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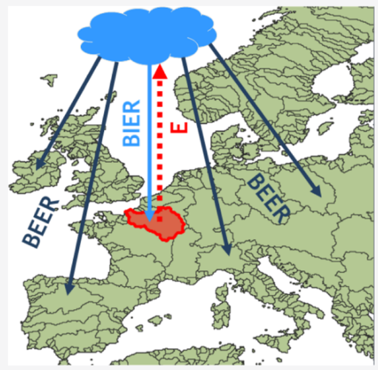

ABSTRACT: Water consumption along value chains of goods and services has increased globally and led to increased attention on water footprinting. Most global water consumption is accounted for by evaporation (E), which is connected via bridges of atmospheric moisture transport to other regions on Earth. However, the resultant source−receptor relationships between different drainage basins have not yet been considered in water footprinting. Based on a previously developed data set on the fate of land evaporation, we aim to close this gap by using comprehensive information on evaporation recycling in water footprinting for the first time. By considering both basin internal evaporation recycling (BIER; >5% in 2% of the world's basins) and basin external evaporation recycling (BEER; >50% in 37% of the world's basins), we were able to use three types of water inventories (basin internal, basin external, and transboundary inventories), which imply different evaluation perspectives in water footprinting. Drawing on recently developed impact assessment methods, we produced characterization models for assessing the impacts of blue and green water evaporation on blue water availability for all evaluation perspectives. The results show that the negative effects of evaporation in the originating basins are counteracted (and partly overcompensated) by the positive effects of reprecipitation in receiving basins. By aggregating them, combined net impacts can be determined. While we argue that these offset results should not be used as a standalone evaluation, the water footprint community should consider atmospheric moisture recycling in future standards and guidelines.

KEYWORDS: *water footprint, water consumption, life cycle assessment, life cycle impact assessment, WAVE, atmospheric moisture, evaporation recycling*

1. INTRODUCTION

According to recent estimates, over two billion people live in highly water-stressed countries[1] and about four billion people face severe water stress at least one month per year.[2] The last two United Nations World Water Development Reports highlighted that water stress levels are expected to increase due a growing demand for water-intensive goods and services and the effects of climate change.[3,4] The effects of goods and services on water use can be assessed through the life cycle-based water footprint method, which has gained increased attention over the past few years.[5] There are different approaches to water footprinting: volumetric approaches focusing on water productivity assessments and impact-oriented approaches assessing the potential local or regional consequences of water use along a product's life cycle.[6]

Volumetric approaches can be divided into blue water footprinting (consumed surface and groundwater), green water footprinting (consumed soil moisture), and grey water footprinting (dilution parameter to address freshwater pollution).[7] Impact-oriented approaches, on the other hand, rely either on proxies for regional freshwater scarcity,[7−19] or create specific cause-effect chains to describe the potential damage of water consumption to freshwater resources,[12,20] ecosystems,[12,21−25] or human health.[12,26−28] In most cases, they describe the impacts of blue water consumptive use, while only a very limited number of studies[7−11] refer to the impacts of green water consumption (GWC).

Most water footprinting methods have in common that they do not include information on the fate of evaporated blue and green water resources. As a result, evaporated water is usually considered consumed, even though it could partly reprecipitate within the same basin or contribute to the replenishment of water resources through reprecipitation elsewhere. Berger et al. (2014, 2018)[14,15] argued that for some regions significant shares of evaporated water might return via the direct reprecipitation to the originating basin within short time intervals,[29] which should be accounted for in water footprinting. Based on this, they developed water accounting and vulnerability evaluation (WAVE+).[15] On the accounting side, this method considers

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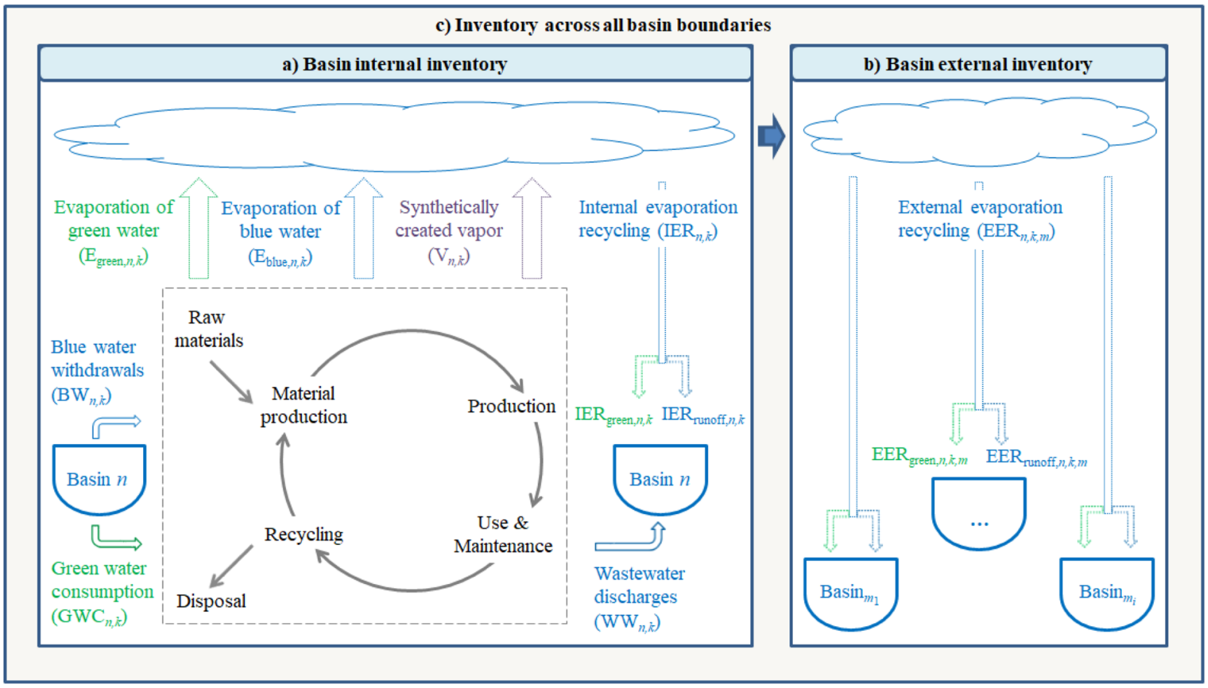

Figure 1. Basin (n) and month (k) specific water inventory flows of the proposed three-part water inventory scheme with ER taking place in both the originating basin (n) and various outlying basins (m_1 to m_i). ER either contributes via surface runoff and infiltration into the groundwater to the replenishment of blue water stocks ($IER_{runoff,n,k}$; $EER_{runoff,n,k,m}$) or refills the regional green water resources ($IER_{green,n,k}$; $EER_{green,n,k,m}$); adapted from ref 15, Copyright 2018 American Chemical Society.

the basin internal evaporation recycling (BIER) ratio, which significantly reduces evaporative water consumption within specific drainage basins.[15] The BIER was calculated based on the length of the basin in the direction of the main moisture flux and the average regional length scale of the evaporation recycling (ER) process.[14,15] The latter was derived from the atmospheric moisture tracking model WAM-2layers (water accounting model-2layers).[30,31] Each basin was assumed to be a square; this non-optimal assumption simplified the calculation and ensured that the determination of ER was not dependent on a basin's shape.[14,15] Finally, effective consumption (evaporation minus the runoff-relevant part of the calculated BIER) was determined and multiplied by a regional proxy for blue water scarcity.[15] The resulting WAVE+ characterization factors can be used to describe the potential impacts of evaporative blue water consumption (BWC) on regional freshwater deprivation and are available at a monthly resolution for more than 8000 basins.[15] The concept of the BIER has also been used to improve LCA-based green water footprinting.[11] However, no water footprinting model so far includes comprehensive information on ER patterns across basin boundaries. Therefore, current methods are unable to quantify water supply effects to external basins, which result from evaporative water consumption in a specific source basin. The share of evaporated water reprecipitating in external drainage basins is termed the basin external ER (BEER) ratio.[15]

