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Enhancing the Water Accounting and Vulnerability Evaluation Model: WAVE+

Markus Berger,*[,†] Stephanie Eisner,[‡] Ruud van der Ent,[§] Martina Flörke,[∥] Andreas Link,[†] Joseph Poligkeit,[†] Vanessa Bach,[†] and Matthias Finkbeiner[†]

[†]Chair of Sustainable Engineering, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany

[‡]Norwegian Institute of Bioeconomy Research, P.O. Box 115, NO-1431 Ås, Norway

[§]Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O. 80.115, 3508 TC Utrecht, The Netherlands

[∥]Center for Environmental Systems Research, University of Kassel, Wilhelmshöher Allee 47, 34109 Kassel, Germany

Supporting Information

ABSTRACT: Due to the increasing relevance of analyzing water consumption along product life cycles, the water accounting and vulnerability evaluation model (WAVE) has been updated and methodologically enhanced. Recent data from the atmospheric moisture tracking model WAM2-layers is used to update the basin internal evaporation recycling (BIER) ratio, which denotes atmospheric moisture recycling within drainage basins. Potential local impacts resulting from water consumption are quantified by means of the water deprivation index (WDI). Based on the hydrological model WaterGAP3, WDI is updated and methodologically refined to express a basin's vulnerability to freshwater deprivation resulting from the relative scarcity and absolute shortage of water. Compared to the predecessor version, BIER and WDI are provided on an increased spatial and temporal (monthly) resolution. Differences compared to annual averages are relevant in semiarid and arid basins characterized by a high seasonal variation of water consumption and availability. In order to support applicability in water footprinting and life cycle assessment, BIER and WDI are combined to an integrated WAVE+ factor, which is provided on different temporal and spatial resolutions. The applicability of the WAVE+ method is proven in a case study on sugar cane, and results are compared to those obtained by other impact assessment methods.

INTRODUCTION

In its recent report 'Global Risks 2018', the World Economic Forum rated the water crisis as one of the main world's challenges—even more severe than food and fiscal crises.[1] The awareness of water scarcity related problems in many parts of the world and their link to daily products and global trade has been raised by concepts like "Virtual Water[2]" or initiatives like the Water Footprint Network.[3] More recently, methods assessing local impacts of water use along products' life cycles have been developed resulting in the establishment of an international water footprint standard (ISO 14046).[4]

Some of those impact assessment methods estimate the local consequences of water consumption based on freshwater scarcity.[5−9] Other methods model the specific cause effect chain of water consumption leading to potential damages on human health (due to malnutrition[5,10,11] or infectious diseases[10,12]), ecosystems (terrestrial,[5,13,14] aquatic,[15] coastal,[16] wetlands[17]), and freshwater resources.[5,18] Comprehensive reviews of existing approaches can be found in refs 19−23.

One of the scarcity based impact assessment models is the water accounting and vulnerability evaluation model (WAVE) published in *Environmental Science and Technology* four years ago.[8] On the accounting level, the atmospheric evaporation recycling via precipitation within drainage basins was considered for the first time, which can reduce water consumption volumes by up to 32%. In order to express local impacts of water consumption, WAVE analyzed the vulnerability of basins to freshwater depletion based on local blue water scarcity. The water depletion index (WDI) was determined by relating annual water consumption to availability (runoff) and additionally considering water stocks (lakes and aquifers). In order to consider absolute freshwater shortage in addition to relative scarcity and to avoid that dessert regions show a result of zero if consumption is zero, WDI was set to the highest value in semiarid and arid basins.

So far, the WAVE model provided factors for basin internal evaporation recycling and water scarcity on a spatially explicit (basins and countries) but not on a temporally explicit level (monthly data) used in recent methods.[9,24] However, the three parameters water consumption, basin internal evaporation recycling, and water scarcity are expected to show contrary effects during particular seasons. For instance, in dry summer months water consumption can be higher than the annual

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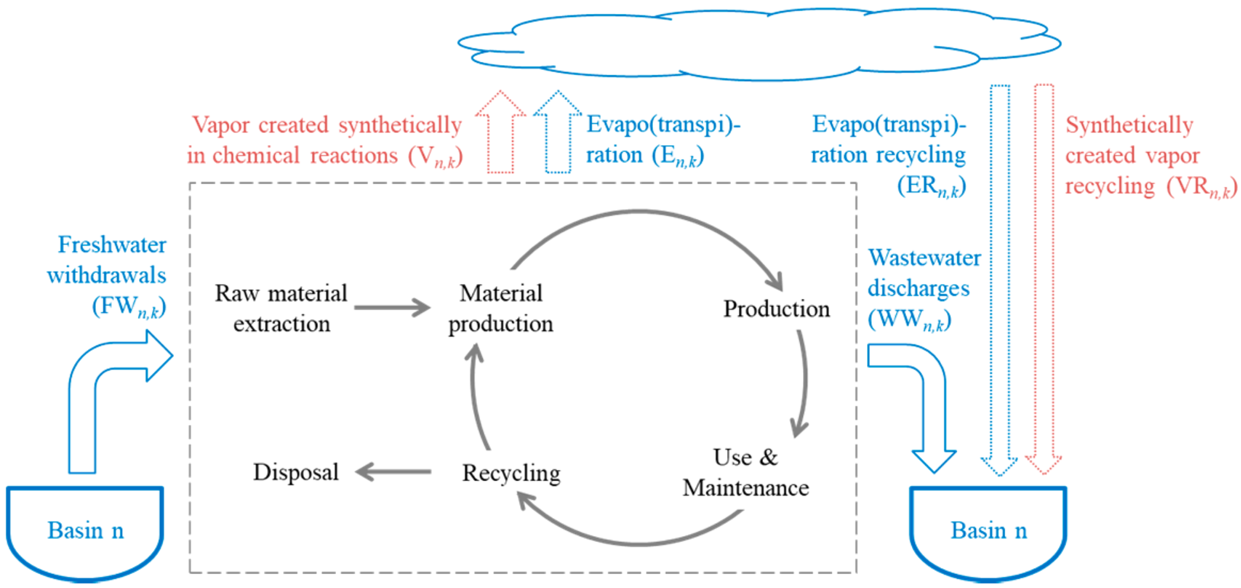

Figure 1. Basin (n) and monthly (k) specific water inventory flows along the life cycle of a product considered in WAVE+. Adapted from ref 8. Copyright 2014 American Chemical Society.

average, while the basin internal evaporation recycling could be lower and water scarcity can be more severe than the annual means. These contrary effects are expected to lead to an accumulation of inaccuracies when considering an annual temporal resolution. This is a severe shortcoming especially for agricultural goods which are produced during particular seasons only.

