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Water Availability Indices – A Literature Review

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NOMENCLATURE AND ABBREVIATIONS

AET	Actual Evapotranspiration
AWARE	Available Water Remaining
BOD	Biological oxygen demand
BWA	Blue water availability
BWAI	Blue Water Availability Index
BWC	Blue water consumption
BWSI	Blue Water Shortage Index
CTA	Consumption-to-availability
CF	Characterization factor
EFR	Environmental flow requirement
EPI	Environment Pressure Index
ER	Effective rainfall
ET	Evapotranspiration
EWR	Environmental water requirement
GBWSI	Green-Blue Water Shortage Index
GWA	Green water availability
GWAI	Green Water Availability Index
GWBW	Green and blue water
GWD	Green water depth
GWSI	Green Water Scarcity/Shortage Index
HDI	Human Development Index
HUC	Hydrological Unit Code
IWRM	Integrated water resources management
LCA	Life cycle assessment
MAR	Mean annual runoff
MARG	Mean annual renewable groundwater
PET	Potential evapotranspiration
RF	River fragmentation
SETAC	Society of Environmental Toxicology and Chemistry
SRF	Strongly regulated flow

UNEP	United Nations Environment Programme
USGS	U.S. Geological Survey
WAI	Water Availability Index
WaSSI	Water Supply Stress Index
$WaSSI_{i,s}$	Sectoral Water Supply Stress Index
WSI	Water/Watershed Stress/Scarcity/Sustainability Index
WSSRI	Water Supply Sustainability Risk Index
WTA	Withdrawal-to-availability
WULCA	Water Use in Life Cycle Assessment

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1 INTRODUCTION

Fresh water is a critical resource for humanity and the ecosystem. In general, water resources can be partitioned into two major categories: blue water and green water (Falkenmark and Rockström 2006). Precipitation that runs off or percolates into the deep aquifer is defined as blue water, and precipitation that filtrates into soil, which eventually returns to the atmosphere as evaporation, is called green water (Hoekstra *et al.* 2011). For human purposes, green water is almost exclusively used for agricultural production, but blue water can be used for multiple competing sectors, such as irrigation and municipal water.

Since population distribution, climatic and hydrologic conditions vary significantly around the world (Kummu *et al.* 2014), there is often a mismatch between water demand and water supply. In fact, most populated regions are also water-scarce areas (Kummu and Varis 2011). In order to quantify to what extent water supply may fall short of human and environmental needs, a diverse set of water availability indicators has been developed over the past 30 years. Major categories of indexes include water crowding indexes and various demand-to-supply ratios. In more recent studies, the need to preserve water for ecosystem services was also recognized (Smakhtin *et al.* 2005, Pastor *et al.* 2014).

The U.S. resides in an area with abundant freshwater resources, and more than 80% of its regions are not water stressed. However, in recent years, 13.7% of the U.S. has experienced water stress on an annual basis (Moore *et al.* 2015). In the summer especially, the western regional hot spots increase. These areas would be particularly sensitive to climate change. It is undeniable that tensions between water demand and water resource supply in the energy and agriculture sectors need to be examined on a consistent basis in order to improve water management programs nationwide. Among the proposed means of quantifying the water resources available for sustaining production at the regional level, the water availability index is one of the key metrics that enable analysis to address regional water demand and water supply issues.

To assess whether freshwater is a constraint for basic human needs and economic development in a region, a number of efforts have been made over the past few decades to develop a generic index to quantify the relationship between water demand and water resources in a regional context. Conceptually, water availability can be defined as a function of relative supply and demand (Averyt *et al.* 2013). However, it is surprisingly complex and difficult to identify a commonly accepted generic water scarcity or water availability indicator in practice. Definitions of "demand" and "supply" vary substantially among studies, making it difficult to compare results across these studies directly. The challenge of consensus building is due, in part, to the lack of one or a set of clearly defined and commonly shared questions for water availability assessment. The Water Use in Life Cycle Assessment (WULCA), a working group of the UNEP SETAC Life Cycle Initiative, has made some progress on developing a consensus-based water scarcity midpoint method (Boulay *et al.* 2015), but this ongoing effort is aimed specifically at life cycle assessment (LCA) applications. For a broader audience, there is a lack of consensus. A review of existing water indexes can be a helpful reference for researchers interested in harmonizing different methodologies or developing new water scarcity or availability indices.

To date, most studies and reviews on the subject of water availability have been focused on blue water (Savenije 2000, Rijsberman 2006, Brown and Matlock 2011), despite the importance of green water to terrestrial ecosystems and agriculture (Savenije 2000, Schyns *et al.* 2015). While irrigation for agriculture dominates blue water withdrawals (>70%), irrigation water accounts for only 16% of global consumptive water use for crop growth and the remaining 84% of the agricultural water supply comes from green water (Falkenmark 2013). The key role of green water in agricultural production implies that green water availability is also important for human purposes. However, only minor efforts have been made to develop a robust green water availability or scarcity index. The consumption-to-availability green water indicator proposed by Hoekstra et al. (2011) is the most comprehensive one by far, but it has not been operational, owing to the difficulty of getting the required data. Schyns *et al.* (2015) made the first effort to provide a comprehensive review of existing green water scarcity indices. They concluded that it is time for water scarcity assessment to include green water. Therefore, a comprehensive assessment that explicitly evaluates both blue and green indices is needed.

For this report, we reviewed a number of major existing blue and green water availability indicators. A detailed description of individual indicators can be found in the next section. We compared the strengths and weakness of different types of indicators, and via extension from existing metrics. This study focuses on physical water availability; indicators and concepts focusing on socio-economic water scarcity (Sullivan *et al.* 2003, Seckler *et al.* 1998) are outside the scope of this review. In addition, this study focuses on fresh water; therefore, saline water and seawater were not included.

2 DESCRIPTION OF WATER AVAILABILITY INDICES

Over the past 30 years, concerns over overexploitation of water resources have led to a multitude of methods and indicators to assess the relationship between water use and freshwater resources. A summary of these indicators by major categories can be found in the Appendix. The Falkenmark indicator, developed in the 1980s (Falkenmark 1989), which measures per capita water availability, laid an important foundation for assessing water security around the world. Several global studies have assessed water scarcity status by comparing per capita water share to the water supply required to achieve food self-sufficiency (Rockström *et al.* 2009, Kummu *et al.* 2014, Gerten *et al.* 2011). While the Falkenmark indicator is straightforward and easy to calculate, it oversimplifies regional differences by assuming equivalent per capita water demand globally or within each country. More importantly, it does not reflect water stress caused by increasing demands from economic development.

