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Water Scarcity Footprint of Hydropower Based on a Seasonal Approach - Global assessment with sensitivities of model assumptions tested on specific cases

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Abstract

According to ISO 14046 the quantification of the water scarcity footprint (WSFP) of hydropower reservoirs has to consider (1) the evaporation of water from the surface of the reservoir, (2) the baseline evaporation of water of the same area before the reservoir has been built, and (3) the water scarcity index of the location of the reservoir on a spatially and temporally explicit level.

When a reservoir has a storing function, e.g., for irrigation in the dry season, monthly water scarcity indexes have to be used in order to calculate the WSFP, since storage in wet seasons and release in dry seasons can counteract water scarcity and lead to a reduction of overall water scarcity in the watershed.

This paper builds on previous research regarding detailed hydropower modeling and extends the water scarcity assessment to include and advance new methods for identifying sensitivities in monthly WSFP of hydropower due to the choice of impact assessment methods. We applied the global analysis to 1473 hydropower plants covering >100 countries, and added a detailed assessment for a subset of important power plants to discuss the limitations of global assessments. We thereby provide the most complete WSFP of global hydropower with state-of-the-art methods, assess the robustness of the global model and different methodological choices, and provide new monthly average AWARE CFs on watershed level.

The results show that water scarcity can often be mitigated if the net evaporation is compensated by the storage effects. The two water scarcity metrics applied lead to larger differences than expected, since the monthly dynamics of dams can lead to stronger differences than the differences in the applied water scarcity factors. The new insights help to better understand the WSFP of hydropower and its uncertainties.

Keywords:

water scarcity footprint; hydropower reservoir; seasonality; water consumption; power production.

1. Introduction

Hydropower generation is generally classified as the second largest water consuming activity after irrigation (e.g. [1]), and provides ~16% of global power production in 2012. More than 50% of global hydropower is generated in China, Brazil, Canada and the United States [2]. Hydropower has the highest water consumption per unit of electricity produced among major power production types, with estimates of 90 m3/GJ [3] and 68 m3/GJ [1]. The water consumption is defined as the gross evaporation from the reservoir surface. Previous research has highlighted that this is not the most appropriate approach, since water would evaporate from the natural water surface and surrounding ecosystems regardless of the reservoir's storage function. Thus net water consumption estimates have been provided for water scarcity footprint assessments (e.g. [3-7]). This has been discussed in detail by [8], [9].

Various data on hydropower water consumption are published in the literature. However, there has been limited work done on a global level. We have therefore based our research on both previous detailed global assessments for 1473 individual hydropower plants [7] and a recent publication with 2235 reservoirs [10]. The latter calculates gross evaporation, but focuses on different methods for evaporation estimates and allocation to different uses of the reservoirs.

In order to assess water scarcity footprints (WSFP) based on ISO 14046 [11], monthly and spatially explicit characterization factors (CF) need to be applied to monthly water consumption of the reservoirs [4]. The same applies for assessing water consumption impacts within the framework of Life Cycle Assessment (LCA) [5, 12]. Previous research on a global level [7] used a modified approach of the water stress index [13] and expanded it with an assessment of flow change impacts on ecosystem quality, which goes beyond the water scarcity footprint. In order to provide an analysis that can serve as a benchmark, we applied both the watershed level (>11’000 units) recommended CFs of the UNEP working group “WULCA” (AWARE, [14] and the published CFs with the same resolution (WSI, [15]). As most CFs are to be used for marginal changes in water flows only and changes in runoff through hydropower might be non-marginal, we also applied average CFs to test the sensitivities of the scarcity assessment.

Additionally, we address the question of allocation between power production, irrigation and other reservoir purposes, which is a very sensitive step in the calculation of hydropower WSFP. Between monthly varying CF values and allocation assumptions, it is possible that hydropower WSFP estimates reported in previous scientific literature tend to overestimate the real water consumption and the resulting impacts on both water resource availability and the environment.

The objectives of this paper are to (1) provide the most complete water footprint assessment of global hydropower using state-of-the-art water scarcity assessment, (2) assess the robustness of the global model with a detailed assessment of important hydropower plants and different methodological choices, and (3) develop and provide average AWARE CFs to be applied for further assessments.

2. Materials and Methods

2.1. Global gross and net water consumption of hydropower plants

We selected all 1473 hydropower plants from [7] for this analysis, and used their monthly data for the inflows and outflows, as well as evaporation and seepage, in order to calculate the net water consumption (CS) for each month t:

$$CS(t) = IF(t) + P(t) - OF(t) - AET(t) - SP(t) = NET(t) + dS(t) \quad (1).$$

The annual net consumption represents the sum of monthly CS(t) values. IF is the inflow, P precipitation, OF outflow, SP seepage and AET is the actual evapotranspiration of the surrounding land cover, which is used as proxy for natural evapotranspiration at the location of the reservoir before its construction. NET is the net evapotranspiration and dS is the storage change. It has to be noted that this state-of-the-art global data does not account for a detailed assessment of vegetation and reservoir dynamics and their effect on evapotranspiration.