In order to address the challenge of lacking temporal resolution in WAVE, to update the model based on latest data and methodological findings, and to ease applicability, this work introduces the WAVE+ model. WAVE+ provides a method for the accounting of water use and for assessing potential local impacts of water consumption, which can be used in water footprinting according to ISO 14046[4] and life cycle assessment according to ISO 14044.[25] The following sections present the enhancements in the water accounting and the vulnerability evaluation models which can be summarized as follows:

- Data update including increased temporal resolution (monthly) of the basin internal evaporation recycling (BIER) ratio using the atmospheric moisture tracking model WAM2-layers[26]
- Data update including increased temporal (monthly) and spatial (5 arcmin instead of 0.5 deg) resolution of the water depletion index (WDI) using WaterGAP3[27]
- Methodological refinements in the impact function and increase in the discriminative power of the WDI factors
- Integrated consideration of a basin's vulnerability to freshwater deprivation resulting from relative scarcity and absolute shortage of water
- Combination of BIER and WDI in an integrated WAVE + factor promoting applicability
- Provision of WAVE+ factors for sub-basins and world regions in addition to basins and countries

To enable a smooth reading and understanding, the updated results are presented and discussed directly after the description of the methodological enhancements in each section. Subsequently, a case study on the water footprint of sugar cane (to be precise: water scarcity footprint according to ISO 14046) is presented to prove the applicability of the WAVE+ model and to compare results to those obtained by other methods. Furthermore, methodological differences between the WAVE+ model, its predecessor version (WAVE),[8] and the Available Water Remaining (AWARE) consensus model[9] of the Water Use in LCA (WULCA) group are discussed along with resulting practical implications.

■ WATER ACCOUNTING MODEL

Freshwater consumption denotes the fraction of water use (i.e., total withdrawal), which is not returned to the originating basin due to evapo(transpi)ration, product integration, and discharge into other watersheds or the sea.[28] In practice, water consumption in a basin n and month k ($WC_{n,k}$) is calculated by subtracting wastewater discharges ($WW_{n,k}$) from freshwater withdrawals ($FW_{n,k}$). However, this procedure neglects the fact that substantial shares of the evapo(transpi)rative water consumption ($E_{n,k}$) and synthetically created vapor resulting from the combustion of fossil fuels ($V_{n,k}$) can be recycled within the atmosphere via precipitation in relatively short time and length scales.[29,30]

Therefore, the WAVE+ model explicitly accounts for the shares of evapo(transpi)ration ($ER_{n,k}$) and synthetically created vapor ($VR_{n,k}$) which are returned to the originating basin n in the month k via precipitation as shown in Figure 1. Next to wastewater discharges ($WW_{n,k}$), those shares are additionally subtracted from freshwater withdrawals ($FW_{n,k}$) to determine the effective water consumption ($WC_{\text{eff},n,k}$) (eq 1).

$$WC_{\text{eff},n,k} = FW_{n,k} - WW_{n,k} - ER_{n,k} - VR_{n,k} \quad (1)$$

As shown in eqs 2a and 2b, the evaporation recycling ($ER_{n,k}$) and vapor recycling ($VR_{n,k}$) within a basin n and month k are determined by multiplying volumes of evapo(transpi)ration ($E_{n,k}$) and synthetically created vapor ($V_{n,k}$) with the basin internal evaporation recycling ratio ($BIER_{n,k}$) and the runoff fraction ($\alpha_{n,k}$).

