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LCA Water Footprint AWARE Characterization Factor Based on Local Specific Conditions

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Abstract
A Water Footprint based on Life Cycle Assessment (LCA) methodology is a modern approach to the assessment of impacts of water use on the environment. The Available WAter REmaining (AWARE) method is the recommended characterization method by the WULCA Working group to perform a water consumption impact assessment in LCA. The published values of AWARE characterization factor were computed using the hydrological model at the country and main river basin levels only. These "average" values can be imported into the LCA software and used for LCA studies. The scale of available AWARE data could be insufficient for studies at a local level due to heterogeneous conditions in various countries or large river basins. In our study, we use runoff data from the Europe region available in the Global Runoff Data Centre for computation of "regionalized" AWARE values and compare them with AWARE values at the country and river basin levels. The analysis of computed values indicates that the variance of AWARE values can be very large in some countries and river basins.

Keywords: Water footprint – life cycle assessment – characterization factor – hydrological conditions

1. Introduction

Water is a key element of development of many countries. Water resources should be managed as an integral part of a nation's social and economic development (Koudstaal, Rijsberman, & Savenije, 1992). Environmental sustainability should also be assessed with regard to water resources. For example, the 'greenest' electricity scenario of the International Energy Agency (IEA, 2012) in terms of carbon footprint reduction is the worst in terms of their consumptive water use increase (Mekonnen, Gerbens-Leenes, & Hoekstra, 2016). There are different approaches to assessing sustainability of water use. A water footprint based on Life cycle assessment (LCA) principles (ISO, 2014) evaluates the various environmental impacts of a product or service throughout its entire life cycle. Another approach, based on a "volumetric" water footprint (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011), quantifies and maps green, blue and grey water use, assesses the sustainability, and formulates response strategies. The next approach, based on environmentally-extended input-output analysis, provides a simple and robust method for evaluating the linkages between economic consumption activities and environmental impacts, including the harvest and degradation of natural resources (Kitzes, 2013).

The applicability of all three approaches is highly dependent on the input data. Studies using these approaches very often incorporate generic or global data into the assessment. For our research we selected LCA-based water footprint assessment and specifically we

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focus only on water resource depletion (water availability/scarcity footprint). Although water is a global resource, water scarcity/unavailability is a local or regional issue and the impacts of water use vary with location and with time (Wichelns, 2017) and should be assessed on the local or regional conditions. Water use is multiplied by a characterization factor which reflects their relative contribution to the environmental impact, quantifying how much impact a product or service has in water scarcity/unavailability category. This study is focused on the AWARE method. The authors of the AWARE method provide values of characterization factor at country and watershed levels. We used regional hydrological data for computation of "regionalized" values of characterization factor. These "regionalized" values were compared with values of characterization factor available for import to the LCA software.

2. Methodology and Data

2.1 Characterization model

The Life Cycle Initiative Flagship project on LCIA indicators has chosen the AWARE method as a consensus impact method. AWARE represents Available WAter REmaining per area in a watershed after the demand of humans and aquatic ecosystems has been met. It assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived (Boulay et al., 2016, 2017; Frischknecht & Jolliet, 2016). The AWARE characterization factor is calculated as the normalised water Availability Minus the Demand (*AMD*) of humans and aquatic ecosystems and is relative to the area ($m^3 \cdot m^{-2} \cdot month^{-1}$ or $m^3 \cdot m^{-2} \cdot year^{-1}$). The *AMD* value is normalised with the world average result ($AMD_{world\ average}$ = 0.0136 $m^3 \cdot m^{-2} \cdot month^{-1}$ or $AMD_{world\ average}$ =12×0.0136 $m^3 \cdot m^{-2} \cdot year^{-1}$) and inverted, and hence represents a relative value in comparison with the average m^3 consumed in the world (the world average is calculated as a consumption-weighted average). The AWARE characterization factor values are available on the web page www.lifecycleinitive.org. The values of AWARE characterization factor available on this web page for main watersheds and for countries were modelled with values of availability and human demand obtained from the WaterGAP model (Flörke et al., 2013; Müller Schmied et al., 2014) and environmental demand was modelled by a model from Pastor et al. (2014). In this paper, we use the term "modelled AWARE" for these values. These modelled AWARE values are available for agricultural use or a domestic/industrial use and for "unknown" use.

Data at national or main watershed levels are insufficient for some studies. For example, it is a case of comparison between similar or the same product produced in the different parts of the same country/watershed. WaterGAP is a hydrological model and each model is only an approximation of reality. We use real hydrological data for computation of *AMD* and AWARE values.