We used the power generation from [2] and compared it to the installed capacity in the World Electric Power Plants Database (WEPP) database [3]. As a check, evaporation calculations were compared to the new total water consumption (gross evaporation) estimates of the total reservoir operation from the 529 matching entries of Hogeboom et al. [10], based on the ID of the Global Reservoir and Dam (GRanD) database [17] of each power plant, as both studies are using GRanD as a data source.

2.2. Gross and net water consumption of selected major hydropower plants

In order to check the robustness of our global assessment and provide specific data on major hydropower plants, we evaluated 13 large hydropower plants, which have been evaluated in a report published by the International Aluminium Institute (IAI) [18]. These hydropower plants (compiled in Table 1), were evaluated to highlight the behavior of the scarcity assessment as a function of monthly CFs and evaluate the sensitivity of dam operation data.

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	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

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

2.3. Allocation of water consumption to electricity production

We applied the allocation factors (AF) from Scherer and Pfister [7], which are based on the ranking of reservoir purposes.

$$CS\_allocated = CS \cdot AF \qquad (2).$$

Additionally, we calculated the electricity value per hydropower plant based on the energy production at an average price of 0.1 USD/kWh and compared it to the total value reported per dam by Hogeboom et al.

[10]. From this, we derived value based AFs as the value share of the electricity. We also compared the hydropower plants with the allocated impacts from [10] based on the total evaporation and per GJ evaporation data for each dam. For the case of the High Aswan dam, we can directly use the allocation result shown in their paper per country, as it is the only one in Egypt.

2.4. Water scarcity footprint assessment

Water scarcity footprints need to be modeled on a spatially and temporally explicit level [11]. For this, we multiplied CS(t) with monthly CFs on a watershed level (global coverage, >11’000 units) from the UNEP working group recommended marginal “AWARE” method ($AWARE_{marginal}$, [14]), the marginal ($WSI_{marginal}$) and average (WSI_{avg}) CFs for monthly WSI [15], and the non-marginal AWARE CFs ($AWARE_{avg}$), calculated as described below.

Both, AWARE and WSI are reporting m^3 H_2Oe per m^3 water consumed. AWARE reports H_2Oe in equivalents of the world average water availability situation (i.e. m^2 area required to provide $1m^3$/year of water after environmental and human demand is met). The CFs range from 0.1 – 100 (1 being the world average water availability situation). WSI range from 0.01 – 1 and report H_2Oe in equivalents of water consumed under extreme water scarcity. The total monthly water scarcity footprint ($WSFP_{dam}$) and the WSFP per GJ electricity ($WSFP_{el}$) are calculated based on annual electricity generation in GJ (AEG) as follows:

$$WSFP_{dam}(t) = CS(t) \cdot CF(t) \qquad (3),$$

$$WSFP_{el}(t) = CS(t) \cdot CF(t) / (AEG / 12) \cdot AF \qquad (4).$$

For calculating the non-marginal AWARE CFs ($AWARE_{avg}$) we integrated the scarcity function over the human consumption and divided by the human consumption (as done in [15]). We assume that the non-marginal changes of the individual hydropower plants do not affect the global reference significantly and thus we set it to a constant value based on [14]. Thus, the integrated scarcity factor (SF_{avg}) of $AWARE_{avg}$ before the normalization with the global reference and the cut-off can be calculated as follows:

$$SF_{avg} = (A \cdot \ln(|AMD_{natural}|) - A \cdot \ln(|AMD_{actual}|)) / C_{human} \qquad (5),$$

where A is the area of the watershed, AMD is availability minus demand, and demand includes human water consumption (C_{human}) and environmental water requirements. Data is taken from Boulay et al. [14]. It is then normalized by the world average scarcity factor (SF_{global}) based on the original AWARE method to derive $AWARE_{avg}$ CFs. The normalized result (SF_{avg}/SF_{global}) is set to a CF of 100, if CF >100 or if $AMD_{actual} \leq 0$. In case of $C_{human} = 0$, $AWARE_{avg}$ equals $AWARE_{marginal}$.

3. Results

3.1. Global assessment

The evaporation flows between the two papers used in the analysis match well (see SI), especially considering the large uncertainties in both the calculation of evaporation from various data sources as well as from the application of different evaporation equations, as shown by [10].

The gross and net water consumption for each power plant is reported in the supporting information, including monthly impact assessment results obtained using the described methods. Global total annual water consumption of all hydropower is calculated to be $4.4 \cdot 10^{11}$ m^3 for net and $7.4 \cdot 10^{11}$ m^3 for gross consumption. Net water consumption corresponds to ~50% of crop water consumption based on [1] and indicates that hydropower net water consumption is the biggest water consumer after agriculture.