$$ER_{n,k} = E_{n,k} \cdot BIER_{n,k} \cdot \alpha_{n,k} \quad (2a)$$

$$VR_{n,k} = V_{n,k} \cdot BIER_{n,k} \cdot \alpha_{n,k} \quad (2b)$$

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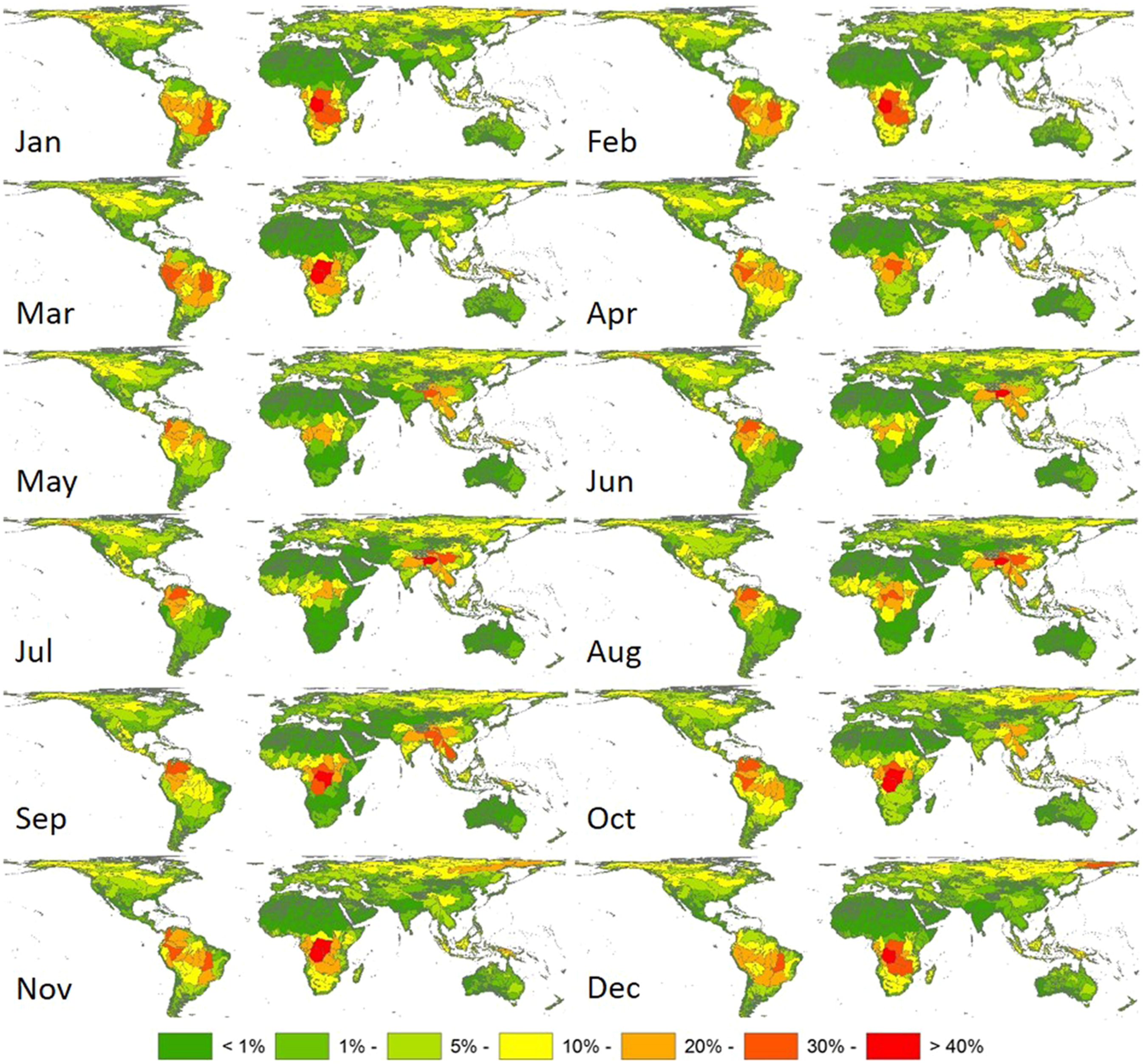

Figure 2. Basin internal evaporation recycling (BIER) ratios denoting the fractions of evaporated water returning to the originating basins via precipitation.

BIER represents the share of evapo(transpi)ration which is returned to the originating basin via precipitation. It is calculated by means of local evaporation recycling length scales provided by the updated atmospheric moisture tracking model WAM2-layers[26] in a 1.5 deg resolution. Based on an area-weighted average evaporation recycling length scale for each of the ca. 8.200 basins derived from the hydrological model WaterGAP3,[27] the BIER values presented in Figure 2 are determined according to the procedure comprehensively described in the original WAVE method.[8] All maps in this manuscript and in the Supporting Information were created using the ArcGIS software.[31]

As it can be seen in Figure 2, high BIER values above 30% can be found in South America, the Himalayas, and Central Africa. Thus, relevant shares of evapo(transpi)ration and synthetically created vapor can be returned to the originating drainage basin via precipitation. However, these regions show a strong seasonal variation. For example, the BIER values in the Congo basin range from 0% in July to 50.2% in December. Since the share of evaporation recycling increases with distance,[29] large drainage basins tend to show higher BIER values than small basins. Figure 2 also shows that BIER is very low (<1%) in desert areas like the Sahel zone or Central Australia throughout the year. Thus, evaporation recycling can reduce the effective water consumption in water abundant regions, whereas the water consumption in water scarce regions remains unaffected.

WAVE+ focuses on blue water (ground- and surface water[2]), and since only a fraction of BIER will be available as runoff (the rest re-evaporates), the runoff fraction ($\alpha_{n,k}$) is considered as an additional factor in eqs 2a and 2b. It relates the long-term average runoff (R), i.e. groundwater recharge and surface runoff, to the total precipitation (P) within a basin n and month k. Updated $\alpha_{n,k}$ factors have been determined based on

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WaterGAP3 and are shown in Figure S1 in the Supporting Information. While the runoff fraction is constantly high (>60% in e.g. Ecuador and Peru) or constantly low in some regions (<20% in e.g. South Africa or Central Australia), it varies strongly throughout the year in most of the world's basins.

By multiplying $BIER_{n,k}$ (Figure 2) with $\alpha_{n,k}$ (Figure S1), the runoff-relevant basin internal evaporation recycling ($BIER_{runoff,n,k}$) is determined and shown in Figure S2 in the Supporting Information. Since α is particularly low (<40%) in Central Africa during those months in which BIER is highest, large BIER ratios determined in e.g. the Congo basin (50.2% in December) are reduced when considering the runoff fraction of the evaporation recycling (17.2% in December). Even though $BIER_{runoff}$ is below 5% in most of the world's drainage basins and months, it reduces blue water consumption significantly (10−28%) in basins in Central Africa, the Himalayas, Ecuador, and Peru during parts of the year.

In addition to the basin internal evaporation recycling (BIER), it would also be interesting to consider the basin external evaporation recycling (BEER). As shown in Figure S3 in the Supporting Information, BEER denotes the fraction of evapo(transpi)ration which returns as precipitation to other than the originating basin. In this way it can be considered that evapo(transpi)ration which leaves the basin causes water consumption in the originating basin but water gains in the receiving basins. However, predicting the exact locations in which evaporation will return as precipitation is very complex and beyond the scope of this work.

■ VULNERABILITY EVALUATION MODEL

In addition to determining the effective water consumption on the volumetric level, WAVE+ aims at analyzing the potential local impact that can result from water consumption in a particular basin and month. Similar to other methods,[5,9] these impacts are defined as the risk to deprive other users of using freshwater when consuming water. The risk of freshwater deprivation (RFD) can be determined by multiplying the effective water consumption in each basin n and month k with its corresponding water deprivation index ($WDI_{n,k}$)

$$RFD = \sum_n \sum_k (WC_{eff,n,k} \cdot WDI_{n,k}) \tag{3}$$

where $WDI_{n,k}$ denotes the vulnerability of a basin n to freshwater deprivation in month k and, thus, expresses the potential to deprive other users when consuming water in this basin and month.