2.2 Hydrological data

Observed runoff in the rivers can be described as available water remaining after the demand of humans has been met. This runoff cannot be wholly used by humans because ecological flow must be maintained in the river. Long-term available water remaining after the demand of humans has been met can be calculated as an average value of observed runoff. So we have to subtract the water demand of the aquatic ecosystem from observed runoff and divide the final value by catchment area to get a regionalized *AMD* value.

Daily water flows between 1st January 1981 and 31st December 2010 from 922 stations on 702 rivers in the "Europe & Mediterranean Asia" region (GRDC, 2016) were used for calculation of the average runoff (Q_A) and average monthly runoff (Q_M) in these stations during the whole period. The selection of stations was based on the existence of daily water flow time series and the existence of the catchment area values in the GRDC database. The 30-year interval 1981-2010 was chosen in an agreement with World Meteorological Organization standards (WMO, 2016).

We used the very simple Montana method (Tennant, 1976) for calculation of demand of aquatic ecosystems. Tennant uses 10% of the average flow as a minimum instantaneous flow recommended to sustain a short-term survival habitat for most aquatic life forms; 30% of the average flow is recommended to sustain a good survival habitat, and 60% of average flow to provide excellent to outstanding habitat. We used only 10% and 30% limits in our analyses. AMD for each station *s* was calculated by Eq. 1 for annual step and by Eq. 2 for monthly step.

$$AMD_s^{year} = \frac{T_i \times (1 - coef) \times Q_{A,s}}{Area_s} \tag{1}$$

$$AMD_s^{month} = \frac{T_i \times (1 - coef) \times Q_{M,s}}{Area_s} \tag{2}$$

Where:

$$T_i = \begin{cases} 365.25 \times 86400 & for\ a\ year \\ 28.25 \times 86400 & for\ February \\ 30 \times 86400 & for\ April;\ June;\ September\ and\ November \\ 31 \times 86400 & for\ other\ months \end{cases}$$

$$coef = \begin{cases} 0.1 & for\ 10\%\ limit \\ 0.3 & for\ 30\%\ limit \end{cases}$$

The AWARE characterization factor was then calculated by normalisation with the world average result.

3. Results

In the first step, we analysed 96 rivers (from 702) with more than 1 station for the variance values in different stations on each river. The variance was calculated by Eq. 3. The statistics of the results are in Tables 1 and 2.

$$variance = \frac{AWARE_{max} - AWARE_{min}}{AWARE_{max}} \tag{3}$$

Table 1. The number of rivers with *variance* of AWARE (Tenant's coef. = 0.1)

	0%	0-5%	5-10%	10-15%	15-20%	20-30%	30-40%	40-50%	50-75%	>75%
Year	1	14	10	13	8	14	14	12	9	1
Jan	0	8	8	14	11	14	14	7	15	5
Feb	0	10	11	7	8	19	12	5	18	6

Mar	0	11	7	11	6	17	14	8	19	3
Apr	3	5	9	10	12	16	12	14	13	2
May	8	7	11	11	8	15	13	6	12	5
Jun	5	11	9	12	8	15	12	6	14	4
Jul	3	7	9	11	8	16	16	8	12	6
Aug	3	10	5	9	12	15	13	9	16	4
Sep	0	14	5	13	14	10	9	11	17	3
Oct	1	5	11	7	17	17	16	10	11	1
Nov	1	12	11	11	9	15	16	10	10	1
Dec	1	10	11	10	11	14	18	9	10	2

Table 2. The number of rivers with *variance* of AWARE (Tenant's coef. = 0.3)

	0%	0-5%	5-10%	10-15%	15-20%	20-30%	30-40%	40-50%	50-75%	>75%
Year	0	13	10	14	8	15	13	12	10	1
Jan	0	7	8	14	11	14	14	7	16	5
Feb	0	10	11	7	8	19	11	6	18	6
Mar	0	11	7	11	6	17	13	9	19	3
Apr	1	5	9	9	11	18	14	13	14	2
May	2	8	13	10	10	15	12	9	11	6
Jun	2	12	8	12	5	16	14	8	14	5
Jul	2	7	7	13	6	16	16	10	13	6
Aug	2	10	5	10	12	13	12	11	17	4
Sep	0	14	4	13	13	10	11	8	20	3
Oct	1	5	11	7	17	16	15	10	13	1
Nov	1	11	11	11	8	15	18	10	10	1
Dec	0	10	10	10	11	15	18	8	12	2