In general, the chosen impact assessment method has a very strong influence on the final result. This is largely due to the relatively high discrepancies in the monthly patterns for the tested CFs (e.g. only in 29% of all watersheds the month with highest CF matches for $AWARE_{avg}$ and WSI_{avg}), in combination with the large monthly storage - even though AWARE and WSI generally correlate well on a global level [19]. The main issue is that for hydropower water scarcity assessments with large storage activity, the differences among months are crucial, as this often decides whether the net WSFP is positive or negative. For nearly three quarters of the power plants (1074), results from the four sets of CFs applied (WSI_{avg}, $WSI_{marginal,}$ $AWARE_{avg}$ and $AWARE_{marginal}$) agreed on whether the result was net positive or negative. Of these unanimous results, 906 had a negative WSFP and 168 had a positive WSFP (i.e. an increasing water scarcity impact). The latter accounted for 19.5% of the power generated in the dataset. For the other 399 units, both negative and positive WSFP results were obtained among the different sets of CFs, thus a water scarcity footprint of 0 was assumed.

Globally, the water scarcity footprint of hydropower for those power plants with WSFP>0 (unanimously among the four sets of CFs) is shown in Table 2 based on energy production and allocation from [7]. It should be noted that AWARE ranges from 0.1 to 100 while WSI ranges from 0.01 to 1, which means that

AWARE results are generally a factor of 100 larger than WSI results: If we apply this factor to get AWARE-equivalent m^3 H_2Oe, we have 544, 831, 838, 883 m^3 H_2Oe / GJ for WSI_{avg}, $WSI_{marginal}$, $AWARE_{avg}$ and $AWARE_{marginal}$. The AWARE results are very close to each other and to the marginal WSI results, while WSI_{avg} results are considerably lower. On global average, the sensitivity to the sets of CFs selected is therefore low (coefficient of variation is 20.0%), but it can be significant on a case by case level, as discussed in section 4.2. The average net water consumption of power production with only positive WSFPs is 70.6 m^3/GJ. Scaling to the total power production in the dataset, the average net water consumption is 13.7 m^3/GJ. Fig 1 presents a map of the WSFP results of all power plants analyzed in this study, using $AWARE_{avg}$ CFs.

Table 2. WSFP results for global assessment. Numbers are in m^3 H_2Oe /GJ electricity produced and based on those dams where all four sets of CFs agreed on a net scarcity impact (19.5% of generated hydropower in the database).

	net ET	**WSI_{avg}**	**$WSI_{marginal}$**	**$AWARE_{avg}$**	**$AWARE_{marginal}$**
Only positive WSFP	70.6	5.44	8.31	838	883
Scaled to 100% Hydropower production	*13.7*	*1.06*	*1.62*	*163*	*172*

