# Authors' Response

Review and classification of indicators of green water availability and scarcity

hess-2015-213

Dear Nadia Ursino,

We are glad that Referee #2 – who originally reviewed our manuscript – is completely satisfied with the revision and accepts the paper as is.

Referee #3 – who has seen the manuscript for the first time after revisions had been made – advises to reject the manuscript based on a referee report of a few sentences with the argumentation that it is not suitable for publication as a research article. Clearly, Referee #3 did not realize that the manuscript is a review article. In our opinion, it should be clear that it is a review article, since it is mentioned in the title, the objective and the scope of the study (section heading 2.5).

To address the second comment by Referee #3, we have added the following sentences in the introduction that explicitly state the relevance of the study:

"In this review, we make an inventory of existing indicators of green water availability and scarcity and classify them based on their scope and purpose of measurement. The classification allows us to discuss similarities and differences between indicators and give advice on how the various indicator classes could be used to measure different kinds of green water availability or scarcity. This is useful in order to properly include limitations in green water availability in water scarcity assessments."

Please see the marked up version of our revised manuscript below.

On behalf of all co-authors,

Your sincerely,

Joep Schyns

Twente Water Centre
University of Twente
Enschede, The Netherlands

# Review and classification of indicators of green water availability and scarcity

**J. F. Schyns[1], A. Y. Hoekstra[1] and M. J. Booij[1]**

[1] Twente Water Centre, University of Twente, Enschede, The Netherlands

Correspondence to: J. F. Schyns (j.f.schyns@utwente.nl)

# Abstract

Research on water scarcity has mainly focused on blue water (surface- and groundwater), but green water (soil moisture returning to the atmosphere through evaporation) is also scarce, because its availability is limited and there are competing demands for green water. Crop production, grazing lands, forestry and terrestrial ecosystems are all sustained by green water. The implicit distribution or explicit allocation of limited green water resources over competitive demands determines which economic and environmental goods and services will be produced and may affect food security and nature conservation. We need to better understand green water scarcity to be able to measure, model, predict and handle it. This paper reviews and classifies around 80 indicators of green water availability and scarcity and discusses the way forward to develop operational green water scarcity indicators that can broaden the scope of water scarcity assessments.

# 1 Introduction

Freshwater is a renewable resource that is naturally replenished over time when moving through the hydrological cycle (Oki and Kanae, 2006;Hoekstra, 2013). Precipitation forms the input of freshwater on land. Subsequently, it takes the blue or the green pathway back to the ocean and atmosphere before eventually returning as precipitation again (Falkenmark, 2003;Falkenmark and Rockström, 2006;Falkenmark and Rockström, 2010). The water that runs off to the ocean via rivers and groundwater is called the blue water flow. The green water flow is formed by the water that is temporarily stored in the soil and on top of vegetation and returns to the atmosphere as evaporation instead of running off (Hoekstra et al., 2011). As suggested by Savenije (2004), we use in this paper the term evaporation (instead of the often used term evapotranspiration) to refer to the vapour flux from land to atmosphere, which includes soil evaporation, evaporation of intercepted water, transpiration and in some cases (e.g. rice or swamp vegetation) open-water evaporation. About three-fifth of the precipitation over land takes the green path and two-fifth the blue path (Oki and Kanae, 2006).

Both blue and green water flows are made productive for human purposes. Blue water is used for industrial and domestic purposes and irrigation in agriculture. Green water sustains crop production, grazing lands, forestry and terrestrial ecosystems (Rockström, 1999;Rockström et al., 1999;Savenije, 2000;Gerten et al., 2005). These systems provide food, fibres, biofuels, timber and livestock products and other ecosystem services humans benefit from (Millennium Ecosystem Assessment, 2005;Gordon et al., 2010).

Although freshwater is renewable, this does not mean that its availability is unlimited. In fact, freshwater is also a finite resource (Hoekstra, 2013). Over a certain period, there falls a certain amount of precipitation. This limits both blue and green water availability in time. Human society cannot appropriate more water than is available. The finiteness of freshwater in combination with the various competing demands for water, makes water a scarce resource.