Most impact assessment indicators for water consumption[5,10,32] are based on a ratio of annual water consumption to availability and, thus, express relative freshwater scarcity only. Often this leads to findings that very dry regions, like the Sahel zone or Central Australia, are not water scarce—because consumption is close to zero.[33] In WAVE+ we assume that the vulnerability of a basin to freshwater deprivation and, thus, the impacts of water consumption can be influenced by both relative water scarcity and absolute water shortage. We therefore provide water deprivation indexes for relative scarcity (WDI_{RS}) and absolute shortage (WDI_{AS}) and combine them into an integrated index (WDI) as described in the following subsections.

Water Deprivation Index Based on Relative Water Scarcity (WDI_{RS}). The development of WDI_{RS} starts with a consumption-to-availability (CTA) ratio, which relates annual water consumption (C) to availability (A). As comprehensively described in the original WAVE method,[8] the CTA is enhanced to a more meaningful water scarcity indicator by additionally considering surface water stocks (SWS) and an adjustment factor for the availability of groundwater stocks (AF_{GWS}). Recent data for consumption, availability (runoff), and surface water stocks are derived from WaterGAP3.[27] This model provides the data on a 5 arcmin resolution which is aggregated to the basin level. Updated CTA* values, determined for each basin according to eq 4, are presented in Figure S4 in monthly resolution.

$$CTA^*_{n,k} = \frac{C_{n,k}}{A_{n,k} + SWS_{n,k}} \cdot AF_{GWS,n} \tag{4}$$

The relevance of considering ground- and surface water stocks and the influence of parameter settings in the underlying calculations has been analyzed by a set of sensitivity analyses in the original WAVE paper. It reduces the result of the scarcity assessment by up to 20% in many water abundant basins and, thus, increases the relative difference between water scarce and water abundant regions. Since the calculation procedure and the underlying data have not changed significantly, the main findings of these analyses are still considered valid.

By means of a logistic function (Figure 3) the physical scarcity ratio CTA* is translated into the vulnerability of a basin to freshwater deprivation expressed by WDI_{RS}, which can be understood as an equivalent volume of water that another user has been deprived of due to a volume of water consumed.

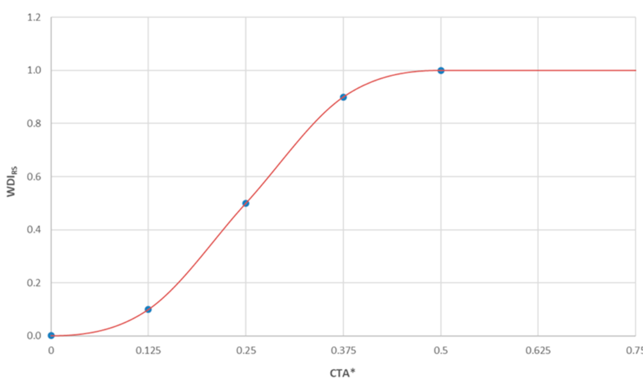

Figure 3. Logistic function determining WDI_{RS} based on CTA*; S-curve leads to larger changes in WDI resulting from changes in CTA* in medium scarcity ranges 0.125 < CTA* < 0.375 compared to low (CTA < 0.125) and high scarcity ranges (CTA > 0.375) and reaches a maximum of 1 at CTA* = 0.5.

The function shown is fitted to obtain WDI values of 0.001, 0.1, 0.5, 0.9, and 1 at CTA* values of 0, 0.125, 0.25, 0.375, and 0.5, respectively. The resulting S-curve acknowledges the fact that in both water abundant and water scarce regions, the vulnerability of a basin to freshwater deprivation does not rise linearly with the physical scarcity ratio. The WDI values obtained from CTA* according to the logistic function are shown in Figure S5 in the Supporting Information.

Water Deprivation Index Based on Absolute Water Shortage (WDI_{AS}). In order to acknowledge absolute water shortage, WDI_{AS} is determined based on the ratio of potential evapotranspiration (PET) to precipitation (P) derived from WaterGAP3 shown in Figure S6 in the Supporting Information. According to the function presented in Figure

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4, WDI_{AS} is set to 0.2 at the semiaridity threshold ($PET/P = 2$) and 0.5 at the aridity limit ($PET/P = 5$) as classified by UN

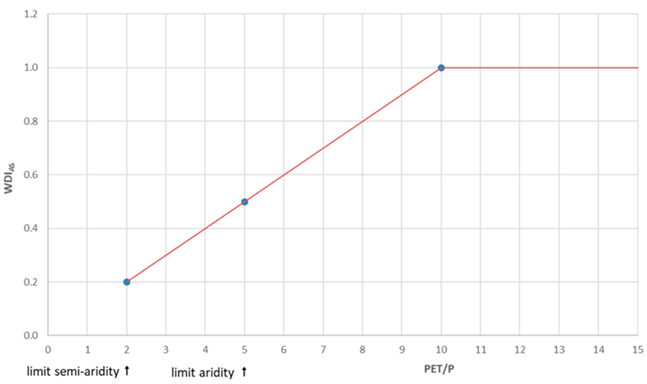

Figure 4. WDI_{AS} determined as a function of the ratio of potential evapotranspiration (PET) to precipitation (P).

Environment.[34] The function is set to reach the maximum of 1 if PET exceeds ten times P. It should be noted that this setting represents a model choice to acknowledge that absolute water shortage can influence the vulnerability of a basin to freshwater deprivation and, thus, the potential to deprive other users when consuming water in this basin.

Integrated Water Deprivation Index (WDI). After developing water deprivation indexes based on the relative scarcity and absolute shortage of water as described above, an integrated WDI is determined as the maximum of WDI_{RS} and WDI_{AS} (Figure 5). In most basins and months, WDI_{RS} is decisive for the integrated WDI. Absolute water shortage determines the integrated WDI in 28−39% of the basins.