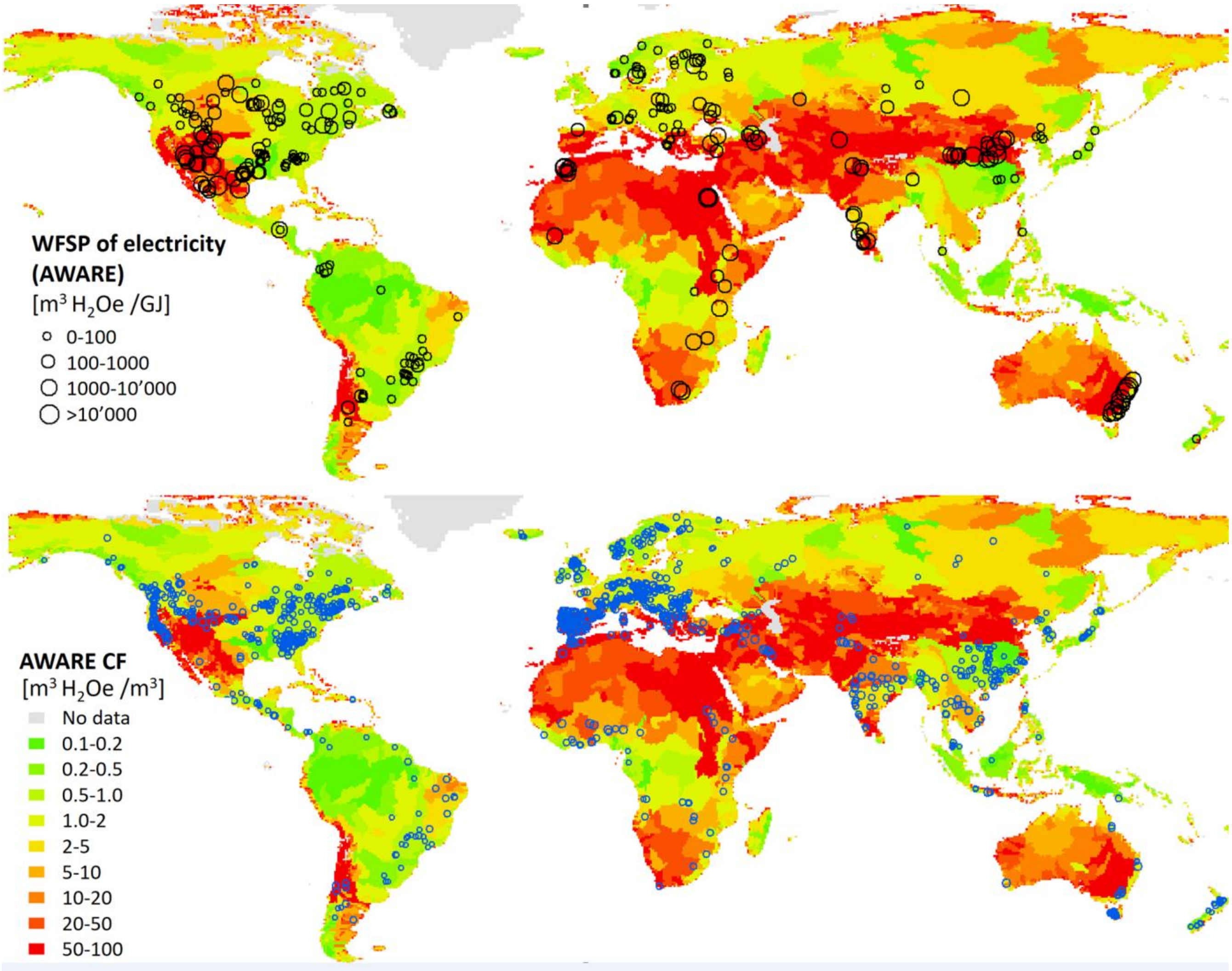

Fig 1: Water scarcity footprint (WSFP) of hydropower. WSFP of individual hydropower plants reported in H_2O_e / GJ electricity (top) and indication of dams with WSFP below 0 (bottom), based on the $AWARE_{avg}$ characterization factor (CF). The underlying map shows the default annual AWARE CF from Boulay et al. [14].

3.2. Allocation

The installed capacity of the 764 power plants with a match in the WEPP database [3] was compared to the reported energy production used in this study [7]. We assumed the overall global capacity factor to be around 44% [7], while Hogeboom et al. [10] assumed it to be 34%. There is a significant mismatch of reported power production that can be partially explained by unknown operation types and annual fluctuations. The power production data vary between the two scientific studies on water footprint, even though the ratio of the allocated gross water consumption of Scherer and Pfister [7] over Hogeboom et al. [10] is 1.80 for all matches (incl. allocation) and 3.75, for the 289 matches where no allocation is applied by Hogeboom et al. (SI, XLS, Table “global comparison”). The analyzed studies cover different years, but other factors might explain the difference, since the calculation of the gross ET deviates by a factor of almost 3 (Appendix).

3.3. Detailed WSFP assessment of selected reservoirs

In order to present the dynamics of monthly assessments and the use of more detailed data for estimating monthly water consumption, the results of monthly WSFP calculations for three of the 13 selected reservoirs (Cahora Bassa, Aswan High and Three Gorges) are shown in Table 3 – 5. The detailed assessment of 13 dams is based on the report of [18] and the monthly water balance is compared to the global assessment.

Table 3. Water balance of Cahora Bassa dam. Inflow, Outflow and Consumption from detailed assessment and consumption of global assessment (flows in 10^6 m^3) and WSFP using different characterization factors in 10^6 m^3 H_2Oe.

			Net Consumption		Footprints (WSFP)			
Month	Inflow	Outflow	Detailed	Global	$\text{AWARE}_{\text{marginal}}$	$\text{AWARE}_{\text{avg}}$	$\text{WSI}_{\text{marginal}}$	WSI_{avg}
Jan	16261	10900	5591	*-294*	11434	11409	56.2	56.1
Feb	11074	10844	141	*-8056*	279	277	1.4	1.4
Mar	18430	16772	1524	*-5893*	3689	3637	15.3	15.3
Apr	8180	6041	1843	*4537*	8893	8566	18.7	18.6
May	5711	2207	3185	*3922*	39118	36683	32.6	32.2
Jun	4745	3012	1394	*4123*	20706	20572	14.5	14.2
Jul	4271	5437	-1489	*2171*	-18050	-17955	-15.9	-15.4
Aug	3745	7317	-3921	*707*	-42051	-41853	-44.6	-41.8
Sep	3157	4930	-2112	*2448*	-20500	-20413	-27.0	-23.9
Oct	3166	3348	-531	*2959*	-3851	-3839	-8.2	-6.7
Nov	3667	5275	-1852	*-1417*	-10655	-10627	-26.6	-22.3
Dec	5847	5421	457	-1405	1651	1648	4.6	4.6
Total			**4230**	***3802***	**-9337**	**-11896**	**21.1**	**32.2**

Table 4. **Water balance of Aswan High dam.** Inflow, Outflow and Consumption from detailed assessment and consumption of global assessment (flows in 10^6 m^3) and WSFP using different characterization factors in 10^6 m^3 H_2O_e.