Water scarcity is becoming increasingly important for multiple reasons. The growing world population leads to rising demands for food, energy and other water-consuming goods and services (Hejazi et al., 2014;WWAP, 2015). Moreover, people’s diets are changing toward more livestock-based products, due to rising incomes and continuing urbanization (Molden, 2007). Such diets are more water and land intensive (Erb et al., 2009;Kastner et al., 2012;Odegard and van der Voet, 2014). Policies towards more energy production from biomass create additional pressure on water and land (Hejazi et al., 2014). On top of this, a changing climate with increased variability and more extremes (IPCC, 2013) amplifies water scarcity (WWAP, 2014).

Given that green and blue water resources are limited and there are competing demands for both, green water as well as blue water are scarce. Therefore, it is surprising that research and debate on water scarcity have been, and still are, mainly focused on blue water (Vörösmarty et al., 2000;Rijsberman, 2006;Vörösmarty et al., 2010;Wada et al., 2011;Hoekstra et al., 2012;WWAP, 2014, 2015). Although the importance of green water has increasingly gained acceptance since Falkenmark (1995) drew attention to it in the mid-1990s (Savenije, 2000;Rockström, 2001;Rijsberman, 2006;Liu et al., 2009;Hanasaki et al., 2010;Hoekstra and Mekonnen, 2012), the notion of green water scarcity is only limitedly addressed in literature (Falkenmark, 2013a, b;Falkenmark et al., 2007). While the need to incorporate green water in water scarcity indicators and assessments has already been expressed since the beginning of this millennium (Savenije, 2000;Rockström, 2001;Rijsberman, 2006;Falkenmark and Rockström, 2006), only a few attempts have been made so far in the form of combined green-blue water scarcity assessments (Rockström et al., 2009;Gerten et al., 2011;Kummu et al., 2014) (discussed in detail in Sect. 3.2).

Green water scarcity refers to the competition over limited green water resources and allocation over competing demands. This allocation occurs mostly implicit and indirect, since generally it is land that is been allocated to a certain use. This indirectness of allocation, together with the absence of a price, makes green water scarcity invisible in our economy. This does not mean, though, that green water resources are not scarce, since using green water for one purpose makes it unavailable for another purpose. We need to measure how scarce green water is in order to answer questions like: Can we produce enough food, feed, fibres, bioenergy and forestry products with limited availability of water resources and suitable land? and; How can we do so without compromising natural ecosystems and other sectors that put a claim on water and land resources? For studying these crucial questions, a sole assessment of blue water scarcity is insufficient.

Therefore, it is due time that more attention is given to green water scarcity and how we can measure it. In this review, we make an inventory of existing indicators of green water availability and scarcity and classify them based on their scope and purpose of measurement. The classification allows us to discuss similarities and differences between indicators and give advice on how the various indicator classes could be used to measure different kinds of green water availability or scarcity. This is useful in order to properly include limitations in green water availability in water scarcity assessments.~~This paper reviews and classifies indicators of green water availability and scarcity and discusses the way forward to develop operational green water scarcity indicators.~~

~~-~~A review of green water scarcity indicators is new in its kind. Past reviews of water scarcity indicators (Savenije, 2000;Rijsberman, 2006) date back a while and hence do not include recent developments in the field, especially those related to the inclusion of green water. There exist multiple reviews of indicators of aridity (Wallén, 1967;Walton, 1969;Stadler, 2005) and drought (World Meteorological Organization, 1975;Wilhite and Glantz, 1985;Maracchi, 2000;Tate and Gustard, 2000;Keyantash and Dracup, 2002;Heim, 2002;Hayes, 2007;Kallis, 2008;Mishra and Singh, 2010;Sivakumar et al., 2010). We classify and discuss these indicators in an overarching way. First, we discuss the multiple dimensions of water availability and scarcity and sharpen the scope of this review (Sect. 2). Next, we classify and review green water availability and scarcity indicators (Sect. 3). Finally, we draw conclusions and discuss future research directions (Sect. 4).