We previously developed a global data set on the fate of land evaporation.[32] The data relating to ER patterns could potentially be integrated into water footprinting. In contrast to the WAVE+ method,[15] this data set is based on a more explicit run of the moisture tracking model WAM-2layers,[31] which was applied in parallel time steps on a global grid in 1.5° latitude × 1.5° longitude resolution.[32] As a result of the model application, for each land cell's evaporation, the overall average atmosphere and surface of reprecipitation in the wind direction could be determined at a monthly resolution.[32] This information on the fate of evaporation was then aggregated to the shapes of geographical units such as basins and countries.[32]

Based on this approach, the main goal of this work is to include comprehensive information on the fate of evaporated water across basin boundaries in water footprinting for the first time. We further divide this into four sub-goals: first, we develop a new volumetric water accounting scheme. This aims to integrate both BIER and BEER data into volumetric green and blue water footprinting. The accounting scheme should be ready-to-use, and all relevant factors made publicly available. Second, we produce characterization models for impact-oriented water footprinting, which improve on the existing WAVE+ method.[15] In addition to evaluating blue water deprivation effects in a source basin, the enhancement should enable us to consider the positive blue water supply effects to outlying basins resulting from bridges of atmospheric moisture transport. Third, all factors derived on the inventory and impact assessment level are tested within a case study. Finally, we discuss the resulting implications for water footprinting.

2. MATERIALS AND METHODS

2.1. Accounting Scheme for Volumetric Water Footprinting. We propose a new volumetric water accounting scheme, which is based on the following three types of inventories: (a) a basin internal inventory, (b) a basin external inventory, and (c) an inventory which extends across all basin boundaries. Figure 1 gives a schematic overview of these inventories. The basin internal inventory (a), as shown on the left in Figure 1, is considered the current state-of-the-art inventory and is based on the volumetric accounting step of the WAVE+ method.[15] The figure shows the most relevant water inflows and outflows along a product's life cycle. Water from a

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Environ. Sci. Technol. 2021, 55, 10231−10242

specific source basin n might enter the product system in a certain month k either through withdrawals of blue water ($BW_{n,k}$) or via GWC ($GWC_{n,k}$) of relevant land-use production systems. Water might leave the product system, on the other hand, via wastewater discharges ($WW_{n,k}$) or evaporation ($E_{n,k}$). For simplicity, other possible water outflows, such as wastewater discharges to external basins or the sea, are not displayed. The total amount of evaporation leaving the product system can be described as shown in eq 1

$$E_{n,k} = E_{\text{green},n,k} + E_{\text{blue},n,k} + V_{n,k} \tag{1}$$

$E_{\text{green},n,k}$ refers to the evaporation of green water (evaporated soil moisture), $E_{\text{blue},n,k}$ to the evaporation of used blue water resources (e.g., evaporation of applied irrigation water), and $V_{n,k}$ to synthetically induced evaporation processes (e.g., vapor creation during the combustion of fossil fuels).[7,15] Part of the evaporated water might get recycled within short time intervals via reprecipitation within the originating basin,[15] which is represented in Figure 1 by the term internal ER ($IER_{n,k}$). To a certain extent, this part contributes to both the regeneration of blue water via surface runoff and infiltration into the groundwater ($IER_{\text{runoff},n,k}$) and the refilling of green water resources in soils ($IER_{\text{green},n,k}$). The main methodological enhancement of our accounting scheme, however, is the additional consideration of a basin external inventory, as displayed on the right in Figure 1. This consists of external ER ($EER_{n,k,m}$) processes, which refer to further transported atmospheric moisture reprecipitating in various outlying basins (m_1 to m_i). By analogy with basin internal recycling processes, externally recycled moisture flows can also be divided into flows refilling either regional blue ($EER_{\text{runoff},n,k,m}$) or green water resources ($EER_{\text{green},n,k,m}$). Combining the basin internal and external inventories produces an inventory which extends across all the basin boundaries (c). We assume all recycling processes taking place within the same month of evaporation, which is justified by the average global recycling times being significantly lower than a month (e.g. 8 days as estimated by Shiklomanov and Rodda[29]). In the following, our proposed rules for green and blue water accounting are specified according to the three inventory perspectives. In each case, the presented accounting formulas refer to water consumption occurring in a specific source basin n and month k. For product systems comprising several basins and periods, overall water consumption and resulting external water gains are determined by aggregating overall relevant basins and months.

2.1.1. Basin Internal Accounting. According to Bayart et al. (2010),[33] used freshwater is considered consumed "when release into the original watershed does not occur because of evaporation, product integration, or discharge into different watersheds or the sea". Based on this, BWC within a certain basin and month ($BWC_{n,k}$) can conventionally be defined as the difference between the water abstractions occurring in the basin and return flows via wastewater discharges (eq 2)[15]

$$BWC_{n,k} = BW_{n,k} - WW_{n,k} \tag{2}$$

GWC, on the other hand, can be expressed by the sum of green water evaporation and green water resources incorporated into the product system ($I_{\text{green},n,k}$),[7] as shown in eq 3

$$GWC_{n,k} = E_{\text{green},n,k} + I_{\text{green},n,k} \tag{3}$$

However, in order to account for ER processes, we need to consider the basin- and month-specific BIER ratio ($BIER_{n,k}$; dimensionless).[15] $BIER_{n,k}$ describes the share of evaporation which returns to the originating basin via reprecipitation[15] and refills the source basin's blue water resources ($BIER_{\text{runoff},n,k}$) and green water stocks ($BIER_{\text{green},n,k}$). Both ratios lead to a reduction in water consumption within source basins. With regard to blue water, the resulting effective BWC ($BWC_{\text{eff},n,k}$) within a certain basin n and month k can be described as shown in eq 4a

$$BWC_{\text{eff},n,k} = BWC_{n,k} - IER_{\text{runoff},n,k} \tag{4a}$$

where $IER_{\text{runoff},n,k}$ is defined as shown below

$$IER_{\text{runoff},n,k} = E_{n,k} \times BIER_{\text{runoff},n,k} \tag{4b}$$

By analogy with $BWC_{\text{eff},n,k}$, eq 5a introduces effective GWC ($GWC_{\text{eff},n,k}$). This term represents the difference between the GWC of the considered land-use production systems and the amount of internal ER in the form of green water ($IER_{\text{green},n,k}$)

$$GWC_{\text{eff},n,k} = GWC_{n,k} - IER_{\text{green},n,k} \tag{5a}$$

where $IER_{\text{green},n,k}$ is defined as follows

$$IER_{\text{green},n,k} = E_{n,k} \times BIER_{\text{green},n,k} \tag{5b}$$

2.1.2. Basin External Accounting. In contrast to basin internal water accounting, basin external water accounting relates to external water gains resulting from evaporative water consumption. At this point, the basin- and month-specific BEER ratio ($BEER_{n,k}$; dimensionless) needs to be taken into account, denoting the average share of evaporated water reprecipitating over the sum of all external drainage basins. $BEER_{n,k}$ comprises two parts: one part contributes to the replenishment of blue water resources in external drainage basins ($BEER_{\text{runoff},n,k}$) and another refills external green water stocks ($BEER_{\text{green},n,k}$). The external water gains are represented by $EER_{\text{runoff},n,k}$ and $EER_{\text{green},n,k}$ in Figure 1 and are calculated as shown in eqs 6 and 7

$$\begin{aligned} EER_{\text{runoff},n,k} &= E_{n,k} \times BEER_{\text{runoff},n,k} \\ &= E_{n,k} \times \sum_m BEER_{\text{runoff},n,k,m} \end{aligned} \tag{6}$$

$$\begin{aligned} EER_{\text{green},n,k} &= E_{n,k} \times BEER_{\text{green},n,k} \\ &= E_{n,k} \times \sum_m BEER_{\text{green},n,k,m} \end{aligned} \tag{7}$$

where $BEER_{\text{runoff/green},n,k}$ represents either the runoff or green water share of evaporated water being recycled aggregated over all external receptor basins m_1 to m_i.