A number of indices based on withdrawal-to-availability (WTA) (Vörösmarty *et al.* 2005, Averyt *et al.* 2013) or consumption-to-availability (CTA) ratio (Hoekstra *et al.* 2012, Brauman *et al.* 2016) have been developed to measure the relationship between human water use and freshwater availability. In recent years, concerns over freshwater habitat degradation have led to the concept of “environmental water requirement” (EWR) (Smakhtin *et al.* 2005). Original WTA- or CTA-based indicators were modified by setting aside a portion of runoff or stream flow as the EWR (Hoekstra *et al.* 2011, Smakhtin *et al.* 2005, Wada 2013). The challenge of including EWR in water availability indicators is that the amount of water needed to sustain freshwater ecosystems is highly variable, depending on the region and the flow season (Pastor *et al.* 2014).

Boulay *et al.* (2014) classified indicators into three categories (Table 1) on the basis of use-to-resource ratios (WTA or CTA). Although the Hydrocentric category seems ideal, it is technically difficult to measure renewable water availability at spatial and temporal scales consistent with human needs, because of the time delay in returning flow and extensive geospatial variations. Similarly, the Ecocentric category requires quantifying the ecosystem/environment water requirement, which often introduces uncertainty. In the section below, most existing blue and green water availability accounting methods can be considered as either Anthropocentric or Ecocentric indices.

In addition to use-to-resource-based indicators, the need for a generic scarcity-based midpoint indicator for water use impact assessment emerged from the LCA community (Kounina *et al.* 2012, Bayart *et al.* 2010). After comparison of multiple methods, the WCULA recommended a characterization factor (CF)-based method called the Available Water Remaining (AWARE) method (Boulay *et al.* 2016). AWARE provides a simple approach to weight water consumption by CF, but the suitability of the CF method is still under debate (Hoekstra 2016, Pfister *et al.* 2017).

TABLE 1 Categories of indicators based on use-to-resource ratio

Category	Index
Anthropocentric	$Fn(\frac{Human\ Use}{water\ availability})$
Ecocentric	$Fn(\frac{Human\ Use}{water\ availability - environmental\ water})$
Hydrocentric	$Fn(\frac{Total\ Demand\ *}{Renewable\ water\ availablity})$

*Total demand includes human and natural water demands.

To date, green water availability and its spatial variability have not, despite their importance, been the focus of water scarcity analysis. Part of the reason is that it is difficult to clearly define available green water resource (Hoekstra *et al.* 2011, Gerten *et al.* 2011). Among existing green water indicators, most of them compare per capita blue-green water availability to water requirements for food production (Rockström *et al.* 2009, Gerten *et al.* 2011, Kummu *et al.* 2014). A few use-to-availability-based indicators have been proposed in the literature (Hoekstra *et al.* 2011, Núñez *et al.* 2013), but none of them is widely used.

2.1 BLUE WATER INDEX OVERVIEW

Starting in the 1980s, indexes have been developed to analyze population-driven blue water scarcity (Falkenmark 2013). This type of index evaluates whether basic human water needs can be satisfied, especially in naturally water-poor regions. Indicators in this category measure water stress by calculating the ratio of population or water demand determined by human needs per capita to blue water availability.

The remaining blue water indices are represented by either water withdrawal or water consumption. Water use is frequently represented by water withdrawals, as these data are measurable and readily available. However, a portion of water withdrawal for production activities can be returned to the water source, and should not be ignored. Therefore, using withdrawals as water use may overstate water shortages. Consumption-based metrics were developed to account for net water use. The concept of "water footprint" (Chapagain and Hoekstra 2004, Hoekstra *et al.* 2011) measures the volume of water consumed (consumptive water use) during the entire production cycle of a product in a region. Available blue water resources have been defined as annual surface runoff (or, sometimes, stream flow), with water storage (lakes, reservoirs, etc.) as an optional supply.

Long-term observation data for surface runoff are not always available, so many studies utilized simulated runoff data obtained from hydrological models, such as the LPjmL model (Bondeau *et al.* 2007) and the WaterGAP model (Hunger and Döll 2008). Roy et al. (2012)

proposed a simpler high-level mass-balance approach to calculate available blue water as the difference between precipitation (P) and potential evapotranspiration (PET). PET was estimated using the Hamon method.

2.1.1 Blue Water Indices Based on Per Capita Water Resources

The Falkenmark indicator and its thresholds (Falkenmark 1989)

The Falkenmark indicator (Falkenmark 1989) is one of the most widely used measures of water stress. The indicator measures the number of people competing for a unit flow (cap 10^6 $m^{-3}year^{-1}$), or inverted, per capita availability (m^3 cap^{-1} $year^{-1}$). The latter is more commonly used in the literature. It compares per capita share of total annual runoff calculated by Equation 2.1 to a set of predefined thresholds of water stress status (Table 2). The indicator focuses on basic human water needs and surface water runoff sources and directly relates water stress status to population size.

$$\text{Falkenmark indicator} = \frac{Annual\ Runoff}{Population\ size} \qquad \text{(Eq. 2.1)}$$

TABLE 2 Classification of the Falkenmark indicator

Category	Index (m^3 cap^{-1} $year^{-1}$)
No stress	>1,700
Stress	1,000–1,700
Scarcity	500–1,000
Absolute scarcity	<500

Fixed diet and catchment-scale water availability with Falkenmark thresholds

Rockström et al. (2009) estimated that a 1,300 m^3 cap^{-1} $year^{-1}$ water supply, including both green and blue water resources, is required to produce a standard diet (Falkenmark and Rockström 2004), assuming 3000 kcal per capita per day, of which 20% is animal protein. The standard diet is assumed for all populations in the world. Blue water availability is defined as the sum of blue water available in rivers B_R (runoff), in lakes and reservoirs B_L (storage), and in groundwater B_G (storage), multiplied by a factor of 0.7 to account for a predetermined environmental flow requirement (EFR) of 30%.

Blue water availability (BWA) = (B_R+ B_L + B_G) * 0.7
Green water availability (GWA) = evapotranspiration (ET) from cropland and permanent pasture
The sum of water availability (GWBWA) = BWA + GWA

GWBWA, together with the human water requirement for a standard diet, is then used to calculate a Green-Blue Water Shortage Index (GBWSI) (Equation 2.2). In addition to GBWSI, Blue Water Shortage Index (BWSI) and Green Water Shortage Index (GWSI) were also defined as Equations 2.3 and 2.4, respectively. Rockström et al. (2009) classified the water stress or shortage status of a region by comparing GBWSI, GWSI and BWSI to a combination of blue and green water thresholds (Table 3).

$$\text{GBWSI} = \frac{GWBWA\ of\ a\ country}{\text{population of that country}} \qquad \text{(Eq. 2.2)}$$

$$\text{BWSI} = \frac{BWA\ of\ a\ country}{\text{population of that country}} \qquad \text{(Eq. 2.3)}$$

$$\text{GWSI} = \frac{GWA\ of\ a\ country}{\text{population of that country}} \qquad \text{(Eq. 2.4)}$$

TABLE 3 Classification of green-blue water stress/shortage status

Category	Index (m^3 cap^{-1} year^{-1})
Total water shortage	GBWSI< 1,300
Green water freedom under blue water shortage	GBWSI> 1,300 and BWSI< 1,700
Green water freedom under chronic blue water shortage	GBWSI> 1,300 and BWSI< 1,000
Blue and green water freedom	BWSI> 1,700 and GWSI> 6,00
Green water shortage	GWSI< 600
Blue water freedom under green water shortage	BWSI> 1,700 and GWSI< 6,00

Variable standard diet and catchment-scale water availability (Gerten et al.)