# 2 Multiple aspects of water availability and scarcity

The concepts of water availability and scarcity are examined in Sects. 2.1 to 2.4. We will reflect on these concepts in broad terms, not yet focussing on green water. In Sect. 2.5 we detail the scope of the indicators discussed in this paper.

## 2.1 Water availability and scarcity

A straightforward definition of water scarcity is: “an excess of water demand over available supply” (FAO, 2012). Various other definitions of water scarcity exist that aim to be more inclusive:

“An imbalance between supply and demand of freshwater in a specified domain (country, region, catchment, river basin, etc.) as a result of a high rate of demand compared with available supply, under prevailing institutional arrangements (including price) and infrastructural conditions.” (FAO, 2015)

“When an individual does not have access to safe and affordable water to satisfy her or his needs for drinking, washing or their livelihoods we call that person water insecure. When a large number of people in an area are water insecure for a significant period of time, then we can call that area water scarce.” (Rijsberman, 2006)

Considering these definitions, we can conclude that water scarcity is not something that is experienced by a single person on a particular moment (day or week). Rather, it is experienced by a larger community within a certain geographic area (e.g. catchment or country) and relates to larger time-scales (months or years).

The concept of scarcity describes a relation between humans and nature (Baumgärtner et al., 2006). Nevertheless, we can distinguish water scarcity mainly caused by natural conditions of low water availability from scarcity mainly induced by a large human demand relative to natural availability. The latter can also occur in naturally water abundant areas (Pereira et al., 2002).

Until now we have spoken about physical water scarcity, referring to the situation where there is insufficient water to meet human demand. If human, institutional and financial capital limit access to the water, the term economic water scarcity applies (Seckler et al., 1999;Molden, 2007). In a broader sense, Ohlsson (2000) defines social resource scarcity as the situation in which social resources required to successfully adapt to physical water scarcity fall short.

## 2.2 Relative and absolute water scarcity

According to economic theory, water is a scarce good, because it carries opportunity costs, which are the benefits foregone from possible alternative uses of the water (FAO, 2004). This is a form of ‘relative scarcity’ based on the assumption of substitutability of goods (Baumgärtner et al., 2006). Water can be scarce in the relative sense also in water-abundant areas, because allocating water to purpose A implies it cannot be allocated to purpose B. In other words, water for purpose A is scarce in relation to water for other purposes. In common language we are inclined to say that at some times water is scarce and at other times it is not. In economic sense, water is always scarce; the degree of water scarcity can vary though, it can even be zero if alternative uses and thus competition is absent.

We speak of ‘absolute scarcity’ when according to Baumgärtner et al. (2006) “scarcity concerns a non-substitutable means for satisfaction of an elementary need and cannot be levied by additional production”. This means that in an area with a limited amount of water resources (that cannot be increased), at a certain level of consumption, water for elementary purposes (e.g. drinking and food production) will no longer be substitutable with water use for less essential purposes. In this case, there is ‘absolute scarcity’ of water. Whether water is scarce in the absolute or relative sense thus depends on the degree of water scarcity: relative water scarcity turns into absolute scarcity when the boundaries of water exploitation are approached.

### 2.3 Blue and green water

Freshwater essentially stems from precipitation, which partitions into green and blue water (Falkenmark and Rockström, 2006;Falkenmark and Rockström, 2010). As discussed in the introduction of this paper, water availability and scarcity can pertain to both blue or green water resources, separately or in combination (Falkenmark, 2013a).

