa dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	16261	352	376	125	10746	5495	0.010	55
Feb	11074	318	354	118	10691	58	0.010	1
Mar	18430	352	403	181	16535	1540	0.010	16
Apr	8180	341	416	305	5955	1818	0.010	18
May	5711	352	401	342	2175	3157	0.010	32
Jun	4745	341	388	355	2970	1404	0.010	15
Jul	4271	352	389	354	5360	-1447	0.011	-15
Aug	3745	352	486	467	7214	-3836	0.011	-44
Sep	3157	341	554	545	4860	-2052	0.013	-26
Oct	3166	352	611	599	3300	-496	0.015	-8
Nov	3667	341	555	524	5200	-1808	0.014	-26
Dec	5847	352	451	312	5344	395	0.010	4
Total	88255	4148	5382	4228	80349	4228	0.011	22

Table 5: Water balance of Aswan High dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	4134	1527	840	700	6810	-4342	1.00	-4342
Feb	2134	1379	931	799	6445	-5822	1.00	-5822
Mar	1393	1527	1229	1085	6457	-6734	1.00	-6734
Apr	1492	1477	1479	1442	5458	-5479	1.00	-5479
May	2620	1527	1605	1577	5707	-4638	1.00	-4638
Jun	3008	1477	1650	1648	7447	-5918	1.00	-5918
Jul	7106	1527	1579	1575	9540	-3965	0.79	-3123
Aug	32917	1527	1468	1463	10926	20461	0.22	4566
Sep	40336	1477	1292	1272	10375	28463	0.41	11739
Oct	15666	1527	1158	1077	5964	8094	0.86	6995
Nov	6956	1477	866	706	6001	-682	0.92	-630
Dec	2486	1527	749	588	6304	-5505	0.99	-5443
Total	120248	17974	14846	13932	87432	13932	0.85	-18830

Table 6: Water balance of Three Gorges Dam dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	9625	169	58	38	18358	-8911	0.014	-129
Feb	8853	152	51	23	17883	-9168	0.020	-188
Mar	11331	169	92	58	19406	-8223	0.050	-409
Apr	30581	163	114	64	31229	-736	0.103	-76
May	32999	169	128	59	32714	214	0.137	29
Jun	42584	163	161	73	38602	3913	0.017	65
Jul	70287	169	163	54	55617	14503	0.012	169
Aug	75691	169	140	47	58937	16633	0.011	186
Sep	51504	163	127	59	44080	7296	0.011	79
Oct	31490	169	101	63	31787	-470	0.011	-5
Nov	16600	163	61	40	22642	-6178	0.012	-74
Dec	11270	169	46	26	19368	-8268	0.013	-105
Total	392815	1985	1242	605	390622	605	0.034	-457

Table 7: Water balance of Liujianxia dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	1062	25	9	7	1231	-197	0.99	-194
Feb	948	22	11	9	1163	-239	1.00	-239
Mar	1056	25	16	14	1228	-198	1.00	-198
Apr	1087	24	21	19	1247	-183	1.00	-183
May	1318	25	24	22	1386	-89	1.00	-89
Jun	1634	24	27	24	1577	34	1.00	34
Jul	1632	25	25	22	1576	35	1.00	35
Aug	3001	25	22	18	2401	585	0.79	461
Sep	2780	24	16	12	2268	492	0.91	446
Oct	2131	25	14	12	1876	231	0.81	187
Nov	1208	24	10	8	1319	-138	0.40	-55
Dec	1152	25	9	7	1286	-161	0.70	-113
Total	19009	291	205	172	18558	172	0.88	92

Table 8: Water balance of Laxiwa dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	539	1.0	0.3	0.2	735	-197	0.99	-194
Feb	464	0.9	0.4	0.3	689	-226	1.00	-226
Mar	491	1.0	0.6	0.5	706	-216	1.00	-216
Apr	666	1.0	0.7	0.7	814	-149	1.00	-149
May	648	1.0	0.8	0.7	803	-155	1.00	-155
Jun	1213	1.0	0.8	0.7	1151	61	1.00	61
Jul	1554	1.0	0.8	0.5	1361	192	1.00	192
Aug	2232	1.0	0.7	0.5	1780	452	0.79	356
Sep	1863	1.0	0.5	0.3	1552	310	0.91	281
Oct	1527	1.0	0.5	0.4	1344	181	0.81	146
Nov	791	1.0	0.4	0.3	891	-101	0.40	-40
Dec	670	1.0	0.3	0.2	816	-147	0.70	-103
Total	12658	11.7	6.9	5.3	12641	5.3	0.88	-47