2.1.3. Accounting Across all Basin Boundaries. The transboundary accounting scheme combines the basin internal and external inventories. From the newly defined transboundary perspective, water is only considered consumed if it reprecipitates over the sea and, thus, is not directly recycled within either the source basin or one of the various external drainage basins on Earth. Within this context, we define the terrestrial ER ratio ($TER_{n,k}$; equals $BIER_{n,k}$ + $BEER_{n,k}$) as the share of evaporated water reprecipitating over land. By analogy with $BIER_{n,k}$ and $BEER_{n,k}$, $TER_{n,k}$ comprises two components, one responsible for the regeneration of blue water resources ($TER_{\text{runoff},n,k}$) and another one leading to the direct replenishment of green water resources on Earth ($TER_{\text{green},n,k}$). The latter two terms serve to determine basin- and month-specific transboundary BWC ($BWC_{\text{t\_b},n,k}$) and GWC ($GWC_{\text{t\_b},n,k}$), respectively, as shown in eqs 8 and 9

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Environ. Sci. Technol. 2021, 55, 10231−10242

$$\mathrm{BWC}_{\mathrm{t\_b,blue},n,k} = \mathrm{BWC}_{n,k} - E_{n,k} \times (\mathrm{TER}_{\mathrm{runoff},n,k}) \quad (8)$$

$$\mathrm{GWC}_{\mathrm{t\_b,green},n,k} = \mathrm{GWC}_{n,k} - E_{n,k} \times (\mathrm{TER}_{\mathrm{green},n,k}) \quad (9)$$

As an alternative to eqs 8 and 9, transboundary water consumption can also be determined by calculating the difference between effective water consumption ($\mathrm{BWC}_{\mathrm{eff},n,k}$; $\mathrm{GWC}_{\mathrm{eff},n,k}$) and the associated external ER ($\mathrm{EER}_{\mathrm{runoff},n,k}$; $\mathrm{EER}_{\mathrm{green},n,k}$).

2.2. Characterization Models for Impact-Oriented Blue Water Footprinting. In order to derive characterization models for impact-oriented blue water footprinting, the three-part water inventory scheme presented above (Figure 1) was combined with the vulnerability evaluation model of the WAVE+ method.[15] The suggested characterization models are only applicable for evaporative water consumption and aim to combine comprehensive knowledge on the fate of evaporated water with regional blue water scarcities. To determine the latter, we used the basin- and month-specific water deprivation index (WDI) from the WAVE+ method,[15] which describes "the potential to deprive other users when consuming water in this basin and month".[15] The WDI considers relative blue water scarcity based on a consumption-to-freshwater availability ratio, where availability refers to monthly renewable freshwater volumes.[15] We also integrated useable additional surface water stocks (lakes, wetlands, and dams), an adjustment factor for groundwater stocks and absolute blue water shortage (derived from the ratio of regional potential evaporation to precipitation).[14,15] The index is based on data from the global hydrological model WaterGap3[34] and can take values between 0.001 and 1. A value of 1 denotes the highest water deprivation potential, while a value of 0.001 indicates the lowest possible deprivation. The values for the WDI are available with global coverage and can be seen at a monthly resolution in Figure S1 of Supporting Information. For more detailed insights into how they were derived and a wider ranging discussion, see Berger et al.[15]

2.2.1. Characterization Model for the Basin Internal Inventory. The characterization model for the basin internal inventory builds on the WAVE+ method[15] and is represented by the basin- and month-specific WAVE+ characterization factors (eq 10)

$$\mathrm{WAVE}+_{n,k} = (1 - \mathrm{BIER}_{\mathrm{runoff},n,k}) \times \mathrm{WDI}_{n,k} \quad (10)$$

If the occurring evaporation $E_{n,k}$ relates only to blue water, this must simply be multiplied by the associated WAVE+ factor to determine the risk of blue freshwater deprivation in a certain source basin n and month k ($\mathrm{RFD}_{\mathrm{blue},n,k}$). If, however, other types of evaporation also play a role ($E_{\mathrm{green},n,k}$; $V_{n,k}$), $\mathrm{RFD}_{\mathrm{blue},n,k}$ needs to be adjusted by subtracting the resulting additional effects of ER on a basin's blue water availability, as shown in eq 11

$$\mathrm{RFD}_{\mathrm{blue},n,k} = E_{\mathrm{blue},n,k} \times \mathrm{WAVE}_{n,k} - (E_{\mathrm{green},n,k} + V_{n,k}) \times \mathrm{BIER}_{\mathrm{runoff},n,k} \times \mathrm{WDI}_{n,k} \quad (11)$$

2.2.2. Characterization Model for the Basin External Inventory. Regarding the basin external inventory, basin- and month-specific external WAVE factors ($\mathrm{WAVE}_{\mathrm{ext},n,k}$) were defined as characterization factors. They combine the values for $\mathrm{BEER}_{\mathrm{runoff},n,k,m}$ with the WDIs of the respective receptor basins (eq 12) and account for the aggregated beneficial water supply effects of evaporated water on external basins.

$$\mathrm{WAVE}_{\mathrm{ext},n,k} = \sum_{m} (\mathrm{BEER}_{\mathrm{runoff},n,k,m} \times \mathrm{WDI}_{m}) \quad (12)$$

The more evaporated water is recycled in somewhat water-scarce regions, the higher the weight given to the potential replenishment effect by $\mathrm{WAVE}_{\mathrm{ext},n,k}$. Multiplied by the overall evaporative water consumption in the source basin, $\mathrm{WAVE}_{\mathrm{ext},n,k}$ serves to determine the blue water replenishment potential due to evaporative water consumption in a source basin n and month k ($\mathrm{FRP}_{\mathrm{blue},n,k}$), as shown in eq 13

$$\mathrm{FRP}_{\mathrm{blue},n,k} = E_{n,k} \times \mathrm{WAVE}_{\mathrm{ext},n,k} \quad (13)$$

2.2.3. Characterization Model for the Transboundary Inventory. At this point, the $\mathrm{WAVE}+_{n,k}$ and the $\mathrm{WAVE}_{\mathrm{ext},n,k}$ factors were combined to form a transboundary WAVE factor ($\mathrm{WAVE}_{\mathrm{t\_b},n,k}$; eq 14)

$$\mathrm{WAVE}_{\mathrm{t\_b},n,k} = \mathrm{WAVE}+_{n,k} - \mathrm{WAVE}_{\mathrm{ext},n,k} \quad (14)$$

If only blue water evaporation is present, multiplying $\mathrm{WAVE}_{\mathrm{t\_b},n,k}$ by $E_{n,k}$ serves to determine the overall risk of basin transboundary freshwater depletion ($\mathrm{RFD}_{\mathrm{t\_b,blue},n,k}$). Where there are also green ($E_{\mathrm{green},n,k}$) or synthetically created vapor flows ($V_{n,k}$); on the other hand, $\mathrm{RFD}_{\mathrm{t\_b,blue},n,k}$ is determined according to eq 15

$$\mathrm{RFD}_{\mathrm{t\_b,blue},n,k} = E_{\mathrm{blue},n,k} \times \mathrm{WAVE}_{\mathrm{t\_b},n,k} - (E_{\mathrm{green},n,k} + V_{n,k}) \times \mathrm{BIER}_{\mathrm{runoff},n,k} \times \mathrm{WDI}_{n,k} \quad (15)$$

$\mathrm{RFD}_{\mathrm{t\_b,blue},n,k}$ offsets the negative impacts of evaporative BWC with the beneficial blue water supply effects from all evaporated water sources. It determines the net risk of blue water deprivation across all basin boundaries on Earth, which result from evaporative water consumption in a source basin n and month k.