Instead of using the same threshold (1,300 m^3 cap^{-1} year^{-1}) for all countries, Gerten et al. (2011) calculated the amount of water required to produce the standard diet mentioned above for each country individually, to account for regional differences. The Green-Blue Water (GWBW) Scarcity Index (Equation 2.5) for a country was defined as the ratio of total GWBW availability (Equation 2.6) to the total amount of water required to produce the standard diet in each country. The latter was simulated using the LPJmL model. In this method, blue water resource is defined as 40% of total runoff in a catchment, assuming that 60% of the runoff is allocated to environmental requirements, such as runoff discharges needed to maintain aquatic habits. Green water resource is defined as ET from cropland and grazing land. Gerten *et al*. (2011) did not break down the Scarcity Index into different categories (e.g., high or low scarcity).

GWBW Scarcity Index for a country =

$$\frac{\boldsymbol{GWBW\ availability\ of\ a\ country}}{\boldsymbol{Water\ requirement\ for\ producing\ standard\ diet\ for\ the\ country}} \qquad \text{(Eq. 2.5)}$$

$$\text{GWBW availability} = \frac{\sum BWA_b + GWA_b}{Population\ size}, \qquad \text{(Eq. 2.6)}$$

where

GWA_b	=	green water resource in basin b,
BWA_b	=	$0.4 * R_b$,
R_b	=	total runoff in basin b, and
Population size	=	number of people living in a country.

Variable diet and catchment-scale water availability with climate threshold (Kummu et al.)
Using the GWBW Scarcity Index developed by Gerten et al. (2011) (Equation 2.5), Kummu et al. (2014) calculated the status of water scarcity by country for each of the 30 years from 1977 to 2006 to take climatic variability into consideration. By measuring the frequency with which an area falls below a country's threshold value (water requirement for producing the standard diet) over the 30-year period, a country's water scarcity status can be classified as shown in Table 4. Notice that per capita water requirement for producing the standard diet varies by country, as assumed by Gerten et al. (2011).

TABLE 4 Classification of water scarcity status by climate-based water stress frequency

Category	Index
No scarcity	0% of the years
Sporadic scarcity	1–25% of the years
Medium frequent scarcity	25–50% of the years
Highly frequent scarcity	50–75% of the years
Recurrent scarcity	75–99% of the years

2.1.2 Indices Based on Water Withdrawals

Water Stress Index (Vörösmarty et al.)
The original Water Stress Index (WSI), developed by Vörösmarty *et al.* (2005), is also called the Index of Local Relative Water Use. It is formulated as

$$\boldsymbol{WSI = \frac{DIA}{Q}} \quad , \qquad \text{(Eq. 2.7)}$$

where **D, I,** and **A** stand for water withdrawals for the domestic, industrial, and agricultural sectors, respectively, and **Q** refers to river corridor discharge (discharge accumulated along the river network). This index considers the withdrawal-to-availability resource ratio (WTA ratio) by including regional total water withdrawals and stream water flow. This method divides a study area into regular grids, and WSI is calculated for each grid.

The ratios were adopted from previous studies (Raskin *et al.* 1997). Water stress begins when withdrawals rise above 10% of **Q**. Therefore, it assumed that if WSI is greater than 0.2, then water stress can be a limiting factor for economic growth. When WSI is greater than 0.4, water stress is considered high (Table 5).

TABLE 5 Classification of Water Stress Index values (Raskin *et al.* 1997)

Category	Index
Low	<0.1
Moderate	0.1–0.2
Medium	0.2–0.4
High	>0.4

Water Stress Index (Pfister et al.)

The WSI of Pfister *et al.* (2009) is a variation of the original WSI (WTA ratio):

$$\boldsymbol{WSI = \frac{1}{1+e^{-6.4WTA\left(\frac{1}{0.01}-1\right)}}} \qquad \text{(Eq. 2.8)}$$

$$WTA = \begin{cases} \sqrt{VF} * WTA \; for \; SRF \\ VF * WTA \;\; for \; non \; SRF \end{cases}$$

First, a variance control factor (VF) was used to take climatic variability into consideration. Second, stream flow was classified as strongly regulated (SRF) or non-SRF on the basis of the river fragmentation (RF) ratio. If RF>50%, then flow in a watershed was considered as SRF. RF can be calculated as the ratio of the upstream river length of the nearest upstream reservoir of a subbasin outlet to the total upstream river length of a subbasin outlet (Scherer *et al.* 2015). Since WTA is multiplied by VF, it is no longer bounded by 0 and 1, so a logistic function is adjusted for each watershed on the basis of WTA ratios. The resulted WSI ranges from 0.1 to 0.99, where 0.5 corresponds to the 0.4 threshold for the WTA ratio.

Water Supply Stress Index (Sun et al., Averyt et al.)

The Water Supply Stress Index (WaSSI) was developed by Sun *et al.* (2008) to evaluate water stress conditions in the U.S. at the HUC-8 level:

$$\boldsymbol{WaSSI = \frac{WD}{WS}} \;\;, \qquad \text{(Eq. 2.9)}$$

where

WD (water demand) = sum of water use (withdrawals) + public use, and
WS (water supply volume in m^3) = predicted surface runoff + groundwater supply+ return flow.

WaSSI ranges from 0 to +∞. A WaSSI greater than 1.0 means that water use exceeds water availability in that watershed, and water transfer from neighboring watersheds is needed. Sun *et al.* (2008) suggested that WaSSI should not be used to directly compare water stress status among HUCs. Rather, they normalized the WaSSI for each HUC using its frequency distribution over 100 years, and classified the WaSSI into six categories based on percentiles (Table 6).