In contrast to the clear definition of blue water, various definitions of green water exist, defining it as an inflow (precipitation), a stock (rainwater in the soil) or an outflow (evaporation of rainwater). Often, the term ‘green water’ is used to refer to ‘rainwater stored in the soil’ or more specifically plant-available soil moisture in the unsaturated zone (Falkenmark et al., 2007;Falkenmark, 2013a); in this context the term green water is interpreted as a stock. Commonly, the distinction is made between this stock and the green water flow (Falkenmark and Rockström, 2006;Falkenmark and Rockström, 2010). The latter is an outflow, usually defined as actual evaporation over land (referring to the entire land-atmosphere vapour flux, see comment in the introduction), but it has also been defined as transpiration only (Savenije, 2000). Furthermore, some authors include precipitation (i.e. an inflow) in the definition of green water (Weiskel et al., 2014). The latter is in contrast with the definition of Falkenmark and Rockström (2006) (adhered to in this paper) that precipitation is the undifferentiated freshwater resource. Scholars who have tried to quantify green water availability in water scarcity assessments defined it as the actual evaporation flux over land to the atmosphere (Rockström et al., 2009;Gerten et al., 2011;Kummu et al., 2014) (Sect. 3).

While not always made explicit in definitions, an accurate description of the green water storage and flow excludes the part of the storage and vapour flow that originates from blue water resources, which have been redirected to the soil moisture stock by means of irrigation, capillary rise or natural flooding (Hoekstra et al., 2011). In such cases, the green and blue contributions to the soil moisture can be tracked with a model-based water balance approach (see Chukalla et al., 2015).

## 2.4 Water quantity and quality

Water scarcity is not only a function of the quantity of the water resource in relation to the demand, but also the quality of the resource in relation to the required quality for its end-purpose (Pereira et al., 2002). If there is sufficient water available for a certain purpose, but it is polluted to such an extent that it is not usable for that purpose, then water can be considered scarce as long as the means are not available for cleaning the water to a desirable level. Pollution of water resources can thus aggravate water scarcity (FAO, 2012).

Water quality in the case of green water differs from the case of blue water. The quality of green water depends on soil properties such as nutrient availability, nutrient retention capacity and the presence of salts and toxic substances. However, close ties with blue water quality do exist. For example, irrigation water can increase soil salinity when it is salt or brackish and it can also flush out excess nutrients and other substances.

## 2.5 Scope of the review and classification

This paper focuses on green water, water quantity and physical water scarcity and treats both green water availability and scarcity. In the next section, we consider indicators within this scope, including indicators of aridity, agricultural, meteorological and vegetation drought, soil moisture availability and overall green-blue water scarcity. The focus of this paper implies that several concepts and indicators fall outside the scope of the classification. Concepts and indicators focusing on blue water that are out of scope are:

- *Hydrological drought*: concerns the effects of dry periods on surface- and subsurface flows and stocks and is therefore related to blue water. Examples of associated indicators are: Surface Water Supply Index (Shafer and Dezman, 1982); Palmer Hydrological Drought Index (Karl, 1986); several indicators reviewed by Smakhtin (2001).
- *Blue water scarcity*: measures demand for blue water resources versus blue water availability and is thus purely related to blue water. Examples of associated indicators are: the water crowding indicator (Falkenmark et al., 1989), the withdrawal-to-discharge ratio (Vörösmarty et al., 2000), Water Poverty Index (Sullivan et al., 2003); Water Stress Indicator (Smakhtin et al., 2004); Water Stress Index (Pfister et al., 2009); Dynamic Water Stress Index (Wada et al., 2011); Blue Water Scarcity (Hoekstra et al., 2012). Note that some of these indicators also incorporate more than only physical elements of water scarcity (e.g. Water Poverty Index).

Concepts related to broader forms of water scarcity than physical water scarcity that are out of scope are:

- *Socio-economic drought*: concerns imbalances in supply and demand of economic goods due to the physical characteristics of drought (Wilhite and Glantz, 1985;American Meteorological Society, 2013) with effects on the economy and society. The American Meteorological Society (2013) mentions the following effects: loss of income from lower crop yields; reduced spending in rural communities; health issues; mass migration.
- *Social resource scarcity:* see Sect. 2.1.