In the second step, we analysed variance of AWARE characterization factor in the individual countries. All analysed stations are situated in 13 European countries. The least stations are located in Latvia and Netherlands (2 stations per country) and Russia (3 stations). These countries also have a small variance of regionalized AWARE values calculated by Eq. 3 in annual step, with values between 14 and 25 %. The variance of Finland values is 61.0% for both Tenant's coefficients. All other countries have *variance* over 75% for both Tenant's coefficients (Switzerland has *variance* = 74.4% for Tenant's coefficient = 0.1) in annual step. Variance in monthly step is obviously higher than in annual step; for example, the lowest *variance* value in May is 41.9% in the Netherlands and the absolutely lowest monthly *variance* value is 1.46% in September in Latvia.

In the third step, we analysed variance of AWARE characterization factor in 90 catchments (from 163) with more than 1 station. Catchments with the highest number of stations are the Rhine (133 stations), the Danube (110 stations), the Elbe (53 stations), the Loire (43 stations), the Rhone (42 stations) and the Weser (39 stations).

Table 3. The number of catchments with *variance* of AWARE (Tenant's coef. = 0.1)

	0%	0-5%	5-10%	10-15%	15-20%	20-30%	30-40%	40-50%	50-75%	>75%
Year	0	8	4	7	14	10	6	9	18	14
Jan	5	4	6	2	5	14	5	11	23	15
Feb	1	2	8	2	8	12	5	9	23	20
Mar	1	2	7	3	6	11	8	10	23	19
Apr	0	3	5	7	7	7	9	10	31	11
May	0	6	3	7	3	13	4	7	30	17
Jun	1	2	4	6	6	9	12	3	24	23
Jul	2	4	5	2	6	7	11	7	18	28
Aug	2	2	2	5	13	7	7	6	22	24
Sep	0	5	5	6	11	7	5	7	22	22
Oct	1	3	3	6	7	14	11	7	20	18
Nov	2	3	4	12	5	8	16	9	14	17
Dec	3	2	5	3	8	19	14	4	17	15

Table 4. The number of catchments with *variance* of AWARE (Tenant's coef. = 0.3)

	0%	0-5%	5-10%	10-15%	15-20%	20-30%	30-40%	40-50%	50-75%	>75%
Year	0	8	4	7	13	10	7	8	19	14
Jan	1	4	6	4	6	12	7	11	23	16
Feb	0	2	9	2	7	10	7	8	25	20
Mar	0	2	8	3	5	8	10	11	24	19
Apr	0	3	5	7	7	7	8	11	31	11
May	0	4	2	6	3	16	5	7	30	17
Jun	0	2	4	7	6	9	11	2	25	24
Jul	0	4	5	3	7	7	11	7	17	29
Aug	1	2	2	5	14	7	7	6	22	24
Sep	0	5	5	6	9	7	7	7	20	24
Oct	1	2	4	6	6	13	9	9	22	18
Nov	1	3	4	11	6	8	13	12	15	17
Dec	1	2	5	2	10	15	16	6	17	16

In the last step, we compared regionalized values with values modelled by the WaterGAP model. This comparison is very important because the modelled values of AWARE at the country level are available for direct import to the LCA software SimaPro on the webpage of the WULCA project, and thus very often used for water footprint studies. For this comparison, the difference between regionalized AWARE values and modelled AWARE values for "unknown" water use was computed by Eq. 4. In this paper, we describe results for the annual step only, but results for the monthly steps have a similarly large range of values or even larger. The results for country level are in Table 5 and Table 6 contains the results for 9 catchments with more than 20 stations.

$$dif_{max\ |\ min} = \frac{AWARE_{max\ |\ min} - AWARE_{modelled}}{AWARE_{modelled}} \quad (4)$$

Table 5. Comparison of modelled AWARE values at country level in annual step for "unknown" water use with the range of regionalized AWARE values in individual countries

Country code	Number of stations	$AWARE_{modelled}$	Tenant's coef. = 0,1		Tenant's coef. =0,3	
			dif_{Max}	dif_{Min}	dif_{Max}	dif_{Min}
			[% from $AWARE_{modelled}$]			
AT	60	1.27	-10.35	-92.11	15.26	-92.11
CZ	10	1.79	-28.54	-85.11	-8.12	-80.86
DE	206	1.36	+97.33	-92.67	+153.71	-92.25
FI	86	1.94	-54.14	-82.12	-41.03	-77.01
FR	163	6.98	-54.54	-98.32	-41.55	-97.85
GB	213	3.50	+511.80	-97.14	+686.60	-97.14
CH	72	1.34	-70.79	-92.51	-62.44	-92.51
IS	18	0.60	-9.99	-83.27	15.73	-83.27
LV	2	1.45	-46.89	-54.32	-31.72	-41.27
NL	2	1.17	-57.57	-65.82	-45.44	-56.06
RU	3	12.51	-94.84	-96.11	-93.37	-95.00
SE	73	4.41	-76.71	-96.92	-70.06	-96.04
SI	14	0.92	-35.67	-89.09	-17.29	-88.76