TABLE 6 Classification of Water Supply Stress Index values based on frequency distribution (Sun *et al.* 2008)

Category	Index
Normal	>30th–100th percentile
Abnormally stressed	20th–30th percentile
Moderate	10th–20th percentile
Severe	5th–10th percentile
Extreme	2nd–5th percentile
Exceptional	0th–2nd percentile

The Sectoral Water Supply Stress Index ($WaSSI_{i,s}$) of Averyt *et al.* (2013) is a modified version of the WaSSI; it calculates water stress index by different sectors (**s**) for each watershed (**i**) and includes groundwater.

$$\boldsymbol{WaSSI_{i,s} = \frac{WD_{i,s}}{SW_i + GW_i}} \qquad \text{(Eq. 2.10)}$$

In this index, return flow is no longer included in the equation. $\mathbf{SW_i}$ is watershed *i's* annual surface flows (1999–2007), including upstream input, and $\mathbf{GW_i}$ is watershed *i's* groundwater supply, based on reported 2005 groundwater withdrawal rates from the U.S. Geological Survey (USGS). Averyt *et al.* (2013) did not provide thresholds to classify sector-based WaSSI.

Water Stress Index with environmental water requirement (Smakhtin et al.)

The method described by Smakhtin *et al.* (2005) attempts to consider the surface water available for withdrawals while meeting environmental water requirements (i.e. the volume of water needed for the maintenance of freshwater ecosystem functions).

$$\boldsymbol{WSI = \frac{withdrawals}{MAR - EWR}} \quad , \qquad \text{(Eq. 2.11)}$$

where MAR and EWR refer to mean annual runoff and environmental water requirement, respectively. Smakhtin et al. (2005) estimated that EWR ranges from 0.2 to 0.4 globally. This WSI demarcates water stress by a set of thresholds listed in Table.7.

TABLE 7 Classification of Water Stress Index values (Smakhtin *et al.* 2005)

Category	Index
Slightly exploited	<0.3
Moderately exploited	0.3–0.6
Heavily exploited	0.6–1.0
Overexploited	>1.0

2.1.3 Indices Based on Water Consumption

Stream flow-based index (Tidwell et al.)
Tidwell et al. (2012) developed a stream flow-based Surface Water Availability Index formulated as

$$\boldsymbol{WA_s = \frac{CU_w + CU_u}{CU_w + CU_u + Q_A}} \quad , \qquad \text{(Eq. 2.12)}$$

where CU_W and CU_u refer to consumptive use within the basin and consumptive use upstream of the basin, respectively. Q_A is defined as the 20^{th} percentile of gauged daily stream flow, or that flow which is exceeded 80% of the time for the period of record (the length of the record period varies by watershed). Key percentiles (e.g., 20, 40) of daily flow at the HUC-6 level were obtained from the USGS (Stewart *et al.* 2006).

Stream flow and groundwater recharge-based index and threshold (Brauman et al.)
Brauman et al. (2016) defined the Water Depletion Index as the ratio of total water consumption to renewable blue water resources:

$$\boldsymbol{Water\ depletion} = \frac{Water\ consumption}{renewable\ blue\ water} \qquad \text{(Eq. 2.13)}$$

In their study, the renewable blue water resource is defined as runoff + groundwater recharge, where water consumption for multiple sectors (e.g., domestic, agricultural) and average annual renewable blue water resources were both simulated using the WaterGAP 3 model. A grid-based water balance model implemented in the WaterGAP 3 model generated long-term average runoff (1971–2000) for each grid. Runoff from grids in a catchment was routed to the catchment outlet to calculate runoff for each catchment. The WaterGAP 3 model also has a simple groundwater module that simulates groundwater recharging as a fraction of the surface runoff. Unlike surface runoff, there is no groundwater flow between grid cells. A threshold of 0.75 was recommended to identify regions with water depletion problems.

Runoff-based index (Moore et al.)
Moore et al. (2015) defined the Water Scarcity Index as the ratio of water consumption to available runoff:

$$\boldsymbol{Water_{scarcity}} = \frac{\boldsymbol{consumptive\ water\ use}}{\boldsymbol{runoff}} \qquad \text{(Eq. 2.14)}$$

Consumptive water use for all sectors was collected from USGS water use data for 1985, 1990, 1995, and 2000. Runoff refers to upstream accumulated runoff for each 1/8° grid within a given HUC-8 basin. They disaggregated estimated long-term average monthly runoff (1980 to 2000) at the HUC-8 level (Brakebill *et al.* 2011) to the 1/8° grid. Water scarcity for each grid was computed and categorized as unstressed, stressed, or scarce (Table 8). According to Brakebill *et al.* (2011), original runoff data were calculated by dividing observed flow value (e.g., cfs) by areal size of catchments and then converted to annual runoff values (mm*yr-1).

TABLE 8 Classification of Water Scarcity Index values (Moore *et al.* 2015)

Category	Index
Unstressed	<0.2
Stressed	0.2–0.4
Scarce	≥0.4

Runoff and environmental flow requirement-based index and threshold (Hoekstra et al.)
The Blue Water Scarcity Index $\boldsymbol{WS_{blue}}$ of Hoekstra et al. (2011) is formulated as

$$\boldsymbol{WS_{blue}[x,t]} = \frac{\sum \boldsymbol{WF_{blue}[x,t]}}{\boldsymbol{WA_{blue}[x,t]}} \qquad \text{(Eq. 2.15)}$$

$$\boldsymbol{WA_{blue}[x,t]} = \boldsymbol{R_{nat}[x,t]} - \boldsymbol{EFR[x,t]} \qquad \left[\frac{volume}{time}\right], \qquad \text{(Eq. 2.16)}$$

where WF_{blue} refers to the blue water footprint and WA_{blue} refers to the available blue water resource, which is the difference between natural runoff ($\mathbf{R_{nat}}$) and EFR. Natural runoff was defined as the sum of actual runoff and the total blue water footprint within the river basin (Hoekstra *et al.* 2012). It is suggested that the EFR should account for 80% of the mean annual natural flow. The $\boldsymbol{WS}_{blue}$ values 1.0 and 2.0 are used as the thresholds between low and high water stress areas, respectively (Table 9).

TABLE 9 Classification of Blue Water Scarcity Index values (Hoekstra *et al.* 2011)

Category	Index
Low stress	<1.0
Moderate stress	1.0–1.5
Medium stress	1.5–2.0
High stress	>2.0

Non-renewable water resource-based index (Wada)