2.3. Modeling. The calculations of the ER ratios ($\mathrm{BIER}_{n,k}$, $\mathrm{BEER}_{n,k}$, and $\mathrm{TER}_{n,k}$) were based on a global run of the numerical moisture tracking model WAM-2layers[31] within the geographical borders of 79.5° N and 79.5° S latitude. Atmospheric moisture was tracked for evaporation from all land grid cells on a grid with 1.5° spatial resolution. However, as moisture tracking at high latitudes is prone to errors due to high wind speeds compared to the size of the grid cell, the land masses of Greenland and Antarctica (where little water is consumed anyway) were excluded. The underlying principle of WAM-2layers[31] is the water balance, and the required input data for the model are variables such as evaporation, precipitation, wind components, humidity levels, and surface pressures. While our previously developed global data set on the fate of land evaporation[32,35] is based on ERA Interim reanalysis data[36,37] (from 2001 to 2018), for this study we replaced data on evaporation and precipitation with data from the hydrological model WaterGap3.[34] This ensured more consistency when it came to improving the existing impact-oriented water footprinting method WAVE+[15] building on the same input data. The adjustment of the input data used led to a change in the time horizon (from 2001 to 2010) considered for the analysis. The data download for this period took place in 6 hourly time steps at model levels spanning the atmosphere from zero pressure to surface pressure. These were broken down by the model to two layers under well-mixed conditions. The solving of the water balance for each time step across the entire grid was performed

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Environ. Sci. Technol. 2021, 55, 10231−10242

Table 1. Evaluation Parameters Considered within the Case Study; Asterisked Parameters are Exclusively Considered for the Case Study and Not Part of the Impact Assessment Scheme Developed

inventory perspective	accounting parameters considered		impact assessment parameters considered	
basin internal inventory	BWC/GWC BWC_{eff}/GWC_{eff}	(effective) water consumption	RFD_{blue} RFD^{*}_{green}	risk of freshwater deprivation
basin external inventory	EER_{blue}/EER_{green}	external ER	FRP_{blue} FRP^{*}_{green}	freshwater replenishment potential
inventory across all basin boundaries	BWC_{t_b}/GWC_{t_b}	basin-transboundary water consumption	$RFD_{t\_b,blue}$ $RFD^{*}_{t\_b,green}$	risk of basin-transboundary freshwater deprivation

by the computing system of the North German Supercomputing Alliance (HLRN). It was followed by post-processing in ArcGis and Python in order to aggregate the results to basin scales. The basin delineation used was taken from the WaterGap3 model.[34] The procedure described resulted in the determination of monthly BIER, BEER, and TER values for 8223 (sub)basins. To divide those into the respective runoff- and green water relevant recycling ratios ($BIER_{runoff}$, $BIER_{green}$, $BEER_{runoff}$, $BEER_{green}$, TER_{runoff}, and TER_{green}), we used the globally available runoff fraction α from WaterGap3.[34] For an overview of the α values at a monthly resolution, see Figure S2 in Supporting Information.

2.4. Temporal and Spatial Aggregation. Based on the aggregation of absolute water volumes, we derived all parameters on a (sub)basin scale at a monthly resolution. However, in practice, the exact periods and basin locations of water consumption are often unknown. As a consequence, we also compiled temporally aggregated results on the annual level, as well as spatially aggregated results on the country and world region level.

We carried out the temporal aggregation of the results based on the water consumption within the different months of the considered spatial units. That is, if, for example, 80% of a basin's annual water consumption occurs in a specific month, this basin's monthly factor (BIER, WAVE, etc.) will contribute 80% to the annual basin average. In rare cases, monthly data gaps within the raw results of the study prevented us from aggregating to annual averages. This could occur for parameters directly associated with atmospheric moisture modeling such as $BIER_{n,k}$ or $BIER_{runoff,n,k}$ and was due to zero evaporation inputs toward arid regions within certain modeling periods. In order to be able to aggregate to yearly averages in these cases, we filled in missing values through linear interpolation before starting the aggregation. Regarding the spatial aggregation to countries and world regions, the determined factors associated with different area contributions were weighted by grid cell-based water consumption data.

Both the temporal and the spatial aggregation were conducted based on four different types of consumption data: total BWC, agricultural BWC, non-agricultural BWC, and total evaporation (the latter as a proxy for GWC). Depending on the type of study (e.g., blue water footprint for unspecified, agricultural, or industrial systems under study or green water footprint), a practitioner could select the most appropriate aggregation method. All necessary temporally and spatially resolved consumption data were taken from the WaterGap3 model.[34] For the purpose of a statistical assessment, a separate determination of consumption-weighted global averages took place.

At the end of the aggregation processes, the monthly and annual averages were summarized in spreadsheets for all relevant parameters ($BIER_{n,k}$, $BIER_{runoff,n,k}$, $BIER_{green,n,k}$, $BEER_{n,k}$, $BEER_{runoff,n,k}$, $BEER_{green,n,k}$, $TER_{n,k}$, $TER_{runoff,n,k}$, $TER_{green,n,k}$, $WDI_{n,k}$, $WAVE+_{n,k}$, $WAVE_{ext,n,k}$, and $WAVE_{t\_b,n,k}$) and spatial units (basins, countries, world regions, and world averages). These cover data for 8223 basins, 234 countries, and 22 world regions. With regard to basins, we made additional kmz files available for download. These can be loaded into a Google Earth layer and aimed to plot annual averages aggregated based on total monthly BWC of all parameters considered.

2.5. Case Study. We applied the inventory and impact assessment factors produced through this work to a case study in order to test the applicability of the volumetric accounting and impact assessment schemes developed. The case study chosen was the production of one metric ton of wheat within six different drainage basins located in Eurasia and North Africa: the Yangtze (China), the Dnepr (Russia, Belarus and Ukraine), the Enguri (Georgia), the Garonne (France), the Cheliff (Algeria), and the lower Nile basin (Egypt, Sudan, and Ethiopia). The exact information on the locations of these sample basins and their basin delineations is provided in Figure S3 of Supporting Information.

We conducted both volumetric accounting as well as impact-oriented water footprinting. This determined the evaluation parameters displayed in Table 1 for all sample basins.

Regarding the impact assessment, the case study also considered deprivation risks and replenishment potentials with regard to green water. We developed these following the same procedures as for blue water but replaced the WDI by a proxy for green water scarcity. For this, we used green water scarcities[8] according to the Water Footprint Assessment Manual,[7] in which green water scarcity is defined as the ratio of the total volumetric green water footprint in a basin in relation to the green water availability (green water availability = evaporation of green water from land minus evaporation reserved for natural vegetation minus evaporation from land that cannot be made productive). It is important to note that the impact indices for green water scarcity are less mature[7] and only available as yearly averages for countries;[8] this was also the reason why they were not formally integrated into the methodology for this publication. However, by using them in the case study, we aimed to demonstrate the potential for deriving characterization factors in an analogue manner.

We determined the results for all evaluation parameters, while accounting for monthly variations in crop production, blue water consumptive uses, ER patterns, and water deprivation indices. With regard to GWC, in contrast, only data at a yearly resolution was available. The spatially and temporally resolved data on wheat production as well as the data on its blue and GWC were taken from the Pfister and Bayer water footprint database on global crop production (2014).[38] The water consumption indicated was viewed entirely as evaporative water consumption, while consumptive water use due to product integration was considered to be negligibly small. The database is based on the basin delineation of the Water Gap2 model,[39] which differs slightly from the newest WaterGap3[34] version applied in our research. The procedure for matching the

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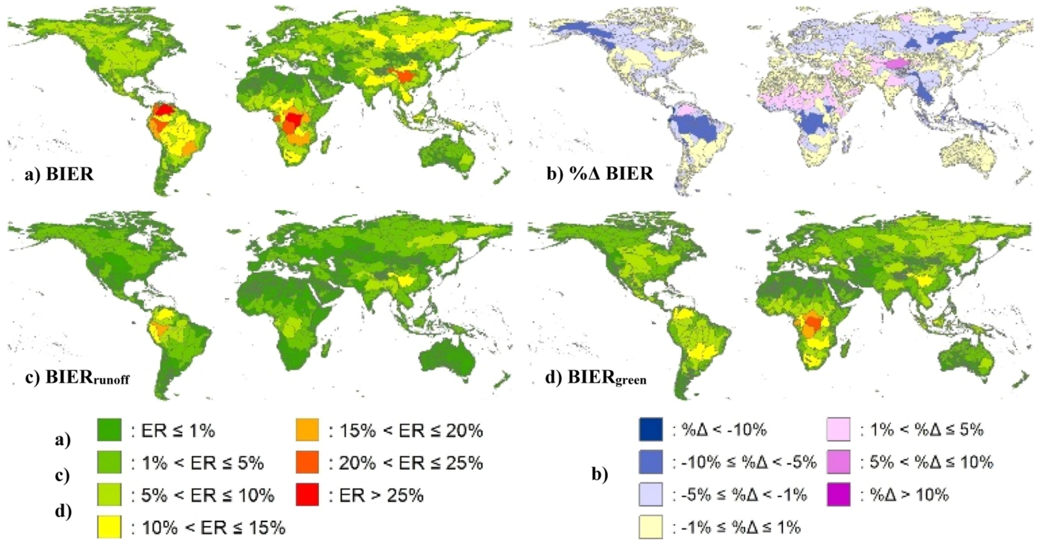

