Water Stress and Water Footprint

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Physical water stress and scarcity are often used interchangeably, or the exact nature of the underlying data is not clearly defined or justified (e.g., water use versus consumption versus withdrawal). A number of authors have noted that there is no widely accepted definition for physical water stress and scarcity.

Comparing different definitions of water stress and scarcity, they seem to be converging on the definition given by the CEO Water Mandate (A NGO affiliated with the United Nations), who defines water scarcity as lack of physical abundance of freshwater resources without considering whether water is suitable for use, and water stress as lack of ability to meet human and ecological demand for freshwater, in terms of water quantity and quality and accessibility to water.

Keywords: water footprint ; water stress

1. Physical Water Stress Indicators

1.1. Per Capita Water Availability

The per capita water availability index was introduced by Falkenmark et al. [1] to evaluate blue water stress, and is defined as the fraction of total annual run-off available for human use [1]. Falkenmark's indicator is simple and intuitive, and data on human population and annual run-off within regions are readily available. These merits make the Falkenmark indicator one of the most widely used blue water scarcity indicators [2]. As green water is important especially for agricultural products [3], this indicator has also been applied in the evaluation of green water scarcity, expressed as per capita green water resources in a region [4][5]. A combination of green and blue water scarcity has been developed to assess water stress caused by both green and blue water [5]. If green and blue water consumption in a certain area is less than the global average level of 1300 m^3/cap/year, then the area is considered as being water scarce [5]. Similarly, a combination of green and blue water consumption was used as part of the planetary boundaries concept that quantifies environmental limits within which humans can safely operate, with a global maximum water consumption of 4000 km^3/year [5][6][7]. Due to the simplicity of the indicator 'per capita water availability', there are a few inherent problems with this indicator: (i) this national and annual based indicator hides scarcity information at smaller spatial and temporal scales [8][2]; (ii) the thresholds ignore variations in demand among countries because of factors such as technology, lifestyle, and climate [9][2][10]; (iii) the indicator treats per capita water availability as a fixed requirement per person [2]; and (iv) it ignores important variations in demand and consumption among countries.

1.2. Withdrawal-to-Availability Ratio

The withdrawal-to-availability ratio is also referred to as a criticality ratio and is defined as "*the ratio of average annual water withdrawals to water availability*" ([11], p. 21). This ratio is a commonly used water quantity stress indicator, and has been widely applied to measure blue water stress in a given area [12][13]. A region can be categorized into severe water scarcity (>40%), water scarcity (20%–40%), moderate water scarcity (10%–20%) and low water scarcity (<10%) [14]. The threshold values have been adopted by the United Nations [15], European Environment Agency [68] and numerous studies (e.g., [16][17]). The development of hydrological models in the past decades allows the modelling of blue water withdrawal and availability globally at a high spatial resolution [18][19], facilitating withdrawal-to-availability ratio-based assessments.

Pfister et al. [20] modified the withdrawal-to-availability ratio by using a logistic function providing water quantity stress levels at continuous values between 0 and 1, in order to use the water quantity stress index as a characterization factor to calculate environmental impacts induced by water withdrawal in a life cycle assessment model. Pfister's water quantity stress index has also been linked to input-output models to convert water footprints into water stress footprints through weighing water footprints with water stress factors reflecting availability at the place of water extraction at high spatial resolution.

1.3. Water Footprint-to-Availability Ratio

It has been frequently argued that it makes more sense to use blue water consumption rather than water withdrawal to assess blue water stress [21][22], as the majority of the extracted blue water becomes eventually return flows, with only a small proportion of the actual water withdrawal being consumed. For example, estimates show that in agriculture, 40% of withdrawn water returns to rivers and lakes and 90%–95% of water withdrawn by industry and households flows back to nature [23]. Thus consumption-to-availability is seen as better suited to assess blue water stress than the withdrawal-to-availability ratio [24]. The consumption-to-availability ratio is generally used to measure blue water scarcity, which is the ratio between blue water consumption and availability. But green water scarcity and water pollution level defined by Hoekstra et al. [24] are also expressed as green/grey water footprint to availability ratio.