			Net Consumption		Footprints (WSFP)			
Month	Inflow	Outflow	Detailed	*Global*	$\text{AWARE}_{\text{marginal}}$	$\text{AWARE}_{\text{avg}}$	$\text{WSI}_{\text{marginal}}$	WSI_{avg}
Jan	4134	6881	-4273	*1287*	-427300	-427300	-4,272.8	-2,915.6
Feb	2134	6512	-5757	*1175*	-575700	-575700	-5,757.0	-4,505.4
Mar	1393	6525	-6658	*1338*	-665800	-665800	-6,658.0	-5,704.2
Apr	1492	5515	-5499	*1434*	-549900	-549900	-5,499.0	-4,920.1
May	2620	5766	-4670	*1478*	-467000	-467000	-4,670.0	-4,297.7
Jun	3008	7525	-5994	*1376*	-599400	-599400	-5,994.0	-5,548.5
Jul	7106	9639	-4060	*1397*	-406000	-406000	-3,197.3	-1,058.0
Aug	32917	11040	20351	*1424*	2035100	2035100	4,541.6	1,474.0
Sep	40336	10484	28375	*1407*	2837500	2837500	11,702.1	3,490.3
Oct	15666	6026	8113	*1421*	811300	811300	7,010.8	2,500.0
Nov	6956	6063	-585	*1281*	-58500	-58500	-540.6	-211.8
Dec	2486	6369	-5410	*-834*	-541000	-541000	-5,349.0	-2,669.5
Total			13933	***14183***	**1393300**	**1393300**	**-18,683.1**	**-24,366.3**

Table 5. Water balance of Three Gorges Dam. Inflow, Outflow and Consumption from detailed assessment and consumption of global assessment (flows in 10^6 m^3) and WSFP using different characterization factors in 10^6 m^3 H_2O_e.

			Net Consumption		Footprints (WSFP)			
Month	Inflow	Outflow	Detailed	*Global*	AWARE$_{marginal}$	AWARE$_{avg}$	WSI$_{marginal}$	WSI$_{avg}$
Jan	9625	19065	-9599	*-7886*	-18966	-17874	-138.8	-116.1
Feb	8853	18612	-9869	*-8212*	-24607	-23152	-201.9	-144.3
Mar	11331	20065	-8848	*-7213*	-19657	-18577	-439.8	-220.3
Apr	30581	31343	-801	*456*	-1424	-1348	-82.7	-32.6
May	32999	32760	237	*1357*	240	221	32.5	11.8
Jun	42584	38376	4228	*5225*	2436	2304	69.9	55.0
Jul	70287	54607	15622	*9879*	5203	5021	182.1	168.9
Aug	75691	57773	17889	*9872*	5078	4935	199.8	189.2
Sep	51504	43602	7842	*8727*	2452	2419	85.2	81.8
Oct	31490	31876	-520	*771*	-204	-201	-5.8	-5.5
Nov	16600	23152	-6667	*-5126*	-4985	-4856	-79.9	-73.1
Dec	11270	20028	-8909	*-7246*	-12637	-12075	-112.7	-100.4
Total			**605**	***605***	**-67071**	**-63182**	**-492.0**	**-185.6**

The Cahora Bassa (Table 3) and High Aswan (Table 4) Dams show a different storage pattern in the detailed assessment, while the total water consumption is a good match between the global and detailed assessment. For the Three Gorges Dam (Table 5), the global pattern of monthly storage matches well with the detailed assessment. The difference in the temporal dynamics of storage in the dams leads to large differences in WSFP, especially for the High Aswan Dam. The comparison for the 13 dams assessed in detail with global data and an annual assessment show that the temporal resolution is of key importance, since total annual water consumption is generally a good match (Table 6). Table 6 also highlights the effect of the chosen CF to quantify the WSFP: While annual average assessments always produce a WSFP > 0, the result of the monthly assessment using WSI$_{avg}$ is less than 0 for 12 of the 13 dams analyzed in the detailed assessment. The global assessment for the nine dams existing in the database shows two dams having a WSFP > 0, i.e. there is one mismatch in the sign of the number between the global and local assessment (Aswan High Dam). In the other eight cases, the difference was within a factor of five (i.e. in the same order of magnitude) and for four of them, the difference was less than a factor two.

Table 6. Comparison between detailed assessment for WSFP determined on an annual and a monthly basis. Flows are in 10^6 m^3, WSFP in 10^6 m^3H2Oe. Global results refer to the main results in this paper, indicating the relevance of specific input data in the local assessments (mainly related to dam operation).