Table 6. Comparison of modelled AWARE values for catchment with more than 20 stations in annual step for "unknown" water use with the range of regionalized AWARE values in individual catchments

Catchment	Number of stations	$AWARE_{modelled}$	Tenant's coef. = 0,1		Tenant's coef. =0,3	
			dif_{Max}	dif_{Min}	dif_{Max}	dif_{Min}
			[% from $AWARE_{modelled}$]			
Rhine	133	0.76	+139.05	-86.86	+207.35	-86.86
Danube	110	1.26	-10.10	-92.09	+15.58	-92.09
Elbe	53	2.06	+30.36	-87.10	+67.60	-83.42
Loire	43	4.65	-63.84	-95.85	-53.51	-94.67
Rhone	42	0.95	-9.13	-89.46	+16.83	-89.46
Weser	39	1.61	-37.90	-82.75	-20.16	-77.82
Dordogne	26	6.63	-83.26	-98.24	-78.47	-97.73
Thames	24	1.87	-5.50	-81.43	21.49	-76.12

4. Discussion and Recommendations for Further Development

In this study, our approach for the determination of water availability and human and aquatic ecosystem demands was different from the approaches of the WULCA Working group. Therefore, our values are not directly comparable with the values published by the Life Cycle Initiative. Nevertheless, it is obvious that the variability of the determined AMD or AWARE values observed within larger areas is significant in both annual and monthly steps. This high variability, together with the fact that the impact of water use on water availability is of local or regional importance (Wichelns, 2017), raises the question of whether the application of AWARE values in large-scale LCA studies is meaningful. This study shows that it is much more reasonable to use regionalized values or at least values related to smaller land units, for example WaterGAP grid cells. The suggestion for Europe could be to derive AWARE values for the individual water bodies defined according to the EU Water Framework Directive (European Union, 2000). That should greatly contribute to the further development of water footprint assessment in practice. There is no doubt that in LCA studies it will be necessary to continue to use generalized AWARE values for such water uses which cannot be accurately localized. An example of such a case is electricity use from the public grid whose origin and particular power plant cannot be exactly determined. In this case the energy mix of the country will probably be used and the calculation will be executed using an "average" value of AWARE characterization factor for the particular country. Measured water flows were used for the design of available water remaining after the demand of humans has been met. This approach is easily applicable for water extraction from rivers and lakes. On the other hand, for other water resources (precipitation, ground waters) it will be necessary to develop different approaches for the derivation of AMD values based on regionalized data. Therefore it is appropriate to clearly define the terms of water availability, human water needs, and aquatic ecosystem demands for particular water resources. These definitions, specifically the approaches of quantification of these values, should be incorporated into the AWARE method. For European ground waters the EU Water Framework Directive bases could be utilized, where "Available groundwater resource" means the long-term annual average rate of overall recharge of the body of groundwater less the long-term annual rate of flow required to achieve the ecological quality objectives for associated surface waters. Water availability varies both throughout the year and especially in the long-term scale. For example, the amount of rainfall is different not only from year to year but it also changes over a longer period thanks to climate change. When using climate and hydrological data such as flow rates and precipitation it would be appropriate to clearly define the time period from which the values for the characterization factor determination are used in order to obtain regionalized AMD values. Using a 30-year period defined by WMO seems to us to be the best approach for more general studies. On the other side, for studies assessing the change between exact times T1 and T2 we recommend using real current data valid in these exact situations to derive AMD values.

5. Conclusions

In the presented article, we performed the derivation of the AWARE characterization factor using site-specific hydrological data and compared them with available data at the level of European countries and basins. The results showed that AWARE values within countries and basins could vary considerably and the application of these values at the large-scale levels could lead to significant misrepresentation of the results. At the same time, the values of AWARE characterization factor may reach different figures by using different approaches for determining input data for characterization factor calculation. According to our findings, we propose several recommendations for the applications of the AWARE method in practice. Nevertheless, we consider the AWARE method as one of the most suitable for the assessment of sustainable water resource management from the point of view of water availability.

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