Limited green water aggravates water stress [25]. Even though green water has properties of both quantity and quality, the definition of green water just describes quantity. The quality of green water is determined by soil properties such as the concentration or retention capacity of nutrients and toxic substances [25]. At present, there is no relevant research on green water quality induced stress. The reason may be that green water quality in the soil is difficult to measure and the usefulness of green water quality assessment for practical purposes remains unclear. Green water scarcity specifically refers to green water quantity stress, and is defined as the ratio of the green water footprint to green water availability [26]. As measurements of green water availability and environmental green water requirements are difficult to obtain, the application of green water scarcity has received only limited attention in the literature [25][27]. The lack of opportunity costs of green water, i.e., the lack of competing uses in other sectors, is often stated as a reason to ignore green water [28][29], which is thus considered as being less important for water management than blue water [30].

For water quality stress, there is one major indicator defined as the ratio of grey water footprint to the actual run-off, also referred to as water pollution level [24]. This indicator can be applied to assess water quality stress of freshwater [31] or discharged wastewater from primary, secondary and tertiary economic sectors [32]. If water quality stress is over 100%, it indicates that available blue water resources cannot dilute polluted water to satisfy water quality standards [26]. As it is a hypothetical indicator, the usefulness of the grey water footprint has been frequently questioned [33][34], yet these arguments have not abated the popularity of this indicator nor its frequent application [35][36][37].

Calculating the grey water footprint is a precondition to measure water quality stress. Grey water footprint calculations created by Hoekstra et al. are based on individual pollutants by selecting the highest grey water footprint of an individual pollutant. However, due to limited water pollution data availability [38], it is challenging to calculate the grey water footprint for all relevant pollutants and then to select the highest one as the final grey water footprint of polluted water. To solve this problem, major representative chemical water pollutants such as Chemical Oxygen Demand (COD) for measuring organic matters and Ammonia Nitrogen (NH_3-N), Total Nitrogen (TN) and Total Phosphorus (TP) for nutrient pollution are the most frequently used pollutants to express water quality [38][39][40], as these pollutants are commonly monitored for freshwater [41][42][43] or discharged wastewater [86,87]. In addition, physical parameters such as temperature and salinity (or electric conductivity) sometimes are also employed to evaluate water quality stress of surface water[31].

However, only focusing on a representative and specific pollutant leaves other pollutants and their interactions unexamined [44][45], which may lead to an underestimation of the grey water footprint and water quality stress. For instance, Vale et al. [46] pointed out that many studies on agricultural products, only considering fertilizers but ignoring pesticides, underestimate the grey water footprint. Similarly, when looking at industrial pollution, cadmium, copper and mercury are critical pollutants for steel production; whereas cadmium is a critical pollutant for cement; and for glass, a critical pollutant would be suspended solids [47]. In contrast, most studies on industrial sectors just chose the same conventional pollutants (i.e., COD and ammonia nitrogen) [39]. Thus, there is a need to investigate critical water pollutants for different processes or sectors providing a foundation for more accurate assessment of the grey water footprint and water quality stress.

To address this deficiency, cumulative effects of multiple pollutants have been the focus in recent studies [48][49][50], by combining footprint accounting with other tools, such as commonly used water quality evaluation tools [48], mass-balance models and fuzzy synthetic evaluation models [51]. But an important limitation of modified grey water footprint methods lies in the selection of pollutants, which requires calculation and analysis of pollution data in advance [48]. For this reason, traditional grey water footprint accounting is still dominating water quality stress assessments.