The Blue Water Supply Stress Index (***BlWSI***) (Wada 2013) measures the fraction of consumptive blue water use that comes from nonsustainable water resources:

$$\boldsymbol{BlWSI} = \frac{\sum_{i=1}^{N}(\boldsymbol{NRGW_{A,i}}+\boldsymbol{SW_{OA,i}})}{\sum_{i=1}^{N}\boldsymbol{CBWU_i}} \quad \text{(Eq. 2.17)}$$

$$\boldsymbol{NRGW_{A,i}} = \max[0, GW_{A,i} - (GWR_{Nat,i} + GWR_{Irr,i})] \quad \text{(Eq. 2.18)}$$

$$\boldsymbol{SW_{OA,i}} = \begin{cases} 0 & (Q_{out,i} \geq Q_{Env,i}) \\ \max(0, Q_{out,i} - Q_{Env,i}) & (Q_{out,i} \geq Q_{Env,i}\ and\ Q_{out,i} < Q_{Env,i}) \\ \max(0, Q_{In,i} - Q_{out,i}) & (Q_{out,i} \leq Q_{Env,i}\ and\ Q_{out,i} < Q_{Env,i}) \end{cases}, \quad \text{(Eq. 2.19)}$$

where

$NRGW_{A,i}$ = non-renewable groundwater abstraction in grid *i*, as calculated in Equation (2.18);
$SW_{OA,i}$ = surface water overabstraction, or the deficit in surface water flow requirement due to consumption in catchment *i*, as calculated in Equation (2.19);
$CBWU$ = the sum of agricultural, industrial, and domestic water consumption in grid *i*;
$GW_{A,i}$ = groundwater abstraction in grid *i*;
$GWR_{Nat,i}$ = natural groundwater recharge in grid *i;*
$GWR_{Irr,i}$ = additional recharge from irrigation return flow in grid *i*;
$Q_{Env,i}$ = EFRs in grid *i*;
$Q_{In,i}$ = inflow to grid *i*.; and
$Q_{Out,i}$ = outflow from grid *i*.

The EFR in this study was set to Q_{90}, or the monthly flow that is exceeded during 90% of the record period (1960–2010). Wada (2013) applied this indicator globally at grid scale (0.5^{O}), and then aggregated grid-level results to the basin scale.

Relative regional water stress (Boulay et al.)
The AWARE Index of Boulay et al. (2016) is formulated as follows:

$$\boldsymbol{AWARE = water\ consumption * CF} \qquad \text{(Eq. 2.20)}$$

$$\boldsymbol{CF} = \frac{World\ mean\ unused\ water\ remaining}{Regional\ unused\ water\ remaining}\ , \qquad \text{(Eq. 2.21)}$$

where CF is the inverse of unused water remaining normalized to the reference flow of the worldwide weighted value. Unused water remaining is the difference between blue water availability and demand. The latter includes both human demand and aquatic ecosystem requirements. The indicator aimed to assess the potential for depriving other users (humans or ecosystems) of water when consuming water in a given area. CF was developed to measure relative user deprivation potential. In other words, water consumption in areas with more abundant water resources may have less impact on other users, and thus lower environmental impacts.

2.1.4 Composite Indices

Composite indices integrate multiple factors into a single metric. This type of metric can be more comprehensive, but detailed data requirements can be a challenge for large-scale studies.

Water Supply Sustainability Risk Index (Roy et al.)
Roy et al. (2012) developed a Water Supply Sustainability Risk Index (WSSRI), whose value is calculated as the sum of five criteria values:

$$\boldsymbol{WSSRI = \sum_{i=1}^{5} criteria_i} \qquad \text{(Eq. 2.22)}$$

The five criteria are shown in Table 10. Each criterion is scored as 1 if the value for a given country meets or exceeds the threshold for that criterion; otherwise, 0 is assigned. The total value of WSSRI therefore can range from 0 to 5, with a higher value signifying higher risk (Table 11).

TABLE 10 The five criteria used in the Water Supply Sustainability Risk Index calculation (Roy *et al.* 2012)

Criterion	Criteria threshold
#1 Available precipitation	Available precipitation (defined as precipitation minus PET) is greater than 25%.
#2 Susceptibility to drought	Summer deficit is greater than 10 in. Summer deficit is defined as the difference between available precipitation and withdrawal in June, July and August.
#3 Growth in water withdrawal	Total freshwater withdrawal increases by more than 20% from 2005 to 2050.
#4 Increased need for storage	Summer deficit increases by more than 1 in. from 2005 to 2050.
#5 Groundwater use	Groundwater withdrawal as a fraction of total withdrawal is greater than 25%.

TABLE 11 Classification of Water Supply Sustainability Risk Index values (Roy *et al.* 2012)

Category	Index
Low risk	<2
Moderate risk	2
High risk	3
Extreme risk	≥4

Watershed Sustainability Index (Chaves and Alipaz)

The Watershed Sustainability Index (WSI) of Chaves and Alipaz (2007) is the mean value of four indicators:

$$\boldsymbol{WSI = \frac{H+E+L+P}{4}} \quad , \qquad \text{(Eq. 2.22)}$$

where H, E, L, and P refer to hydrological indicator, environmental indicator, life indicator, and policy indicator, respectively. The value of WSI ranges from 0 to 1, with higher values meaning a higher sustainability status (Table 12). Each indicator is determined from a set of parameters divided into three levels: pressure, state and response. At each level, a given indicator (e.g., H) receives one of five scores (0, 0.25, 0.5, 0.75, or 1.0) based on predefined thresholds (Tables 13–15). The final score for an indicator (e.g., H) is the average of scores obtained at these three levels, ranging from 0 to 1.

TABLE 12 Classification of Watershed Sustainability Index values (Chaves and Alipaz 2007)

Category	Index
Low	<0.5
Intermediate	0.5–0. 8
High	>0.8

TABLE 13 Description of pressure level parameters for the Watershed Sustainability Index (Chaves and Alipaz 2007)

Indicator	Pressure parameters	Threshold	Score
Hydrology	Δ1: Variation in per capita water availability (m^3 $cap^{-1}yr$) in the basin (1996–2000)	Δ1 ≤ –20%	0
		–20%<Δ1≤ –10%	0.25
		–10%<Δ1≤ 0%	0.5
		0%<Δ1≤ +10%	0.75
		Δ1> +10%	1.0
	Δ2: Variation in the basin's biological oxygen demand (BOD) (1996–2000)	Δ2 ≥ 20%	0
		10%≤Δ2< 20%	0.25
		0%≤Δ2< 10%	0.5
		–10%≤Δ2< 0%	0.75
		Δ2< –10%	1.0
Environment	Δ: Variation in Environment Pressure Index (EPI)[1] (rural and urban) (1996–2000)	Δ≥ 20%	0
		10%≤Δ< 20%	0.25
		5%≤Δ< 10%	0.5
		0%≤Δ< 5%	0.75
		Δ< 0%	1.0
Life	Δ: Variation in per capita income in the basin (1996–2000)	Δ≤ –20%	0
		–20%<Δ≤ –10%	0.25
		–10%<Δ≤ 0%	0.5
		0%<Δ≤ +10%	0.75
		Δ> +10%	1.0
Policy	Δ: Variation in Human Development Index (HDI)-Education[2] (1996–2000)	Δ≤ –20%	0
		–20%<Δ≤ –10%	0.25
		–10%<Δ≤ 0%	0.5
		0%<Δ≤ +10%	0.75
		Δ> +10%	1.0

1: EPI = (% variation of basin agriculture area + % variation of basin urban population)/2
2: HDI is a composite index based on life expectancy, education, and per capita income. HDI-Education is the basin's HDI education sub-indicator.