While WDI is constantly very low throughout the year (<0.01) in large parts of Canada, South America, Central Africa, and Russia, it is constantly very high (>0.90) in most basins in Northern Africa and the Arabian Peninsula. A strong seasonal variation can be observed in e.g. Argentina, the northeastern part of Brazil, India, Southern Europe, and the US.

In most of the world's drainage basins WDI is either very low (blue) or very high (red) with only a few basins showing medium (green - orange) water stress. These rather binary results have already been determined for the CTA* values expressing physical water scarcity (Figure S4 in the Supporting Information). The effect has increased due to the logistic function, which translates CTA* into WDI (Figure 3). This consideration of absolute water shortage in addition to relative scarcity strongly influences the WDI results of particularly dry basins in Northern and Southern Africa, the middle East, Central Asia, and Australia. The magnitude of this change is shown in Figure S7 in the Supporting Information.

As any other impact assessment method for water use, WAVE+ assumes that impacts result from a shortage of water and not from too much water, which can be relevant in basins and months with high precipitation leading to risks of flooding, etc. Here water consumption could be considered having a positive impact, and evaporation recycling could be disadvantageously. However, this impact pathway is beyond the scope of this work.

■ COMBINING WATER ACCOUNTING AND VULNERABILITY EVALUATION: WAVE+ FACTORS

The consideration of the basin internal evaporation recycling (BIER) and the evaluation of a basin's vulnerability to freshwater deprivation by means of WDI are considered as two separate steps because BIER only applies to the evapo(transpi)rative fraction of consumptive water use. Other forms of water consumption,[28] i.e. integration of water in products or discharge into other basins and seawater, cannot be reduced by means of BIER. Moreover, it is intended to allow for a consideration of the atmospheric recycling of synthetically created vapor, which requires to determine the effective water consumption (eq 1) before the analysis of local impacts (eq 3).

However, in practice most water consumption occurs due to evapo(transpi)ration, and the chemical creation of water in the combustion of fossil fuels is rather low. Therefore, an integration of $BIER_{runoff,n,k}$ and WDI in the newly introduced WAVE+ factors is proposed, which is provided in addition to the individual $BIER_{runoff,n,k}$ and WDI factors. As shown in eq 5, $WAVE+_{n,k}$ is determined by reducing $WDI_{n,k}$ by the share of water returned to the originating basin n in month k as blue water ($BIER_{runoff,n,k}$). WAVE+ factors are presented in Figure S8 in the Supporting Information. Since BIER is relatively high in water abundant basins and relatively low in water scarce regions (Figures S2 and S5), the difference between those basins is increased when combining $BIER_{runoff,n,k}$ and WDI in the WAVE+ factors.

$$WAVE+_{n,k} = (1 - BIER_{runoff,n,k}) \cdot WDI_{n,k} \quad (5)$$

The use of the integrated WAVE+ factors is recommended in cases in which evapo(transpi)ration is the dominant form of water consumption (instead of product integration or discharge into other basins or the sea) and in which no relevant amounts of synthetically created vapor are expected. In such cases the risk of freshwater deprivation (RFD) can be determined by multiplying the basin and month specific water consumption $WC_{n,k}$ with its corresponding $WAVE+_{n,k}$ factor and by aggregating the results (eq 6).

$$RFD = \sum_{n} \sum_{k} (WC_{n,k} \cdot WAVE+_{n,k}) \quad (6)$$

■ SPATIAL AND TEMPORAL AGGREGATION

The BIER, $BIER_{runoff,n,k}$, WDI, and WAVE+ factors are determined on the level of drainage basins in a monthly resolution. Even though this reflects hydrologic conditions best, inventory information on where and when water consumption occurs along supply chains is often not available on such a detailed geographic and temporal resolution. Therefore, the BIER, $BIER_{runoff,n,k}$, WDI, and WAVE+ factors are additionally provided in an aggregated form on the annual level and on the levels of countries and world regions. The aggregation methodology and results are presented in the Supporting Information.

Since the hydrological situation in humid and hyperarid basins is rather constant throughout the year, monthly WAVE+ factors presented in Figure S8 do hardly vary over the year and, thus, do not show significant differences to the annual average WAVE+ factors (Figure S9). Hence, a temporally explicit assessment of water consumption in many basins in Russia or Northern Africa is favorable but not urgently necessary. In