2. Water Footprint Accounting

2.1. Bottom-Up Approaches

Water footprint assessment (WFA) [26] and life cycle assessment (LCA) [52] are based on detailed data of individual processes and thus can be classed as bottom-up approaches [53]. WFA and LCA share a generic framework: setting goals and scope; accounting phase; impact assessment phase and interpretation [54]. WFA and LCA serve different goals, as life cycle assessment is a product-focused method, aiming to achieve sustainability of products, while water footprint assessment is a water management approach with a focus on the sustainability of water resources [54][55]. Water footprint assessment was developed with a focus on agricultural sectors and food production processes [56] at its early stage, then extended to industrial sectors, with currently focusing on agricultural and forestry-based production (such as paper, dairy and textile) and energy production (such as bioenergy and electricity) [57], whereas LCA had its starting point with a focus on industrial products and sectors. At the accounting stage of calculating the water footprint, the LCA and WFA communities have an ongoing debate about green and grey water footprint accounting. The WFA community measures blue, green and grey water footprints, but LCA only includes the blue water footprint [54]. The LCA community argues that only net green water (the difference between cropland and natural vegetation) should be counted [55], but it would lead to net negative green water footprints, because evapotranspiration of natural vegetation might be larger than that of croplands [55].Thus, it is unusual to account for green water footprints in LCA. The other issue is with regard to grey water footprint accounting, as the LCA community argues that different indicators such as acidification, eutrophication or toxicity potential are better suited to measure water pollution [79]. Even though LCA does not measure the grey water footprint directly, LCA databases have been applied in water footprint assessments to estimate grey water footprints [47]. For instance, LCA databases such as GaBi, Ecoinvent and Quantis can provide water pollution data for WFA [47][58], and also provide information on up-stream processes [59][60].

2.2. Top-Down Approaches

Top-down approaches provide a framework for quantification of environmental burdens based on national accounts that allows linking the entire supply chain in a production web to final consumption using macro-level approaches and concepts to analyze footprints of individuals, companies, sectors or regions [61]. At its core is the input-output (IO) table depicting monetary flows of goods and services among different economic sectors through trade [62]. IO analysis provides detailed flows between production and consumption at the level of economic sectors provided in national accounts of statistical offices. The input-output model with economic multipliers at its core allows not only the direct effects of environmental impacts through changes in final consumption but also the round-by-round or indirect effects of subsequent expenditures and inputs to each layer of production. This mechanism coupled with environmental extensions such as water consumption per sector enables the analyst to calculate the water footprint throughout the entire supply chain [63][64].Such top-down water footprint accounting has a long history in input-output analysis [65][66], even before the term water footprint was coined in 2002. Environmentally extended input-output analysis (EE-IO) is the most widely used top-down approach to calculate water consumption [67].

Multi-Regional Input-Output (MRIO) analysis [68][69] and water embodied in bilateral trade [70] are both input-output approaches that can be used to calculate water consumption. But the difference is that MRIO analysis traces global supply chains, while the method of water embodied in bilateral trade just traces domestic supply chains and imports. Thus, this difference may lead to inter-regional and international cut-off effects [53] and thus, wrong allocation of footprints [71].

IO and MRIO provide the most complete information about supply chains, whereas bottom-up approaches are not able to capture entire industrial supply chains, by focusing only at the most important processes, leading to inter-sector cut-off compared with top-down approaches [53]. System boundaries of bottom-up approaches can lead to double counting [114] as well as to excluding important flows [72]. A major drawback of input-output analysis is that economic sectors are aggregated and cannot show detailed process information compared with bottom-up approaches [73][74].

So-called hybrid analysis, linking process-based LCA and IO, combines advantages of both LCA and IO. There are three major approaches for hybrid analysis: tiered hybrid analysis [74][75][76][77][78], which essentially combines process and input-output data within a process analysis framework in order to reduce truncation error of a pure process analysis [73], IO-based hybrid analysis [79][80], which is performed by disaggregating industry sectors in the IO table to a more useful resolution, and integrated hybrid analysis [81], which is carried out by connecting an input-output table to a technology matrix based on process data. These hybrid approaches have found a range of applications, for instance to quantify water consumption for wind power [82], shale gas [83], other electricity generation technologies [100], transport fuels [127], and non-electric energy (transport and heating energy) [84].

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