Figure 2. Basin-specific ER ratios for the basin internal inventory perspective averaged over the year (a) BIER, (b) total percentage changes (%Δ) of the updated BIER ratios in comparison to those of the previous WAVE+ publication, (c) runoff-relevant BIER ($\mathrm{BIER}_{\mathrm{runoff}}$), and (d) green water-relevant BIER ($\mathrm{BIER}_{\mathrm{green}}$).

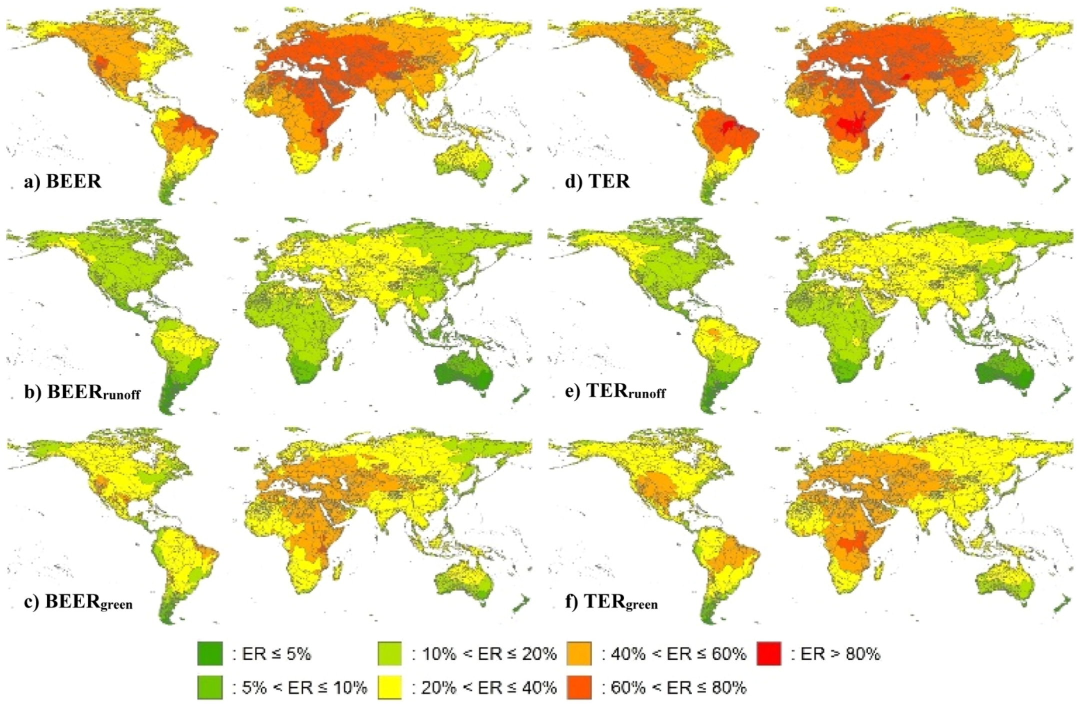

Figure 3. Basin-specific ER ratios for the basin external inventory (a−c) and across all basin boundaries (d−f) averaged over the year; (a) BEER, (b) runoff-relevant BEER ($\mathrm{BEER}_{\mathrm{runoff}}$), (c) green water-relevant BEER ($\mathrm{BEER}_{\mathrm{green}}$), (d) TER, (e) runoff-relevant TER ($\mathrm{TER}_{\mathrm{runoff}}$), and (f) green water-relevant TER ($\mathrm{TER}_{\mathrm{green}}$).

different basin delineations is provided in Table 1 of Supporting Information.

3. RESULTS AND DISCUSSION

3.1. Evaporation Recycling Ratios for Volumetric Water Footprinting. In the following section, all derived factors for volumetric water footprinting are presented on the basis of annual averages (aggregated based on grid cell-based total BWC), while the derived factors at a monthly resolution are provided in the Supporting Information for each case. Figure 2 presents the yearly ER ratios for the basin internal inventory.

Part (a) of Figure 2 shows the updated BIER ratios. Medium (10−15%) to high BIER ratios (>25%) apply mainly to large basins and can be found in the north of South America, in Central Africa, the Himalayas, and in large parts of China and Eastern Russia. Low BIER ratios (≤1%), on the other hand, relate often but not exclusively to smaller basins and are mainly present in North Africa, the Middle East, and Australia. These general trends are in line with the results of the WAVE+ publication[15] based on regional ER length scales. On consumption-weighted global average, BIER amounts to 4.5%. Total percentage changes between the original[15] and updated BIER ratios are shown in part (b) of Figure 2. On this basis, we can summarize that the two approaches produce similar results in most regions. This is especially valid for basins in arid and semi-arid regions, where relatively small shares of evaporated water might get recycled within a basin. However, in approximately 18% of the total amount of basins deviations larger than 5% were determined. Those cases represent mainly basins along the equatorial belt and the west coast of Canada as well as a few basins in Eastern Asia. The differences most probably occur due to a more explicit calculation of the ER which, in contrast to the WAVE+ method,[15] considers the exact shape of the basins to moisture transport direction. Images (c,d) in Figure 2 show the share of the BIER accounted for by runoff ($BIER_{runoff}$) and by refilling the basin internal green water resources ($BIER_{green}$). On average one-third of the BIER contributes to the building of new surface and subsurface runoffs, while two-thirds is responsible for the refilling of basin internal green water stocks. However, there are also a few exceptional cases in which $BIER_{runoff}$ exceeds $BIER_{green}$. Overall, the highest $BIER_{runoff}$ ratios (15—20%) are in the Amazon region, in parts of which both a high BIER and above-average values for the runoff fraction α (see Figure S2) occur. Exceptionally high $BIER_{green}$ ratios, on the other hand, are present in the Congo basin (Central Africa). In this basin, high BIER values coincide with below-average α values leading to $BIER_{green}$ ratios of more than 20%. While we presented the latter parameters on an annual basis, we must stress that a monthly evaluation would be more accurate in most cases. For a detailed overview of the monthly values for the parameters of Figure 2 (BIER, %Δ BIER, $BIER_{runoff}$, and $BIER_{green}$), please see Figures S4 to S7 of Supporting Information.

Figure 3 presents the average annual ER ratios for the basin external inventory (a−c) and across all basin boundaries (d−f). Image (a) in Figure 3 shows the BEER; it demonstrates that for many basins, shares of more than 60% from evaporated water (highlighted in dark orange and red) lead to reprecipitation over external basins. Those basins are mainly located along the northeast coastline of South America, in the Maghreb, East Africa, and in large parts of Eurasia (the Arabian Peninsula, Central and South-East Europe, Western, Central, and Southern Asia). A small basin size and a main moisture flux directed to large continuous areas of land are particularly beneficial for high BEER values. Basins which show a relatively low BEER (<10%), on the other hand, can mainly be found in the south of South America and Southern Australia. Within these regions, larger shares of atmospheric moisture were found to reprecipitate on average over southern ocean areas such as the South Pacific, the South Atlantic and the Indian Ocean. On consumption-weighted global average, BEER amounts to 52.5%. BEER ratios on average much higher than their BIER counterparts (BEER ≫ BIER) highlight the need to consider and evaluate direct moisture transfers toward external basins in addition to the usual basin internal perspective. However, by analogy with the BIER, it is also important to differentiate between ratios responsible for refilling regional blue or green water resources. Image (b) in Figure 3 presents the runoff-relevant BEER ratios, while the green water-relevant BEER ratios are shown in image (c). We can summarize that around one-third of the ER builds on an average new runoff, while the remaining two-thirds contribute to the refilling of green water stocks. Due to ER over a larger geographical area, exceptional cases in which $BEER_{runoff}$ exceeds $BEER_{green}$ are even more rare than for BIER. Finally, images (d−f) in Figure 3 display the different TER ratios (TER, TER_{runoff}, and TER_{green}). Because both the basin internal and external recycling ratios are included, those ER ratios generally have the highest values. For instance, the TER ratio exceeds 80% in a few basins while the consumption-weighted global average amounts to 57%. For an in-depth comparison of the monthly values for the parameters presented (BEER, $BEER_{runoff}$, $BEER_{green}$, TER, TER_{runoff}, and TER_{green}), see Figures S8 to S13 in Supporting Information.