Table 9: Water balance of Tumut 3 / Talbingo dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	16	4	5	3	20	-9	1.00	-9
Feb	14	4	4	2	19	-10	1.00	-10
Mar	16	4	3	2	20	-9	1.00	-9
Apr	15	4	2	1	19	-8	1.00	-8
May	15	4	1	1	19	-9	0.93	-9
Jun	20	4	1	0	22	-5	0.08	0
Jul	63	4	1	0	44	15	0.02	0
Aug	70	4	1	1	48	19	0.02	0
Sep	71	4	2	1	48	19	0.03	1
Oct	58	4	3	2	42	12	0.06	1
Nov	42	4	4	3	33	4	0.49	2
Dec	37	4	5	3	31	1	0.99	1
Total	436	53	31	18	366	18	0.55	-41

Table 10: Water balance of Murray 1 / Geehi dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	23	0.23	0.07	0.05	25	-2.7	1.00	-2.7
Feb	18	0.21	0.05	0.03	22	-4.4	1.00	-4.4
Mar	18	0.23	0.05	0.03	23	-4.3	1.00	-4.3
Apr	17	0.22	0.03	0.01	21	-5.0	1.00	-5.0
May	16	0.23	0.02	0.01	21	-5.1	0.93	-4.8
Jun	18	0.22	0.01	0.00	22	-4.4	0.08	-0.4
Jul	32	0.23	0.01	0.01	31	0.9	0.02	0.0
Aug	38	0.23	0.02	0.01	35	3.3	0.02	0.1
Sep	58	0.22	0.03	0.02	47	11.0	0.03	0.3
Oct	58	0.23	0.04	0.03	47	11.2	0.06	0.7
Nov	31	0.22	0.07	0.05	30	0.5	0.49	0.2
Dec	28	0.23	0.07	0.05	29	-0.5	0.99	-0.5
Total	356	2.68	0.49	0.30	353	0.3	0.55	-20.8

Table 11: Water balance of Murray 2 dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	23	0.02	0.05	0.03	25	-2.7	1.00	-2.7
Feb	18	0.02	0.04	0.02	22	-4.4	1.00	-4.4
Mar	18	0.02	0.03	0.02	23	-4.3	1.00	-4.3
Apr	17	0.02	0.02	0.01	22	-4.9	1.00	-4.9
May	16	0.02	0.01	0.01	21	-5.1	0.93	-4.7
Jun	18	0.02	0.01	0.00	23	-4.3	0.08	-0.4
Jul	32	0.02	0.01	0.00	31	0.9	0.02	0.0
Aug	38	0.02	0.01	0.01	35	3.2	0.02	0.1
Sep	58	0.02	0.02	0.01	47	10.8	0.03	0.3
Oct	58	0.02	0.03	0.01	47	11.0	0.06	0.7
Nov	31	0.02	0.04	0.02	30	0.4	0.49	0.2
Dec	28	0.02	0.05	0.03	29	-0.5	0.99	-0.5
Total	356	0.26	0.31	0.17	355	0.17	0.55	-20.7

Table 12: Water balance of John Day dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	12192	14	2	1	11845	334	0.01	4
Feb	8394	13	3	2	9503	-1121	0.01	-12
Mar	16081	14	5	4	14243	1825	0.01	19
Apr	18516	13	9	7	15744	2758	0.01	29
May	18842	14	13	11	15945	2884	0.02	49
Jun	15214	13	14	13	13709	1492	0.04	64
Jul	7495	14	16	16	8949	-1468	0.22	-322
Aug	8961	14	14	14	9853	-906	0.51	-463
Sep	4931	13	11	11	7369	-2451	0.80	-1958
Oct	8656	14	6	5	9665	-1023	0.10	-100
Nov	8744	13	4	2	9719	-988	0.01	-10
Dec	8063	14	2	1	9299	-1249	0.01	-13
Total	136089	164	100	86	135844	86	0.15	-2714

Table 13: Water balance of Chief Joseph dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	4682	8	1	0	5512	-838	0.01	-9
Feb	4034	7	1	0	5113	-1086	0.01	-11
Mar	6508	8	3	2	6638	-139	0.01	-1
Apr	9934	8	4	4	8751	1175	0.01	12
May	13294	8	6	6	10823	2463	0.02	42
Jun	11122	8	7	7	9483	1631	0.04	70
Jul	7732	8	9	8	7393	331	0.22	72
Aug	6714	8	7	7	6765	-59	0.51	-30
Sep	4306	8	6	6	5280	-982	0.80	-785
Oct	5321	8	3	2	5906	-593	0.10	-58
Nov	4881	8	1	0	5635	-762	0.01	-8
Dec	4001	8	1	0	5093	-1099	0.01	-11
Total	82529	97	49	41	82393	41	0.15	-717