	Net Consumption		**WSFP, Detailed Monthly Assessment**				**Annual CF**	**Global results**
Reservoir	Detailed results	Global results	$AWARE_{marginal}$	$AWARE_{avg}$	$WSI_{marginal}$	WSI_{avg}	**WSI_{avg}**	**WSI_{avg}**
Cahora Bassa	4,230	3,802	-9,337	**-11,896**	21	**32**	**45**	**48**
High Aswan Dam	13,933	14,183	1,393,300	**1,393,300**	-18,683	**-24,366**	**7,758**	**7,991**
Three Gorges Dam	605	605	-67,071	**-63,182**	-492	**-186**	**11**	**-82**
Liujianxia	172	187	79,959	**85,252**	89	**-250**	**89**	**-191**
Laxiwa	5	11	65,834	**72,146**	-50	**-232**	**3**	**-132**
Snow Mountains/ Blowering	99	NA	NA	**NA**	-40	**-29**	**36**	**-57**
Tumut 3 / Talbingo	18	18	-410	**-1,189**	-40	**-30**	**7**	**-6**
Murray 1 / Geehi	0.3	0.3	-1,542	**-1,893**	-22	**-16**	**0.1**	**-6**
Murray 2	0.2	3	-1,529	**-1,876**	-22	**-16**	**0.1**	**-5**
John Day	86	NA	-10,396	**-7,150**	-2,923	**-914**	**4**	**NA**
Chief Joseph	41	NA	-3,277	**-2,887**	-773	**-247**	**2**	**NA**
Grand Coulee	262	NA	-3,574	**1,530**	-1,737	**-488**	**14**	**NA**
The Dalles	46	NA	-11,649	**-7,952**	-3,252	**-1,016**	**2**	**NA**

While, in general, WSFP calculated on a monthly level decreases the total annual WSFP due to storage, it can also have the opposite result, as is shown for the Liujianxia and Laxiwa dams using the $\mathrm{AWARE}_{\mathrm{avg}}$ CFs (see SI); the monthly storage and release is much larger than the annual net consumption and as the $\mathrm{AWARE}_{\mathrm{avg}}$ indicates higher scarcity during the storage periods than during the release, the monthly WSFP is ~ 200 times higher than the WSFP calculated at the annual level for the Laxiwa dam.

3.4. Country average hydropower WSFP

We calculated the national average WSFP of hydropower based on the allocation of dams to countries. The results are presented in the SI. These can be used to calculate impacts of electricity use in background databases. The difference between countries is very high (over several orders of magnitude) for all indicators (see SI, XLS: “country avg results”). This shows the importance of using at least country-specific WSFP results based on highly detailed assessments, as provided in this study, since current implementations of water flows in background databases do not fulfill the ISO 14046 requirements [12].

4. Discussion

4.1. Global assessment

The WSFP quantifies the contribution of a process, in this case of a hydropower reservoir, to water scarcity. If the WSFP is calculated on a monthly basis, the resulting number is in most of the cases negative. This demonstrates that, because of its operation, the reservoir has a positive effect on water scarcity, especially when more water is collected than released in the wet season and more water is released than collected in the dry season. It is debatable whether negative impacts, i.e. benefits, should be reported as such or set to zero, since the uncertainty of dam operation and thus monthly storage is high in global assessments (as shown in Table 6), and if there is a large negative WSFP, the main purpose is likely storage for irrigation. Additionally, variability of water inflow and water demand affect dam operation among years. We suggest to set WSFP for these cases to zero. For calculating country or global averages, we suggest to sum the WSFP of dams with WSFP > 0 and divide it by the total hydropower production of all dams (see Table 2 and SI for country averages). Therefore, our WSFP results are much lower compared to previous studies. As a consequence, the water consumption results reported in background databases should be adjusted, as long as they do not report the values on a monthly level.

From the global analysis, no clear relation between WSFP of dams and the average annual water scarcity in the watershed are observed, as positive and negative WSFP occur in low and high scarcity regions (Fig 1). However, high WSFP of dams mainly occur in water scarce areas.

4.2. Sensitivities

There is a high uncertainty of hydropower WSFPs due to several aspects, including the spatial and temporal variations, as is shown in our comparison of global assessment with local detailed assessments. Additionally, actual climate variation between years and especially in the future is increasing uncertainties, since hydropower dams are long-living infrastructures. On the inventory side (i.e. water consumption), it is important to capture the specific local conditions to properly quantify evaporation losses. This has been discussed in detail by Hogeboom et al. [10] and the effect is presented in Fig. 2. More importantly, based on our comparison with local and global data is the monthly pattern of the storage and release, which is based on limited data availability for the global model as discussed in Scherer and Pfister [7]. This means to better assess the monthly inventory of hydropower dams, better operation data is necessary.

The choice of water scarcity CFs has a significant effect at the dam level, as shown in the detailed assessment and in Fig. 2, even if on the global average, the two methods are quite consistent. The difference between marginal and average CFs is less significant than between AWARE and WSI, which indicates that the average factors are not that important, even though they reduce the impact in general (Fig. 2). The effect is stronger for WSI than AWARE, which might be a result of the cut-off choice at a factor of 100 in AWARE (see section 4.3). However, based on the UNEP consensus report on AWARE [20], marginal CFs should only be applied to conditions with up to 5% change in overall water consumption. For hydropower reservoirs, this can be equated to 5% change in water availability, since the inflow is temporally stored (i.e. consumed) and the outflow is negative consumption. This approach also allows for a more specific assessment of a dam, since relating the net storage to total net water consumption in the watershed neglects the location of the dam within a watershed. The analysis of the detailed dams shows, that in 85% of all months of the selected reservoirs, the storage was >5% compared to the inflow (SI, XLS, Table "Detailed Assessment". These results suggest to generally apply average CFs for hydropower dams.