3.2. Characterization Factors for Impact-Oriented Blue Water Footprinting. Figure 4 presents the derived characterization factors for impact-oriented blue water footprinting. As with the volumetric accounting, all factors are presented as annual averages aggregated based on grid cell-based total BWC. The updated WAVE+ factors are presented in image (a) of Figure 4. They highlight high blue water deprivation potentials (WAVE+ > 0.8) in the southwest of the USA, Mexico, the Andes, Southern Europe, North Africa, the Arabian Peninsula, Central Asia, India, and Australia. Lower values (WAVE+ ≤ 0.2), in contrast, can be observed in Canada, large parts of South America, North and Central Europe, Central Africa and Russia. The consumption-weighted global average of WAVE+ amounts to 0.69. As shown in image (b) of Figure 4, the updated WAVE+ factors did not lead to significant absolute changes compared to the initial values from the WAVE+ publication.[15] In 90% of the basins, the differences in absolute values are negligibly small (<0.001), while larger differences of more than 0.05 occur only in less than 1% of the basins. Image (c) in Figure 4 presents the external WAVE factors ($WAVE_{ext}$), which can be used to estimate positive blue water replenishment potential to external drainage basins. In comparison to the WAVE+ factors, $WAVE_{ext}$ values generally have much lower magnitudes, rarely exceeding 0.075. This is due to the following: first, in large basins, relevant parts of atmospheric moisture are already recycled within the source basin itself as BIER; second, moisture which travels across basin boundaries might reprecipitate in large amounts over the sea, which is then considered to be lost for positive supply effects; third, high $WAVE_{ext}$ values would require reprecipitation over regions with high WDIs but in many cases ER sprawls over regions with a large variety of WDIs; and lastly, only the runoff-relevant fraction accounts for positive blue water supply effects. The highest $WAVE_{ext}$ values ($WAVE_{ext,n,k}$ > 0.05) are present in the Maghreb region, the Arabian Peninsula, and other countries in the Middle East such as Iran and Pakistan. These regions have large areas of land in the direction of their main moisture flux as well as a geographical proximity to basins with high WDI values. The lowest $WAVE_{ext}$ values ($WAVE_{ext}$ ≤ 0.005), on the other hand, can be observed in the most northern and southern regions of the globe where basins show low WDI values and a part of the tracked moisture might also get 'lost' via the northern and southern system boundaries at the 79.5° N/S latitude. On the consumption-weighted global average, $WAVE_{ext}$ amounts to 0.03. Finally, image (d) in Figure 4 presents the transboundary WAVE factors ($WAVE_{t\_b}$); these offset the basin internal deprivation potentials with their positive basin external effects. The overall differences between the WAVE+ and the $WAVE_{t\_b}$ factors are rather small (0.69 compared to 0.66 on a consumption-weighted global average). However, for some regions with high basin internal water deprivation potentials (WAVE+ > 0.99; e.g., within the Maghreb or the Arabian Peninsula), the transboundary WAVE factors ($WAVE_{t\_b}$) are significantly reduced. Furthermore, it can be observed that in regions with rather low water deprivation potentials (characterized through low WAVE+ values), $WAVE_{t\_b}$ turned negative

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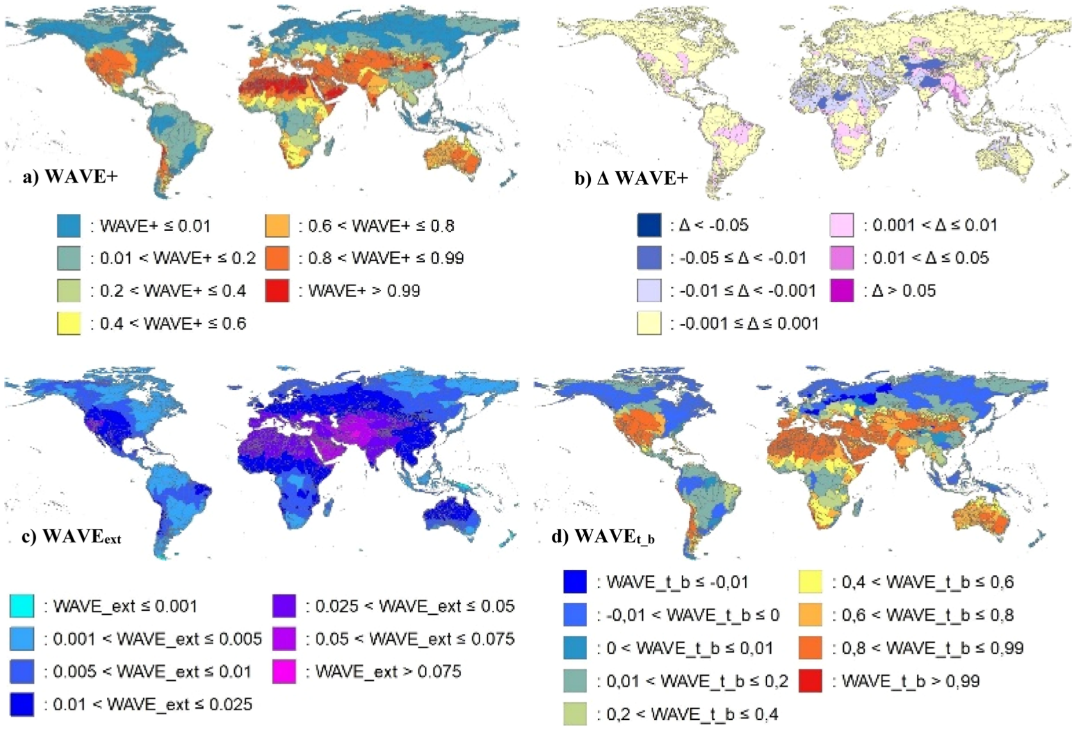

Figure 4. Basin-specific characterization factors for impact-oriented blue water footprinting according to the different inventory perspectives; (a) updated WAVE+ factors, (b) percentage changes (%Δ) of the updated WAVE+ factors in comparison to those of the WAVE+ publication, (c) external WAVE factors ($WAVE_{ext}$), and (d) transboundary WAVE factors ($WAVE_{t\_b}$).

in many cases. In those cases, the positive supply effects toward external basins (with higher water scarcities than the originating basin) outweigh the negative impacts on the source basin. This phenomenon is mainly present in some of the non-water scarce regions in North America, Northern and Central Europe, Russia, and South East Asia and leads to the topic of compensation within water footprinting, which will be discussed in more detail in chapter 3.4 ("Implications for Water Footprinting"). The characterization factors shown in Figure 4 (WAVE+, Δ WAVE+, $WAVE_{ext}$, and $WAVE_{t\_b}$) at a monthly resolution are presented in Figures S14 to S17 in Supporting Information.