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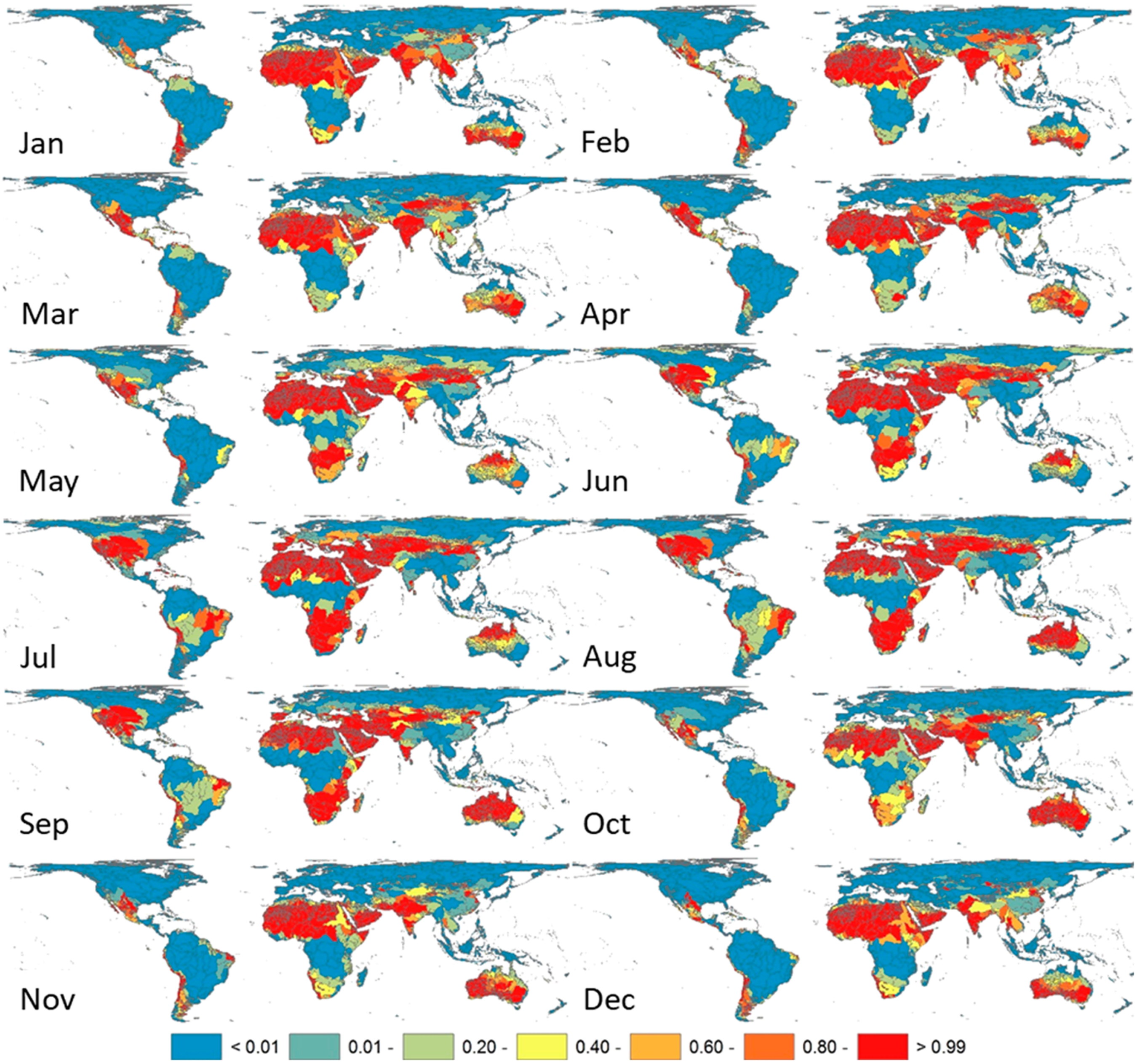

Figure 5. WDI expressing the vulnerability of basins to freshwater deprivation [$m^3_{deprived}/m^3_{consumed}$].

contrast, a monthly assessment is highly relevant in semiarid and arid basins located in e.g. Chile, Spain, or the US as severe changes throughout the year have been identified in both atmospheric moisture recycling and water scarcity. Especially in those regions a temporally explicit assessment of water consumption is strongly recommended for agricultural product systems, which consume water during a particular season only.

■ CASE STUDY

In order to test the applicability of the WAVE+ model, to analyze the validity of results, and to compare the results to those obtained by other methods, a case study on the water footprint of sugar cane production in Australia, Thailand, and Colombia is conducted. Since only water consumption but no pollution is considered, this study represents a water scarcity footprint according to ISO 14046.[4]

Based on the monthly and basin specific blue water consumption of growing 1 t of sugar cane provided by Pfister and Bayer[24] and based on the production shares of the basins in a country, the country-annual average blue water consumption of sugar cane has been determined. Depending on the resolution of the impact assessment method, either the annual country average or the underlying monthly and basin-specific water consumption data can be used for analyzing the resulting local consequences.

Subsequently, the water consumption is multiplied by the impact factors of the WAVE+ method and the predecessor WAVE model[8] as well as the AWARE,[9] WSI,[5,24] and Eco-scarcity[6] methods. Results of the predecessor WAVE model[8] have been determined by first reducing the water consumption by the share of the basin internal evaporation recycling returning as blue water ($BIER_{runoff}$) and then multiplying the effective water consumption with WDI. This procedure is

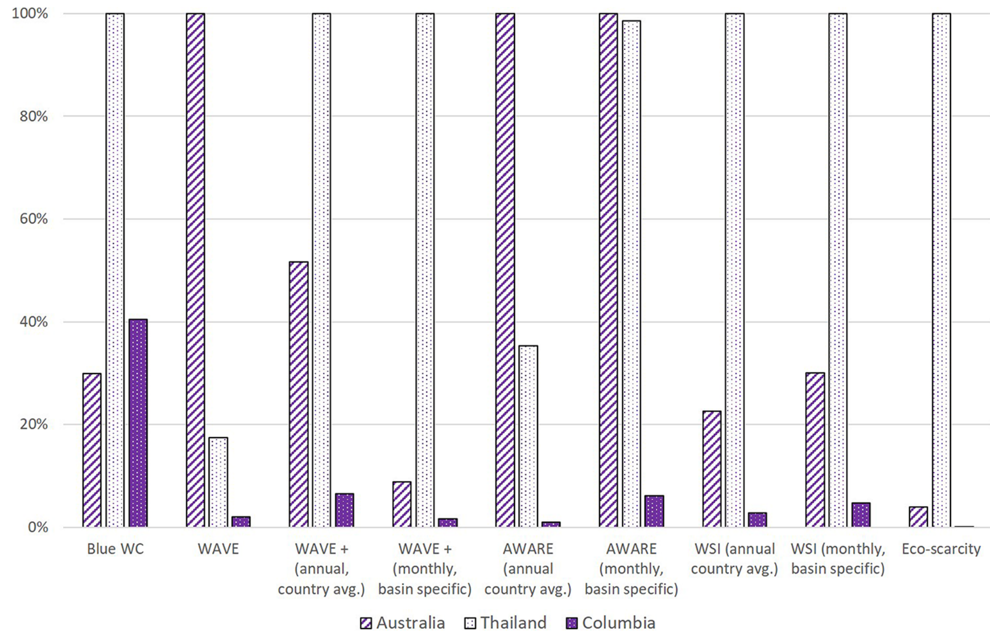

Figure 6. Relative presentation of blue water consumption for producing 1 t of sugar cane in different countries and potential impacts determined by means of the WAVE, WAVE+, AWARE, WSI, and Eco-scarcity methods (based on annual country average and monthly and basin specific impact factors when possible).

combined in the WAVE+ factors (eq 5). Since WAVE+, AWARE, and WSI provide monthly and basin specific impact factors in addition to an annual country average factor, they are applied in both resolutions. Next to a comparison between countries, this allows for analyzing the difference between an annual country average and a monthly and basin specific assessment. Absolute results are shown in Table S1 in the Supporting Information.