Table 14: Water balance of Grand Coulee dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	4566	411	3	0	403	3753	0.01	39
Feb	3997	372	6	1	1479	2146	0.01	23
Mar	6423	411	16	8	2772	3239	0.01	33
Apr	9785	398	31	24	6265	3118	0.01	33
May	13098	411	46	34	13778	-1097	0.02	-19
Jun	10994	398	55	41	17176	-6588	0.04	-283
Jul	7637	411	63	55	21488	-14262	0.22	-3125
Aug	6654	411	56	50	5858	385	0.51	197
Sep	4264	398	41	36	2440	1423	0.80	1137
Oct	5291	411	14	9	3247	1643	0.10	161
Nov	4796	398	6	2	974	3428	0.01	36
Dec	3908	411	3	1	432	3073	0.01	32
Total	81413	4844	341	262	76313	262	0.15	-1735

Table 15: Water balance of The Dalles dam (flows in 10^6 m^3, WSI dimensionless, WSFP in 10^6 m^3 H_2O_e)

Month	Inflow	Seepage	PEV	NEV	Outflow	Consumption	WSI	$WSFP_m$
Jan	13455	56	1	0	12797	607	0.01	6
Feb	9144	50	2	1	10147	-1051	0.01	-11
Mar	17630	56	3	1	15363	2213	0.01	23
Apr	19489	54	5	4	16506	2930	0.01	31
May	19519	56	8	6	16525	2940	0.02	50
Jun	15563	54	9	7	14093	1416	0.04	61
Jul	7601	56	11	10	9198	-1654	0.22	-362
Aug	9077	56	9	8	10106	-1084	0.51	-554
Sep	4994	54	7	6	7596	-2655	0.80	-2122
Oct	8742	56	3	2	9900	-1211	0.10	-118
Nov	9010	54	2	1	10064	-1104	0.01	-12
Dec	8503	56	1	0	9753	-1301	0.01	-14
Total	142727	656	61	46	142047	46	0.15	-3022

Table 16: Derivation of net evaporation from floodplains downstream of the Aswan High dam

Month	Discharge (m^3/s)	Excess* (m^3/s)	Area (km^2)	PEV (10^6 m^3)	NEV (10^6 m^3)
Jan	1547	0	0	0	0
Feb	885	0	0	0	0
Mar	520	0	0	0	0
Apr	577	0	0	0	0
May	980	0	0	0	0
Jun	1165	0	0	0	0
Jul	2676	0	0	0	0
Aug	12314	4564	5020	544	403
Sep	15562	7812	8593	216	36
Oct	5859	0	0	0	0
Nov	2697	0	0	0	0
Dec	930	0	0	0	0
Total	-	-	-	759	439

Discharge exceeding the drainage capacity of 7750 m^3/s

Table 17: Summed monthly water scarcity footprints (m^3 H_2O_e / MWh) of the selected reservoirs

Dam	WC_{gross}	$WSFP_a$	$WSFP_{m,unallocated}$	$WSFP_{m,allocated}$
Cahora Bassa	341.31	2.95	1.38	0.46
Aswan High	2008.89	1849.48	-2548.03	0
Three Gorges Dam	15.55	0.18	-5.72	0
Liujianxia	32.46	27.31	14.58	7.29
Laxiwa	3.33	2.54	-22.62	0
Snow Mountains	98.71	12.26	-103.06	0
Tumut 3 / Talbingo	16.60	7.72	-22.14	0
Murray 1 / Geehi	0.68	0.34	-29.35	0
Murray 2	0.69	0.30	-45.91	0
John Day*	11.83	0.27	-322.30	0
Chief Joseph*	4.99	0.11	-73.35	0
Grand Coulee	16.23	0.33	-82.68	0
The Dalles*	9.95	0.20	-494.57	0

run-of-river dams where WSFP might be assumed to equal zero

Table 18: Summed monthly allocated water scarcity footprints (m^3 H_2O_e / MWh) based on sensitivity analyses (dams with net impacts in some scenarios are bolded)

Dam	Original	Year 2004	Specific attenuation	Irrigation dampening	Watershed irrigation	WSI_{mean}
Cahora Bassa	0.46	0.07	NA*	0	0	0.72
Aswan High	0	0	NA	0	0	0
Three Gorges	0	0	NA	NA	NA	0
Liujianxia	7.29	0	NA	NA	NA	10.48
Laxiwa	0	NA	NA	NA	NA	0
Snowy Mountains	0	0	NA	NA	NA	0
Tumut 3	0	0	NA	NA	NA	0
Murray 1	0	0	NA	NA	NA	0
Murray 2	0	0	NA	NA	NA	0
John Day	0	0	0	NA	NA	0
Chief Joseph	0	22.10	0	NA	NA	0
Grand Coulee	0	6.16	NA	0	0	0
The Dalles	0	0	0	NA	NA	0
Mean**	0.33	3.49	0.33	0.29	0.29	0.48

Not available mostly because it only concerns reservoirs with specific main purposes or from specific countries.

***Weighted by annual hydroelectricity generation considering all 12 selected dams but not the Snowy Mountains scheme*