Although allocation is important in LCA and water footprinting in general, it is particularly important for hydropower given the multi-purpose function of dams (Fig. 2). The water is typically used for two or three processes, i.e. irrigation and/or municipal water supply and generation of electricity. This can be considered an allocation issue at the inventory level. Power production and water supply are joint processes, i.e. the quantity of water used for the generation of electricity and the quantity used for irrigation and municipal supply cannot be varied independently. According to ISO 14044, it is appropriate to apply a market value allocation, especially if there is not a chemically or physically meaningful relation among the different purposes. This means that for the location of each reservoir the average market price per kWh of electricity and the market price for the supply of 1 m^3 of water should be known.

In the allocation procedure based on economic value following Hogeboom et al. [10], the electricity production gets a rather small impact share (See SI; "global comparison"), which is in line with the country average shares they reported (the large share of power plants of their analysis are in China and the US, which mainly have allocation to other uses). In principle, allocation can also be done on the monthly level, since in reality the value of both electricity and irrigation water depends on the market. Thus, the mitigating effect on water scarcity will be mainly driven by non-power demands (i.e. water supply and flood control). This reflects potential improvement of operations to further decrease water scarcity, but economic reasons lead to a combined operation scheme that accounts for all purposes. Therefore, allocation needs to be done carefully and the involved uncertainties clearly discussed. Compared to the monthly vs annual impact assessment and the modeling of monthly water flows, allocation has been of lower importance. Still, future research should include better information of economic values for the different purposes.

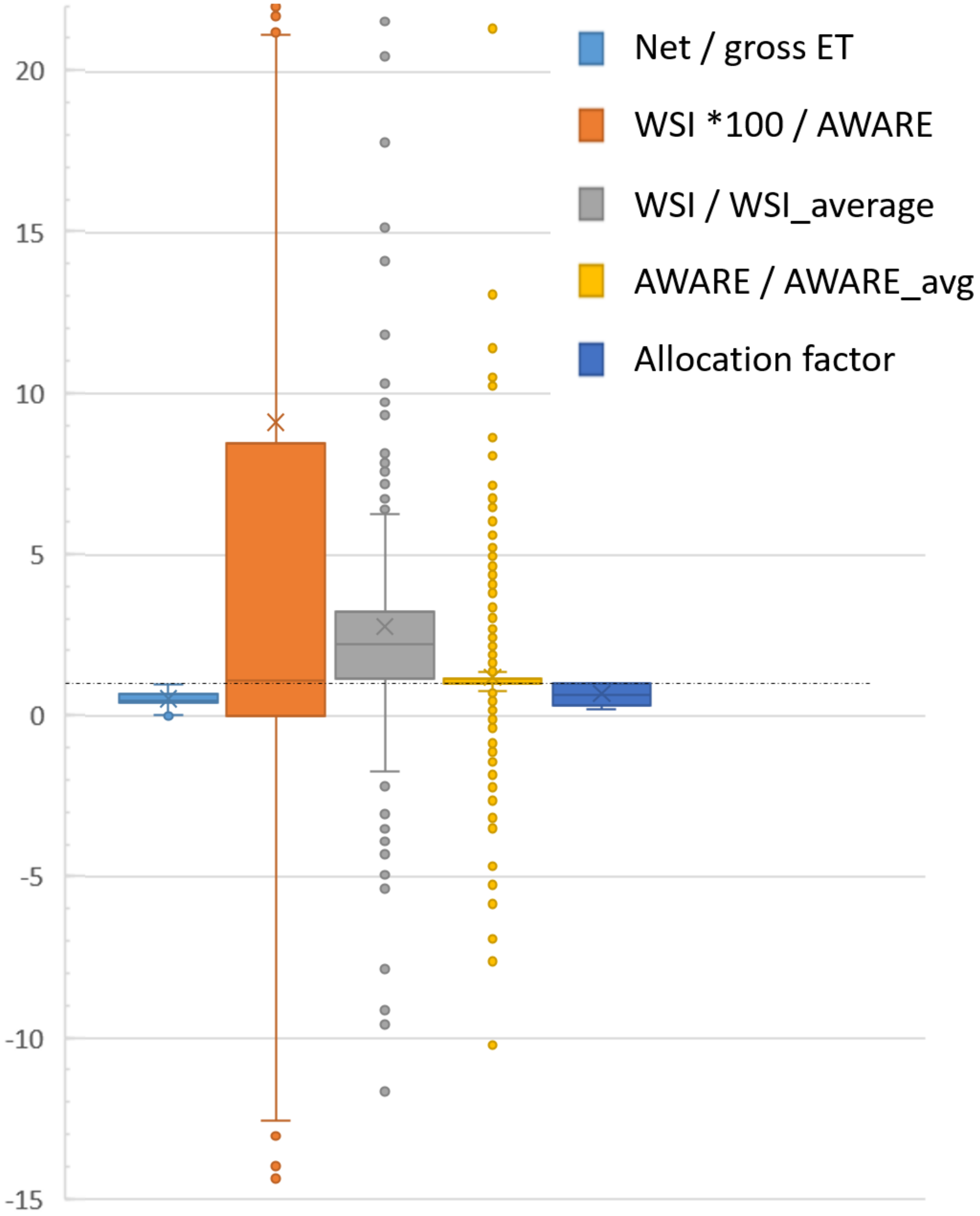

Fig 2: Effect of choices to calculate WSFP of hydropower. Boxplot of the ratios between WSFP of individual hydropower plants when applying different input data: Net ET / gross ET for the water consumption estimate, different methods for characterization factors (CFs), and with or without an allocation factor. For the choice of CFs we report the ratio of WSI (multiplied by a factor of 100 to adjust for the different scales) and AWARE on a