Figure 6 shows the water consumption and impact assessment results of the WAVE, WAVE+, AWARE, WSI, and Eco-Scarcity methods on a relative scale normalized to the highest result of each method. Differences in results obtained by the five methods are comprehensively discussed in the Supporting Information.

DISCUSSION

A specific discussion of the updated and methodologically enhanced BIER, α, $BIER_{runoff}$, WDI, and WAVE+ factors as well as the interlinkages between them and the influence of methodological choices has already been presented in combination with the results in the previous sections. A general discussion on the consideration of BIER in water footprinting, the advanced water scarcity assessment by means of WDI, and on further methodological aspects like the additional consideration of water quality degradation can be found in the original WAVE publication.[8] Since those findings are valid for WAVE+ as well, this section focuses on discussing specific methodological aspects of the WAVE+ in comparison to the predecessor WAVE model. Additionally, a discussion of methodological differences to the AWARE model[9] developed by the WULCA group is presented along with a quantitative comparison of the impact factors. Additionally, practical implications of methodological differences as well as hints when to use which method are provided.

Comparison WAVE+ and WAVE. The WAVE+ model presented in this work updates the database of the predecessor version[8] and contains several methodological enhancements. The individual improvements of WAVE+ compared to WAVE are summarized in Table S2 in the Supporting Information and discussed below.

Recent data from the atmospheric moisture tracking model WAM2-layers[26] is used to update the basin internal evaporation recycling (BIER) ratio. The main improvement of WAM2-layers is a better representation of moisture tracking in a system with wind shear (e.g., in West Africa), by the addition of a second atmospheric layer instead of merely having one layer. The horizontal moisture transport with two layers (and vertical exchange between them) is more realistic than moisture tracking with vertically integrated moisture fluxes. The main benefit is that moisture is not assumed to instantly mix over the entire atmospheric column after evaporation. In the beginning it remains in the lower atmosphere where winds are less strong. Thus, the length scales of the local evaporation recycling decrease and BIER will increase in several basins (especially in temperate zones).

With regard to the vulnerability evaluation part of WAVE+, it should be noted that the term "deprivation" used in RFD and WDI has replaced the term "depletion" used in the original WAVE method. This has been done because the term water depletion is used in recent methodological developments of the WULCA group modeling a concrete impact pathway to resource depletion.[35] However, WDI is considered as a generic impact factor which does not consider a specific cause-effect chain.

A relevant change compared to the predecessor WAVE model is the consideration of a basin's vulnerability to freshwater deprivation based on the relative scarcity and absolute shortage of water by means of WDI_{RS} and WDI_{AS}, which are later combined to an integrated assessment (WDI).

For the determination of WDI_{RS} the latest hydrological data derived from the WaterGAP3 model[27] is used, which describes a climate period from 1981 to 2010 and increases the spatial resolution from a 0.5 deg grid used in WaterGAP2[36,37] to a 5 arcmin resolution. Since the hydrological data is aggregated

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from grid-scale to basins, the increased spatial resolution allows for a more precise basin delineation and leads to a finer detailing of small coastal basins. This has increased the number of basins from ca. 11,700 considered in WAVE to ca. 135,000 basins in WAVE+. However, uncertainty can be high in very small basins (mainly consisting of one 5 arc minute grid cell only) due to uncertainties in the coarse meteorological data driving WaterGAP3 and in the physiographic input data. For this reason basins <1,000 km^2 have been merged with their nearest valid neighbor basin (>1,000 km^2) within a distance of max. 100 km (Figure S11). If no basin >1,000 km^2 was available within 100 km, small neighboring basins have been combined to basin groups. In this way, WAVE+ distinguishes ca. 8,200 basins. Even though the absolute number of basins decreased compared to WAVE, the basin delineation is more precise, and the results are more robust—especially for small coastal basins.

The monthly resolution of underlying hydrological data derived from WaterGAP3 allows for refinements in the setting of the function translating physical scarcity (CTA*) into potential impacts (WDI_{RS}): The logistic function shown in Figure 3 turns 1 at a CTA* of 0.5 (considered as the threshold for severe water stress) instead of 0.25 in the predecessor WAVE model. Setting WDI_{RS} to 1 at a medium level of physical water stress was necessary because an annual average CTA* of 0.25 implies that significantly higher water stress can occur during particular months[38] – especially in semiarid regions. Fitting the S-curve to turn 1 at a CTA* of 0.5 in the new monthly assessment is considered to reflect water stress more realistically and also led to a stronger spreading of the WDI_{RS} factors.

A main challenge in the determination of monthly WDI_{RS} factors is the consideration of intra-annual storage capacities within basins.[24] This has partly been addressed due to the consideration of reservoirs as well as ground- and surface water stocks in WDI_{RS}. Moreover, a monthly temporal resolution requires a higher spatial resolution in basins where the flow time from spring to mouth is longer than one month.[24] Since a basin delineation has been used in which the 35 largest drainage basins have been divided into sub-basins, the flow time is shorter than one month in each (sub)basin.

Case studies[39,40] conducted with the predecessor WAVE model have revealed a shortcoming regarding the limited discriminative power of the WDI_{RS} factors. Ranging from 0.01 to 1, impact assessment results have been mainly influenced by the volume of water consumed. For example, a water consumption of 1 L in a highly water stressed region could not be identified as a hotspot as long as a water consumption of more than 100 L occurred in a water abundant region. For this reason the spreading of WDI_{RS} has been increased by 1 order of magnitude now ranging from 0.001 to 1. As also discussed in the AWARE consensus model,[9] a spreading of the impact factor by 3 orders of magnitude represents the best compromise to balance the influence of the inventory and impact assessment phases on the water scarcity footprint result.