3.3. Case Study. Figure 5 shows the results of the case study; the exact numerical values are provided in Table S2 of Supporting Information. The results for volumetric blue and green water accounting are shown in part (a) of Figure 5. With regard to BWC, there is a wide range of values ranging from 46 m^3 (Yangtze basin) to 1183 m^3 blue water per ton of wheat (Lower Nile basin). The runoff-relevant BIER lowers the effective blue water consumption (BWC_{eff}) in all basins, whereas both the evaporative consumption of blue and green water contribute to the regeneration of blue water resources within the respective source basins. The Yangtze basin is particularly noteworthy. Here, the reduction potential is the highest and BWC_{eff} turns negative, indicating a net surplus generation of blue water due to evaporative water consumption within this basin. This can be explained by both a relatively high parallel consumption of green water and above-average $BIER_{runoff}$ ratios for that basin. Regarding the external ER in the form of blue water (EER_{blue}), the total amounts range from 101 m^3 blue water per ton of wheat for the Garonne basin to 485 m^3 blue water per ton for the Cheliff basin. However, the Enguri basin has the highest share of evaporated water leading to basin external blue water gains: 27% of the evaporated water contributes to the refilling of blue water stocks outside the originating basin. Furthermore, it is remarkable that except for the Lower Nile basin, EER_{blue} is higher than BWC and BWC_{eff} in every case. This can be explained for those basins due to the large amounts of green water evaporation occurring in parallel being partially recycled in the form of blue water outside the source basin. As a result, transboundary BWC ($BWC_{t\_b,blue}$) turns negative, indicating that the wheat production in those basins generates more blue water across all drainage basins than it consumes. Comparing $BWC_{t\_b,blue}$ with BWC or BWC_{eff}, we see that the transboundary perspective has led to significant changes in the general order of the basins, while the best and worst performing basins are the Enguri (−351 m^3 blue water per ton of wheat) and the Lower Nile basin (932 m^3 blue water per ton of wheat), respectively.

GWC, on the other hand, amounts to between 66 m^3 (Lower Nile basin) and 1992 m^3 per ton of wheat (Cheliff basin). Due to the green water relevant BIER, the effective GWC (GWC_{eff}) is reduced in all basins considered. While the reduction effect is relatively minimal in most basins, it has a very high reduction potential of approximately 83% for the Lower Nile basin (GWC_{eff} = 11 m^3 per ton of wheat). This can mainly be explained by the basin's high irrigation needs. These result in large amounts of blue water evaporation in addition to the evaporated green water resources, from which approximately 4% is recycled in the form of green water within the same basin. For the external ER of green water (EER_{green}), values range from 178 m^3 (Garonne basin) to 825 m^3 green water per ton produced wheat (Cheliff basin). EER_{green} values are generally higher than the runoff values. However, due to the fact that most of the new green water generation comes from green water evaporation, EER_{green} is generally below GWC and GWC_{eff}. The Lower Nile basin is the only exception and has an EER_{green} value (603 m^3 per ton of wheat) 9 times higher than its GWC. As such, it is the only basin with a negative transboundary GWC (GWC_{t_b}; −591 m^3

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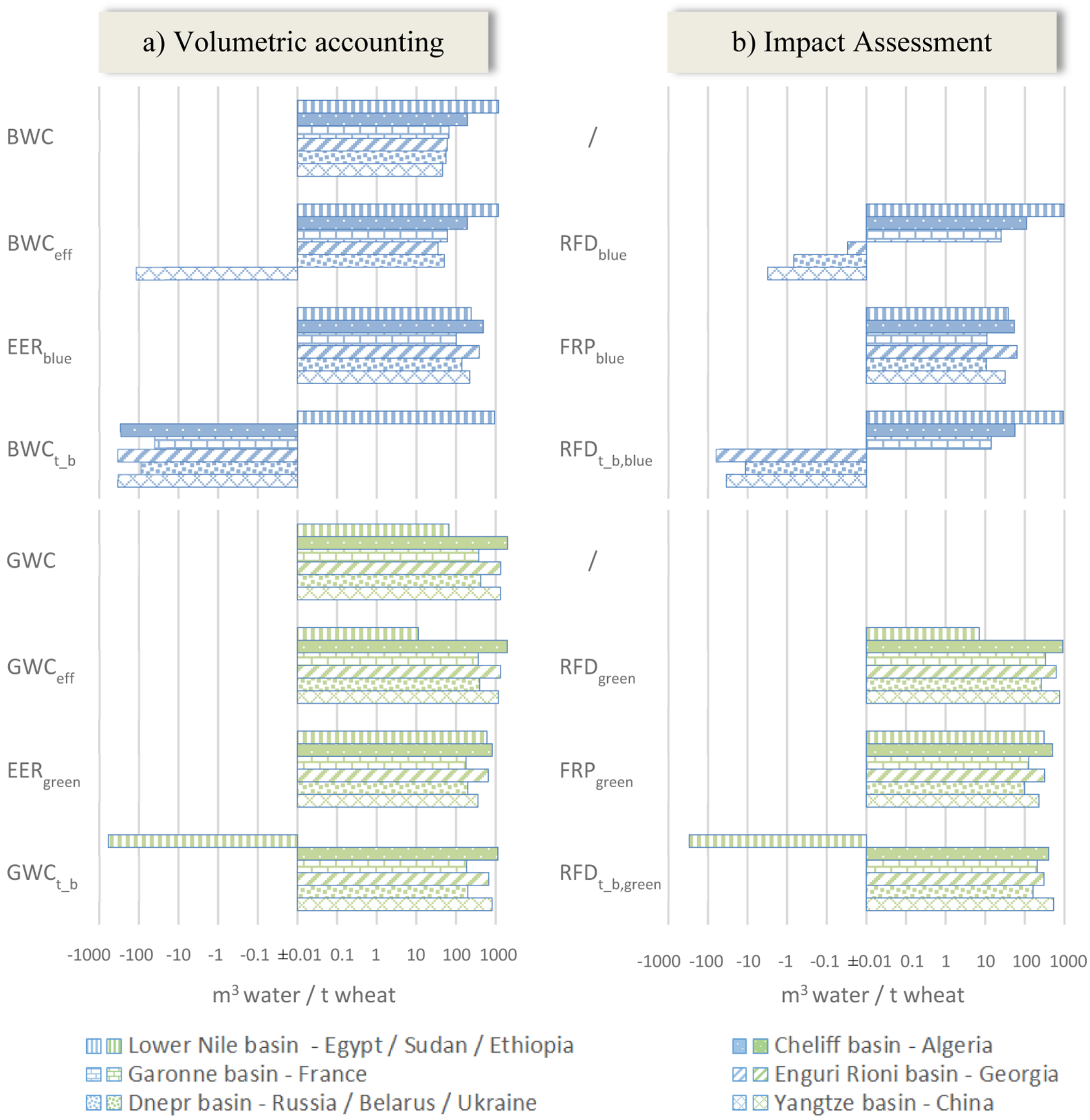

Figure 5. Results for the case study presented on a $\log_{10}$(value) and $-\log_{10}$(|value|) scale, where the latter applies to values with a negative sign. Graph (a) shows the results regarding blue and green water accounting for the production of one ton wheat in the sample basins considered and graph (b) shows the corresponding impact assessment steps with their associated weighted water consumption.

per ton of wheat) indicating a net surplus of green water generation across all drainage basins.

The results for impact-oriented water footprinting are shown in part (b) of Figure 5. With regard to blue water, the risk of freshwater deprivation (RFD_{blue}) ranges from −3 m^3 (Yangtze basin) to 961 m^3 weighted water per ton of wheat (Lower Nile basin). In total three basins have negative values (Yangtze, Dnepr, and Enguri basin) highlighting that the impacts of the BWC occurring in them are outweighed by the positive effects of BIER. Positive impacts of evaporative water consumption on external blue water stocks, on the other hand, are demonstrated by the freshwater replenishment potential (FRP_{blue}). FRP_{blue} has values of between 11 m^3 (Dnepr basin) and 63 m^3 weighted blue water (Enguri basin). The high value for the Enguri basin can be explained by its relatively high runoff-relevant BEER as well as its spatial proximity to potential water scarce receptor basins. Finally, the transboundary risk of blue water deprivation ($RFD_{t\_b,blue}$) offsets the basin internal deprivation risks with positive supply effects toward external basins and has values between −63 m^3 (Enguri basin) and 923 m^3 weighted blue water per ton of wheat (Lower Nile basin).