TABLE 14 Description of state level parameters for the Watershed Sustainability Index (Chaves and Alipaz 2007)

Indicator	State level parameters	Threshold	Score
Hydrology	Long-term (duration was not specified) average per capita water availability (m^3 $cap^{-1}yr$)	Very poor (<1,700 m^3 $cap^{-1}yr$)	0
		Poor (1,700–3,400 m^3 $cap^{-1}yr$)	0.25
		Medium (3,400–5,100 m^3 $cap^{-1}yr$)	0.5
		Good (5100–6800 m^3 $cap^{-1}yr$)	0.75
		Excellent (>6800 m^3 $cap^{-1}yr$)	1.0
	Long-term basin average Biochemical Oxygen Demand (BOD_5) (mg/l)	>10	0
		5–10	0.25
		3–5	0.5
		1–3	0.75
		<1	1.0
Environment	% of basin area with natural vegetation	<5	0
		5–10	0.25
		10–25	0.5
		25–40	0.75
		>40	1.0
Life	Basin HDI weighted by county population	<0.5	0
		0.5–0.6	0.25
		0.6–0.75	0.5
		0.75–0.9	0.75
		>0.9	1.0
Policy	Institutional capacity in integrated water resources management (IWRM)	Very poor	0
		Poor	0.25
		Medium	0.5
		Good	0.75
		Excellent	1.0

TABLE 15 Description of response level parameters for the Watershed Sustainability Index (Chaves and Alipaz 2007)

Indicator	Response level parameters	Threshold	Score
Hydrology	Improvement in water-use efficiency between 1996 and 2000	Very poor	0
		Poor	0.25
		Medium	0.5
		Good	0.75
		Excellent	1.0
	Improvement in sewage treatment between 1996 and 2000	Very poor	0
		Poor	0.25
		Medium	0.5
		Good	0.75
		Excellent	1.0
Environment	Δ: Variation in basin conservation (protected areas and conservation practices) between 1996 and 2000	Δ≤ –10%	0
		–10%<Δ≤ 0%	0.25
		0%<Δ≤ +10%	0.5
		+10%<Δ≤ +20%	0.75
		Δ> +20%	1.0
Life	Δ: Variation in HDI of the basin between 1996 and 2000	Δ≤ –10%	0
		–10%<Δ≤ 0%	0.25
		0%<Δ≤ +10%	0.5
		+10%<Δ≤ +20%	0.75
		Δ> +20%	1.0
Policy	Δ: Variation in the basin's IWRM expenditures between 1996 and 2000	Δ≤ –10%	0
		–10%<Δ≤ 0%	0.25
		0%<Δ≤ +10%	0.5
		+10%<Δ≤ +20%	0.75
		Δ> +20%	1.0

2.2 GREEN WATER INDEX OVERVIEW

While a variety of water availability metrics have been developed for blue water, analysis of green water scarcity is largely unexplored (Hoekstra *et al.* 2011). Previous studies on green water analysis predominantly define green water flow as ET from agriculture land, less the portion of ET originating from blue water resources (irrigation). There is less agreement among researchers on the definition of "green water availability." Rockström *et al.* (2009) define green water availability as total ET from cropland and grazing land. This definition links green water supply to the spatial extent of agricultural land. Hoekstra *et al.* (2011) define green water availability as total ET from a catchment, less ET from unproductive land and preserved natural land. This definition is more comprehensive, but it is hard to determine which part of the catchment should be reserved for the environmental purpose. Studies typically estimate green water resources using hydrological models, such as the CROPWAT (Allen *et al.* 1998), LPJmL (Bondeau *et al.* 2007), SWAT (Arnold *et al.* 1998), and G-EPIC (Liu and Yang 2010) models. Another approach is using effective rainfall as a proxy for green water resource (Núñez *et al.* 2013). Since effective rainfall can be estimated from climate data using empirical methods, it is straightforward to estimate green water availability for a specific site.

2.2.1 Indices Based on Population

Several studies compared per capita share of annual blue and green water supply to the amount of water required to produce a standard diet (Rockström *et al.* 2009, Gerten *et al.* 2011, Kummu *et al.* 2014) to determine the water stress status of a country. See section 2.1.1 above for more details.

2.2.2 Indices Based on Actual and Potential Evapotranspiration

Green Water Stress Index (Wada)

Wada (2013) formulated a Green Water Stress Index (GrWSI) as follows:

$$\boldsymbol{GrWSI} = \frac{\boldsymbol{AET/PET}}{(\overline{\boldsymbol{AET}}/\overline{\boldsymbol{PET}})} \qquad \text{(Eq. 2.23)}$$

where AET and PET refer to actual and potential ET, respectively. $\overline{AET}$ and $\overline{PET}$ refer to long-term (1960–2010) average actual and potential ET, respectively. This index contrasts the ratio of AET/PET with the long-term average to identify the relative availability or stress of soil moisture.

Transpiration efficiency (Rockström et al.)

Rockström *et al.* (2009) defined transpiration efficiency as the ratio between productive green water flow (i.e., transpiration, T) and total green water availability (i.e., ET from cropland and permanent pasture):

$$efficiency = \frac{Transpiration}{ET\ from\ cropland\ and\ pasture} \qquad \text{(Eq. 2.24)}$$

They suggested that countries should try to increase the share of productive green water flow to improve green water productivity.

2.2.3 Index Based on Effective Precipitation

Green Water Scarcity Index (Núñez et al.)

The Green Water Scarcity Index (GWSI) of Núñez *et al.* (2013) measures the ratio between green water footprint (GW) of a 3-year crop rotation (in m^3 m^{-2} $rotation^{-1}$) and the effective precipitation (Pr, in m^3 m^{-2} $rotation^{-1}$) for the same period:

$$GWSI = \frac{GW}{Pr} \quad \text{(Eq. 2.25)}$$

The monthly GW was calculated as the minimum of crop ET and effective precipitation. According to Núñez *et al.* (2013), GWSI is a measurement of "aridity stress" where crops grow. GWSI ranges between 0 and 1, with 1 meaning all effective rainfall is consumed. The index focuses on agricultural consumptive water use.

2.2.4 Index Based on Environmental Water Requirement

Green Water Scarcity Index (Hoekstra et al.)

Hoekstra *et al.* (2011) formulated a Green Water Scarcity Index (WS_{green}) as follows:

$$WS_{green}[x,t] = \frac{\sum WF_{green}[x,t]}{WA_{green}[x,t]} \quad \text{(Eq. 2.26)}$$

$$WA_{green} = ET_{green} - ET_{env} - ET_{unprod} \quad \text{(Eq. 2.27)}$$

WS_{green} measures the ratio between green water footprint and green water resource. WF_{green} and WA_{green} refer to green water footprint and available green water resource, respectively. The latter is defined as total ET within a catchment (ET_{green}) , less ET reserved natural vegetation (ET_{env}) and ET that cannot be made productive in crop production (ET_{unprod}).