Concerning absolute water shortage, WAVE+ contains a separate indicator (WDI_{AS}) which is determined based on a ratio of potential evapotranspiration to precipitation (Figure 4). Compared to setting WDI to the maximum in semiarid and arid basins in a binary way in the predecessor model, the new procedure enables a gradual analysis of potential impacts resulting from aridity. By combining WDI_{AS} and WDI_{RS} to an integrated WDI, WAVE+ acknowledges that a basin's vulnerability to freshwater deprivation can either be determined by the relative scarcity or absolute shortage of freshwater.

When comparing BIER and WDI determined based on annual data of the predecessor WAVE model to the annual BIER and WDI values of the WAVE+ model, which have been determined based on consumption weighted averages of the underlying monthly data, several differences can be observed. The annual average basin internal evaporation recycling tends to be lower in the WAVE+ model. This can be explained by the fact that BIER is lower in dry months in which the water consumption is usually higher. Due to the weighting based on monthly consumption shares, the relatively low BIER values of those dry months dominate the annual averages. Comparing the annual average WDI values of the WAVE+ model (Figure S10) to the WDI of the predecessor version, a more diverse spreading of the WDI values can be observed. The rather binary WDI results obtained in WAVE on the annual level have been obtained in a similar form in WAVE+ on the monthly level, too. However, in WAVE+ the seasonal variation between relatively low water stress in the wet season and comparably high water stress in the dry season is balanced due to the creation of annual averages.

In contrast to the predecessor version, the WAVE+ model provides integrated WAVE+ factors which combine the consideration of $BIER_{runoff,n,k}$ on the inventory level and the evaluation of potential local consequences by means of WDI on the impact assessment level (eq 5). In combination with the provision of annual-, country-, and world region average WAVE+ factors in addition to monthly, basin, and sub-basin specific factors, the applicability of the WAVE+ model has been increased significantly.

Comparison WAVE+ and AWARE. A direct comparison between the WAVE+ and the WULCA group's consensus model AWARE is challenging since the two methods have partly different scopes and follow different modeling approaches. AWARE does not consider effects of atmospheric evaporation recycling considered by means of BIER in WAVE+. The impact assessment model is based on the available water remaining after human and ecosystem water demands have been met (availability minus demand, AMD). Instead of a difference, WAVE+ is based on a ratio of human consumption to availability (considering ground and surface water stocks, CTA*) which is translated into a basin's vulnerability to freshwater depletion by means of a logistic function (WDI_{RS}). In order to acknowledge a basin's absolute water shortage, AMD is related to the basin's area in the AWARE method. The inverse of the basin's area specific availability (low availability leads to high impacts) is divided by the global average area specific availability. This ratio is used as the final impact factor in an interval between 0.1 and 100 [$m^3_{world\ eq}/m^3$]. In the WAVE+ method, absolute water shortage is considered by a separate impact factor (WDI_{AS}) which is determined based on a ratio of potential evapotranspiration to precipitation. The integrated WDI varies by a factor of 1,000 as well (0.001 to 1) but is not put in relation to a global average because it expresses an equivalent volume of water another user is deprived of due to a volume of water consumed [$m^3_{deprived}/m^3_{consumed}$].

A quantitative comparison of the annual and country average impact factors of WAVE+ and AWARE is accomplished by means of a regression analysis presented in Figure S12 in the Supporting Information. The comparison shows that the

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impact factors of most countries are higher in WAVE+ than in AWARE on a relative level. The main reason for this is the different and more stringent way of considering absolute water shortage in WAVE+ described above. As shown in Figure S7, this setting significantly increases the WDI of many basins (and thus countries) throughout the year. The correlation analysis also shows a few extreme outliers (Uganda, Rwanda, and Burundi) in which the relative AWARE factors are up to 200 times higher than the relative WAVE+ factors. The reason for this can be found in the different water scarcity results in the Kagera basin, which is the main basin of those three countries. As shown in Figure S13 in the Supporting Information, this basin is considered as highly water scarce throughout the year in AWARE and as water abundant throughout the year in WAVE+. The reason for this significant difference is the consideration of the environmental water requirement (EWR) in the AWARE method,[9] which is determined as a percentage (30−60%) of the pristine (without human intervention) water availability. In case of the Kagera basin this percentage of the pristine availability is even larger than today's water availability because surface runoff and groundwater recharge have been strongly influenced by the extensive agricultural practice in this region around Lake Victoria. For this reason, the available water remaining is negative, and a maximum impact factor is obtained in AWARE. A more comprehensive analysis of impact assessment methods, including e.g. a correlation analysis of the WSI, Eco-scarcity, and other methods along with an analysis of modeling choices, has been accomplished by Boulay and colleagues.[41]

Considering the methodological and numerical differences between WAVE+ and AWARE, it is challenging to provide a clear recommendation on when to use which method. To a large extent this depends on the goal and scope of the analysis and on the methodological preferences of the user. If, for instance, the practitioner wants to include potential impacts on ecosystems, the AWARE model should be preferred since the environmental water requirement of aquatic species is considered in the available water remaining. If, however, the user wants to consider ground- and surface water stocks in the scarcity assessment, the WAVE+ method should be used.

In general, WAVE+ tends to evaluate more countries as relatively water scarce compared to AWARE (Figure S12) which can be considered a disadvantage if only a few hotspots are to be identified. However, this more conservative approach can also be advantageous if potential risks shall not be overlooked.

The consideration of atmospheric evaporation recycling by means of BIER in the WAVE+ method is independent from the impact assessment step. Hence, BIER can be combined with other impact assessment models, like AWARE, to assess the impacts of the effective water consumption (eq 1) only. This illustrates that the models are not competitive, provide individual strengths and weaknesses, and, thus, are recommended to be applied in parallel to analyze the water footprint profile[4] of the product systems under study.

In order to promote the applicability of the WAVE+ model, the BIER, $BIER_{runoff}$, WDI, and WAVE+ factors are made available free of charge in drainage basin, country, and world region resolutions on both monthly and annual levels in a Google Earth layers and a spreadsheets: http://www.see.tu-berlin.de/wave.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b05164.

Additional explanations, figures, and tables (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +49.(0)30.314-25084. E-mail: markus.berger@tu-berlin.de.

ORCID

Markus Berger: 0000-0002-3012-7470

Notes

The authors declare no competing financial interest.

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