The risk of green water deprivation amounts to between 7 m^3 (Lower Nile basin) and 902 m^3 weighted green water per ton of wheat (Cheliff basin). The potential to replenish external green water resources is much higher than for blue water and has a maximum value of 503 weighted m^3 for the Cheliff basin. From the transboundary perspective, this basin therefore no longer has the highest green water deprivation potential. Furthermore, all risks of freshwater deprivation are significantly lower from a transboundary perspective with values ranging from −298 m^3 (Lower Nile basin) to 534 m^3 weighted green water per ton of wheat (Yangtze basin).

The case study showed the extent to which the different evaluation perspectives influence the results for volumetric and impact-oriented water footprinting. It demonstrated that depending on the evaluation focus (blue or green water; basin internal or basin-transboundary perspective), the order of the basins might change significantly, while different basins could be shown to be the best and worst performing options. On the one hand, this provides an opportunity to evaluate water consumption in water footprinting in a more comprehensive way. On the other, however, this might not necessarily facilitate decision-making processes. This could be explained by a practitioner's uncertainty as to what should be given more weight: the improvement of the water situation within a specific basin where evaporated water consumption takes place or a more utilitarian evaluation which considers the resulting effects on all basins on Earth; the effects of evaporative water consumption on Earth's blue water resources or on its green water stocks.

3.4. Implications for Water Footprinting. The following section discusses the possible implications of the derived factors for water footprinting. The main methodological enhancement of this research is the consideration of the beneficial supply effects of evaporative water consumption on external basins. This led to the definition of two new inventory perspectives: the basin external inventory and the transboundary inventory across all basin boundaries. In the following, we first discuss if the inclusion of those new perspectives is generally in line with existing water footprint guidelines. Therefore, we refer to the two most relevant water footprinting standards: the Water Footprint Assessment manual[7] from the Water Footprint Network and the ISO standard 14046[40] based on life cycle assessment. From the basin external perspective, neither standard explicitly addresses positive water effects through ER in external drainage basins. The ISO standard 14046,[40] however, broadly refers to the possibility of addressing general positive side effects in the interpretation stage of a water footprint (chapter 6.2 f interpretation (6)—"if relevant, description of the positive aspects if any").[40] Nevertheless, it remains unclear if these could be related to basin external supply effects or if they address more technical aspects of the production site. From the transboundary perspective, the question arises as to how both standards are positioned with regard to procedures in which negative and positive effects are offset against each other. In this context, ISO 14046[40] states that a water footprint must not include offsetting, defining this as "a mechanism for compensating the water footprint of a product, process, or organization through activities which reduce water impacts in a process outside the boundary of the product system". Whether or not ER in external drainage basins is included in this definition is debatable. However, we assume that the wording used more likely refers to technological water-saving measures within external product systems rather than the natural processes of ER. The Water Footprint Assessment Manual,[7] on the other hand, does not explicitly ban offsetting in water footprinting. Instead, it emphasizes that an offset of a water footprint should always occur in the basin where the water footprint is located, while simultaneously stressing the ill-defined nature of the term offsetting.[7] In order to shed more light on the matter, there is a need for more information on how to deal with ER in both the originating and external receptor basins in possible future revisions of the standards.

As publicly available standards do not yet provide comprehensive guidance, the question arises of what practitioners using the derived factors should do if they are uncertain as to how to account best for blue and green water evaporative consumption and its associated impacts. In this connection, we consider a preference for either the basin internal or the transboundary perspective on water consumption as a value choice, which needs to be made by the water footprint practitioner. We argue, however, that the transboundary evaluation should not be applied and presented in a standalone manner. This would help to avoid potential misuses, whereby uncommented negative footprints could create the wrong impression that water consumption has no negative impacts at all. The question of whether a basin's blue or green water resources should be given more weight within water footprinting, on the other hand, could in theory be answered on a more scientific basis. However, at this point more enhanced impact assessment models are needed, which quantify the impacts of blue and GWC based on a common effect endpoint such as ecosystem quality or human health.

Considering that on average two-thirds of evaporated water is recycled in the form of green water, the inclusion of ER might imply significant influence on green water footprints. However, the presented case study also showed relevant linkages between green and blue water resources. The evaporation of green water, for instance, could lead to significant reduction potentials regarding the basins' blue water footprints, while the reverse is also possible.

Besides using the derived ratios on ER for the water footprints of individual product systems, it might also be of interest to explore how they could impact perspectives on global virtual water trade studies.[41,42] Based on the global trade of commodities, these studies determine the green and blue virtual water transfers between different countries and world regions[41,42] but so far neglect average atmospheric moisture imports and exports between the regions considered.

Another application focus refers to the detection of possible impacts of land use changes on the water supply to other regions on Earth. In this context, the net green water concept[10,11] could be applied. This accounts for green water based on the difference between the total green water flow and the evaporation flow of its potential natural vegetation. Even though first attempts quantifying evaporation from the potential natural vegetation were provided on a global scale,[10,43] the data basis regarding the application of the net green water concept is still regarded as being immature. Combining net GWC with our derived recycling ratios was outside the scope of this publication but would very likely have led to substantially different case study results. This is due to the fact that net GWC might be negative in most regions, because evaporation under current land covers is expected to be on average slightly lower than evaporation from the potential natural vegetation (e.g., −7% as estimated by Gerten et al.[43]). The green water concept applied in this work (eq 3), in contrast, solely considers evaporation from current land covers and defines GWC as such only on positive scales. While both concepts are accepted practices, practitioners should be aware of their major differences to select the most appropriate accounting concept in accordance to the purpose of the study.

In addition to the positive aspects of ER, we highlight that ER could also, in theory, lead to negative effects. This work shows the limitation that it focuses on the impact assessment side solely on water scarcity-related impacts and does not include the possible negative effects of additional precipitation such as flooding or adverse effects of waterlogging.

With regard to impact-oriented water footprinting, we highlight that the derived recycling ratios could potentially be combined with impact assessment models other than WAVE+[15] (e.g., the method AWARE,[16] which is recommended by the UNEP-SETAC Life Cycle Initiative). However, one has to consider the possibility of different basin delineations in other impact assessment models. If basin delineations should differ substantially from each other, we advise recalculating the ER ratios for the new basin shapes based on the raw results on a grid cell level[32] rather than applying other matching procedures.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c04526.

Water deprivation indices and runoff fractions, methodological supporting information, monthly plots regarding BIER, BEER, and TER, monthly characterization factors for impact-oriented blue water footprinting, and results of the case study in the tabular form (PDF)

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Notes

The authors declare no competing financial interest.

The detailed quantitative results of this paper are too comprehensive to be presented here. They are available online[44] (https://www.tu.berlin/see/forschung/datensaetze-methoden-und-tools/considering-the-fate-of-evaporated-water-across-basin-boundaries-implications-for-water-footprinting/) and include the following:Spreadsheets with the monthly results on a basin scale and all temporal and spatially aggregated results applicable on blue water evaporative usages (useable for the unspecified, agricultural or non-agricultural systems under consideration): $BIER_{n,k}$, $BIER_{runoff,n,k}$, $BIER_{green,n,k}$ $BEER_{n,k}$, $BEER_{runoff,n,k}$ $BEER_{green,n,k}$, $TER_{n,k}$, $TER_{runoff,n,k}$, $TER_{green,n,k}$ $WDI_{n,k}$, $WAVE+_{n,k}$, $WAVE_{ext,n,k}$, and $WAVE_{t\_b,n,k}$ with additional kmz-files loadable into Google Earth layers for basins. Additional spreadsheets including temporal and spatially aggregated results applicable on green water evaporative usages: $BIER_{n,k}$, $BIER_{runoff,n,k}$, $BIER_{green,n,k}$, $BEER_{n,k}$, $BEER_{runoff,n,k}$ $BEER_{green,n,k}$, $TER_{n,k}$, $TER_{runoff,n,k}$, $TER_{green,n,k}$, $WDI_{n,k}$, and $WAVE_{ext,n,k}$

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