3 DISCUSSION AND CONCLUSIONS

3.1 WATER SCARCITY, WATER STRESS, AND WATER AVAILABILITY

"Water scarcity," "water availability," and "water stress" have been used interchangeably in the literature to either label a metric or describe water resource problems. In many cases, these three terms were used in studies without a clear definition. Clarification of the scope and meaning of key terminology is important for making water availability indices comparable. While the meaning of scarcity may sound straightforward in certain contexts, measures and the definition of water scarcity are contested (Rijsberman 2006). Taking the meaning of "water scarcity" as an example, a substantial number of definitions of this term can be found in the literature (Raskin *et al.* 1997, Rijsberman 2006, Kounina *et al.* 2012, ISO 14046 2014).

The term "water scarcity" can also be categorized into several groups by different criteria. One of the criteria is to differentiate measurements based on per capita water availability vs. use-to-availability ratios. Falkenmark (1998) called the former "demographic water scarcity" and the latter "technical water scarcity," but Kounina *et al.*(2012) suggested that water resource per capita reflects socio-economic situations, rather than physical water scarcity. The "absolute scarcity" versus "relative scarcity" classification proposed by Schyns et al. (2015) provides a different perspective. "Absolute scarcity" refers to situations where elementary needs cannot be satisfied, and "relative scarcity" means "scarcity" caused by competing demands from multiple economic sectors. From these definitions, we can conclude that "water scarcity" describes the relationship between human activities and natural water supply. When we talk about "scarcity," it is at least necessary to distinguish "basic or elementary human needs" from "total water demands."

There are few discussions of the difference between "water scarcity" and "water stress" or "water availability." "Water stress" has frequently been defined as the ratio of water withdrawals to water availability (Raskin *et al.* 1997, Pfister *et al.* 2009). Rockström *et al.*(2009) suggested that "water scarcity" is a general term when water is scarce for any reason, while "water stress" refers to situations where water use is limited because of accessibility problems (e.g., infrastructure). Still, some studies (Boulay *et al.* 2015, 2016) consider that the two terms share the same meaning.

Among the three terms, "water scarcity" is more frequently used in the literature, probably because "scarcity" implicitly suggests a concern that water supplies may not be sufficient to meet increasing water demand. "Water availability," on the other hand, may be relatively more "neutral" because the name itself does not signal a warning message.

3.2 AVAILABLE WATER RESOURCE

Identifying which portion of the freshwater resource is available for human use is always a complex issue, because water is not a static resource, but exists in very dynamic cycles of rain, runoff, and evaporation (Rijsberman 2006). Therefore, to describe "available water resource," we need to draw a system boundary. For blue water, most studies define available blue water resource as "renewable surface water" such as runoff and stream flow, with groundwater recharge as an optional component. Spatially, "renewable surface water" resources defined in previous studies may include runoff generated within the watershed only (Roy *et al.* 2012), or more commonly with inflows from upstream watersheds (Vörösmarty *et al.* 2005, Sun *et al.* 2008). Because river discharge will be reduced by upstream water consumption, upstream input is the "unused" part of blue water accumulated along the river network. This "unused upstream input" is subject to changes in upstream consumption. This is not a problem for describing the current demand-to-supply relationship, but the problem interdependency can be a challenge for future scenario analysis, since any change in an upstream watershed will affect upstream input of all downstream watersheds. For green water analysis, interdependency is not a concern, since soil moisture can only be utilized locally for plant growth.

Compared to runoff or stream flow, groundwater resources are less frequently included in water availability indicators. For assessment of blue water resources, ignoring groundwater supply could be a problem because groundwater supplies one-third of the world's population (Raskin *et al.* 1997). Globally, groundwater contributes about 43% of consumptive irrigation water use (Siebert *et al.* 2010). Overuse of groundwater has led to depletion of this valuable resource in many parts of the world (Wada *et al.* 2010). Still, many studies (Moore *et al.* 2015, Roy *et al.* 2012, Mekonnen and Hoekstra 2016) do not include this component as available water resources, probably because data on consistent estimates of groundwater recharging rate, i.e., "renewable groundwater," for a large study area, such as a country, often do not exist. Some studies use hydrological models such as the WaterGAP 3 model to estimate groundwater recharge, but validation can be difficult, since observational data on groundwater recharge are often not available.

So far, we have discussed physically available water resources. Available water supply may be limited by other factors, such as infrastructure capacity (Rijsberman 2006) and water appropriation regulations (Averyt *et al.* 2013). The underlying reason for water scarcity varies from region to region, and physically based metrics may not be the most relevant for certain regions. However, detailed discussion of water scarcity caused by socio-economic factors is beyond the scope of this review.

3.3 USE-TO-RESOURCE RATIO

For indicators based on use-to-resource ratio, a threshold of 20% or 40% is frequently used to demarcate medium or high water stress status (Raskin *et al.* 1997, Vörösmarty *et al.* 2005, Rijsberman 2006, Moore *et al.* 2015). Similar thresholds for green water indicators do not exist. The 40% threshold is also known as the critical ratio (Alcamo *et al.* 2000). This critical ratio (0.4) is often used as a reference without explaining the underlying rationale. Initially, 40% was selected as a critical ratio because a country can only capture about 1/3 of the annual flow using existing infrastructure likes dams and pipes (Raskin *et al.* 1997). However, this ratio is based on estimations of abstraction capacity that were made several decades ago. Therefore, the reliability of the critical ratio is under question.

Interestingly, the 20%/40% threshold-based WTA ratio is now used widely in other contexts (Brauman *et al.* 2016), including evaluations of consumption-to-availability ratios (Moore *et al.* 2015, Hoekstra *et al.* 2012). Given that WTA and CTA ratios can be very different for the same region, using critical ratios as a proxy for CTA ratios is likely inappropriate. If critical ratio is to be used, studies need to address the difference between CTA and WTA ratios.

3.4 INTEGRATION OF BLUE AND GREEN WATER INDICATORS

Defining commonly accepted blue and green water scarcity or availability indicators would be a helpful first step toward making results of water assessment studies more comparable, but the integration of these two indicators remains a challenge. For instance, how can we measure the availability of "soil moisture" and "surface runoff" using the same benchmark? The difficulty lies, partly, in accounting for opportunity costs of green versus blue water. Generally speaking, blue water has a higher opportunity cost than green water because blue water can be utilized by multiple competing sectors, while green water is only naturally available for plants on land. Given the fact that the economic and ecological values of blue water and green water are different (Núñez *et al.* 2013, Ridoutt and Pfister 2010), a direct comparison between blue water and green water availability index values may not be appropriate. However, these two indices can be complementary to each other. For instance, high green water scarcity may lead to an increased irrigation water requirement for an area. Núñez *et al.* (2013) suggested a delta method that considers impacts of marginal changes in green water supply on blue water scarcity. For scenario analysis, they calculated differences in green water footprint (delta change, or dGW) between scenario plants and reference plants (e.g., current crops). They then multiplied the BWSI by dGW to get a weighted dGW value. Still, more studies are needed to integrate blue and green water scarcity indices. For example, one can estimate the opportunity costs of blue versus green water resources to make them comparable economically. Although green water flow is mostly free of charge, the value of the green water supply may be estimated by calculating the cost of blue water needed to compensate for a potential reduction in green water availability.