marginal level (WSI *100 / AWARE), as well as the ratio between marginal and average CFs for WSI (WSI / WSI_average) and AWARE (AWARE / AWARE_avg).

4.3. Effect of limiting AWARE CFs to 100 (cut-off) and of the global reference

The detailed assessment of specific dams showed that AWARE CFs (marginal and average) are at 100 in all months for the case of Aswan High Dam and thus the WSFP is 100 times the net consumption (Table 4). On the other hand, WSI vary over the season: the WSI CF was below 1 from August to October, when the inflow is significantly higher than the outflow. This resulted in a positive WSFP parameter for AWARE and a negative WSFP result for WSI. The difference is due to the fact that AWARE takes into account natural water scarcity per area and has a cut-off at 100. The natural water scarcity is high in the Nile watershed, and thus water storage and release dynamics of dams have no effect at the chosen cut-off, which can be considered a limitation of the cut-off approach chosen by the AWARE method. Additionally, the cut-off also depends on the global average used as a reference.

However, applying average AWARE CFs calculated by an alternative calculation procedure suggested by Boulay et al. [21] would lead to a negative water footprint for the Nile, too. This is due to the fact that they calculate average AWARE CFs, by integrating the marginal CFs after the cut-off, instead of deriving average impacts from the water scarcity impact function as done in this work. Additionally, several issues in the equations and thus results presented in [21] have to be noted: (1) they do not consider the impact of the non-marginal water consumption on the global reference value, which is affected especially if countries or large regions are assessed as a whole (in this work, we assumed the effect to be minor, since single reservoirs have a low influence on the global reference value); (2) they seem to double-count the impact of water consumption below the lower threshold; (3) the equation they present in the appendix for the integral solution between the cut-off values seems to have sign errors for availability and demand. Therefore, caution is advised in using the average CFs from [21].

4.4. Other environmental impacts

A comprehensive water footprint based on ISO 14046 also needs to consider quality changes [11]. This study is restricted to the WSFP, i.e. the contribution of a hydropower reservoir to water scarcity, without consideration of other potential environmental impacts of the reservoir, e.g. to biodiversity, climate change, acidification, eutrophication or ecotoxicity. Therefore, the results cannot be used for claims on an overall environmental burden or benefit or a full water footprint based on ISO 14046. Dams change flow dynamics that affect ecosystems, as quantified by Scherer and Pfister [7], and these effects could be mitigated by adjusting operations [22]. Additionally, dams also change temperature and sediment flows that affect nutrient and other characteristics of water quality, and should be addressed separately. This is required on a case by case basis, since methods in LCA are still missing on a global level. Finally, flooding of terrestrial ecosystems cause land use and land use change impacts [23] and all factors contribute to greenhouse gas emissions [24].

5. Conclusions

This study shows that many hydropower reservoirs, especially those which store water in the wet season and release water in the dry season, can be considered as beneficial in terms of water scarcity if the water scarcity footprint is calculated based on seasonal water scarcity indexes. However, this study was the first to analyze the effect of different water scarcity metrics, as recommended by the water scarcity footprint UNEP working group [20]. The results show the high uncertainty arising from the methodological choice.

For more than a quarter of the power plants the sign of impact does not agree among the tested water scarcity characterization methods, while the global average results varied by a factor 1.6 between the minimum and maximum WSFP estimates.

Nevertheless, while hydropower is identified as having a large share of human induced net blue water consumption (~50%, see above), the impact in terms of water scarcity is generally low: the WSFP of global hydropower is less than 3% of the WSFP of global crop production [15], both measured by WSI_{avg}. The developed approach can be used to assess additional hydropower scheme in more detail or to evaluate potential hydropower plants, such as those analyzed by Hoes et al. [25], in order to assess potential impacts of hydropower expansion.

The main limitations are related to the lack of data on the operation of hydropower dams, which is depending on natural water availability as well as demand for power and other services of the dam (e.g. water supply and flood protection).

Future research should therefore address the regime of hydropower dams in more detail. A special focus should be set on cascades of hydropower dams, since they should be addressed as systems rather than individual power plants.

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Author contributions

SP, LS, and KB designed the research, SP and LS conducted the modelling work and method development, and SP prepared the manuscript with contributions from the co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Supporting Information

The supporting information contains an Appendix with additional methods and results and an XLSX-file with the input data and additional detailed results.