3.5 DATA AVAILABILITIES AND UNCERTAINITIES

Since measured runoff data are only sparsely available, most studies estimated runoff using hydrological models. Nonetheless, for countries with more abundant observational data, studies have utilized observed stream flow as a proxy for water availability. For example, Tidwell et al. (2012) collected flow data from USGS statistics to measure water availability for selective watersheds in the U.S. Compared to runoff or flow data, groundwater recharge data are more scarce. Some studies (Tidwell *et al.* 2012) use base flow as a proxy, but more researchers use hydrological models to estimate groundwater recharge (Brauman *et al.* 2016, Scanlon *et al.* 2012, Wada *et al.* 2010). Previous studies also suggested that the GRACE satellites might be useful to monitor groundwater resources (e.g., Strassberg *et al.* 2009).

Data on water consumption and water resource are often not available at the same spatial and temporal scale. For water scarcity analysis, researchers have to merge heterogeneous data sets with varying spatial and temporal resolutions. Rainfall, which is the primary source of freshwater supply in many regions, varies significantly inter-annually and intra-annually. To account for temporal variation, normal or long-term (e.g., 30-year) average values are often used. Nonetheless, studies (Moore *et al.* 2015, Roy *et al.* 2012) have suggested that analysis should be performed on a monthly basis, because using annual total consumption/resource rather than monthly data may mask seasonal water shortages. For instance, demands for irrigation typically occur during a few months, rather than throughout the year. In this case, a matching of water supply and demand on a monthly basis might be desired. Since monthly water consumption data are rarely available (Boulay *et al.* 2015), downscaling methods can be employed to disaggregate multi-year average consumption data (e.g., USGS water use data) spatially and temporally (Moore *et al.* 2015, Roy *et al.* 2005).

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APPENDIX: SUMMARY OF WATER AVAILABILITY INDICES

Water Source	Category	Description	Key References	Pros and Cons
Blue water	Water crowding	Compares per capita share of total annual runoff to predefined thresholds (if <1700 m^3 cap^{-1} $year^{-1}$, then water supply is under stress).	Falkenmark indicator (Falkenmark 1989)	**Pros**: provides an easy to use threshold to assess water stress status. **Cons**: focuses on basic human demands; ignores regional difference in per capita water demand and adaption capacities.
		Compares total blue and green water supply (m^3 cap^{-1} $year^{-1}$) to water required to produce the standard diet (3000 calories per day, assuming 20% animal protein).	Rockström *et al.* (2009), Gerten *et al.* (2011)	
	Use-to- resource ratio	The ratio of water withdrawals to water resources. The latter can be defined as total runoff or stream flow, with groundwater and storage water as an optional resource.	1) Water Stress Index (Vörösmarty *et al.* 2005) 2) Water Stress Index (Pfister *et al.* 2009) 3) Water Supply Stress Index (Sun *et al.* 2008, McNulty *et al.* 2010)	**Pros**: uses local demand and supply data to generate critical ratios for each country. **Cons**: ignores water withdrawals that are reused or recycled for other sectors.
		The ratio of net water consumption to water resources. Consumption is different from withdrawal because it considers return flow and recycled water use.	1) Surface Water Availability Index (Tidwell *et al.* 2012) 2) Water Depletion Index (Brauman *et al.* 2016) 3) Water Scarcity Index (Moore *et al.* 2015)	**Pros:** focuses on consumptive water use, rather than gross withdrawals. **Cons:** does not consider environmental water requirement (EWR); is anthropocentric.
		Based on withdrawal/consumption-to-resource ratio, but reduces available water supply by reserving a portion of runoff or stream flow as EWR.	1) Blue Water Scarcity Index (Hoekstra *et al.* 2011) 2) Water Stress Index (Smakhtin *et al.* 2005) 3) Blue Water Supply Stress Index (Wada 2013)	**Pros**: is ecocentric, considers EWR. **Cons**: it is often difficult to determine appropriate EWR for individual regions.
		Instead of counting total water availability, regional water availability is limited to remaining or unappropriated water after current	Available Water Remaining Index (Boulay *et al.* 2016)	**Pros**: uses a single weighting factor to measure the potential of depriving another user of water. **Cons**: does not reflect current overall

Water Source	Category	Description	Key References	Pros and Cons
		human and environmental demand (i.e. water needed to maintain freshwater ecosystems) has been met		water stress; EWR part is hard to determine.
	Composite index	In addition to water demand-to-supply ratio, it also considers criteria such as social-economic factors.	Watershed Sustainability Index (Chaves and Alipaz 2007)	**Pros**: comprehensive. **Cons**: requires extensive data input; may not be straightforward to interpret.
Green water	Water crowding	Compares per capita share of annual green and blue water to water required to achieve food self-sufficiency.	Rockström *et al.* (2009), Gerten *et al.* (2011)	Same as blue water crowding indices.
		For each country, it calculates stress status (degree to which per capita blue and green supply falls below standard diet requirements) for each year and accounts for frequency of stress status over a 30-year period.	Kummu *et al.* (2014)	**Pros**: includes seasonal and temporal changes in green water flow. **Cons:** does not provide a critical ratio to describe average local stress status.
	Variation in evapotranspiration (ET)	Contrasts the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) with long-term average (1960–2010).	Green Water Stress Index (Wada 2013)	
	Use-to- resource ratio	Calculates transpiration efficiency as the ratio of productive ET to AET from cropland and pasture land.	Rockström *et al.* (2009)	**Pros**: quantifies share of productive ET consumed by plants. **Cons**: does not address scarcity issue directly.
		The ratio of crop green water footprint to green water resource, defined as effective rainfall.	Green Water Scarcity Index (Núñez *et al.* 2013)	**Pros**: clear and easy-to-use definitions for demand and supply variables. **Cons**: does not consider environmental requirements.
		The ratio of crop green water footprint to green water resource, defined as total ET from a catchment	Green Water Scarcity Index (Hoekstra *et al.* 2011)	**Pros**: explicitly considers EWR. **Cons**: does not address availability for a particular site, and it is hard to

Water Source	Category	Description	Key References	Pros and Cons
		minus environmental and unproductive ET.		estimate land area that should be protected for nature conservation purposes (e.g. preserving biodiversity)

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