Furthermore, the review and classification in this paper excludes indicators that measure drought by combining multiple drought indicators (classified individually) and sometimes other information such as land-use maps. Examples of such indicators are the U.S. Drought Monitor (Svoboda et al., 2002) and the Vegetation Drought Response Index (Brown et al., 2008).

# 3 Green water availability and scarcity indicators

We have identified around eighty indicators of green water availability and scarcity, which we classify into the following categories:

1. *Green water availability indicators* show whether green water availability is low or high and are insensitive to actual water demand. In other words, when the water demand increases, indicator values will not reflect this. Within this category we distinguish *absolute* and *relative* green water availability indicators:
    a. *Absolute green water availability indicators* measure actual conditions of green water availability (in an absolute sense).
    b. *Relative green water availability indicators* measure actual conditions of green water availability compared to conditions that are perceived as ‘normal’, which is often defined as the climate-average or median value of the variable of interest.

    Note that this distinction between absolute and relative indicators is unrelated to and different from the concepts of relative and absolute scarcity earlier discussed in Sect. 2.2.

2. *Green water scarcity indicators* incorporate elements of both water availability and demand and therefore respond – in contrast to green water availability indicators – to changes in water demand as well. We distinguish three different options to measure green water scarcity conceptually (explanation in Sect. 3.2):
    a. *Green water crowding*
    b. *Green water requirements for self-sufficiency versus green water availability*
    c. *Actual green water consumption versus green water availability*

The usage of terms like 'water availability' and 'water demand' can be confusing because in different contexts they have different meanings. The term 'green water availability' is basically used in two different ways. When we speak of 'green water availability indicators' (Sect. 3.1), we refer to indicators that measure the availability of green water in one or another way, *without considering availability in relation to an actual demand for green water*. This is in contrast with green water scarcity indicators that always compare demand to availability. In the case of green water scarcity indicators, the term 'green water availability' specifically refers to the part of the green water flow available for biomass production for human purposes (Sect. 3.2). Also the term 'demand' occurs in two different contexts. When we speak of 'demand' in the context of green water scarcity, we refer to the demand for green water, associated with the production of biomass for human purposes. In the discussion of agricultural drought indicators in Sect. 3.1, the term 'crop moisture/evaporation/water demand' is used to refer to the water needs of the crop for non-water limited growth.

The indicator categories will be discussed in the following sections. Table 1 provides an overview of the categories and summarizes what they measure, which human factors directly influence them and what they are used for. Furthermore, the conceptual diagram in Fig. 1 displays the indicator categories and the factors that influence them.

## 3.1 Green water availability indicators

Indicators of green water availability fall apart in indicators that measure availability in absolute sense or in terms of relative to normal conditions. These two categories are treated in the next two subsections, respectively. Descriptions of various specific green water availability indicators that fall in the two categories are included in Appendices A and B, respectively. The indicator acronyms used in this section are defined in these appendices.

### 3.1.1 Absolute green water availability indicators

Indicators in this category measure green water availability in a certain area (or location) and period (or moment) in an absolute sense. We find here indicators of aridity, agricultural drought, soil moisture and agricultural suitability, which are subsequently discussed in the following. Aridity indicators are purely climatic, while the others are also influenced by the characteristics and management of the soil and vegetation.

#### Aridity indicators

Aridity is seen as a permanent feature of a climate, consisting of low average annual precipitation and/or high evaporation rates, often resulting in low soil moisture availability (Pereira et al., 2002;Heim, 2002;Kallis, 2008). As such, one can say that an aridity map shows the preconditions for vegetation (Falkenmark and Rockström, 2004). Aridity indicators are usually based on long-term average annual comparisons of precipitation versus potential evaporation, temperature or atmospheric saturation deficit, whereby the latter two were often used in the 20th century as proxies for potential evaporation due to lack of data. They have been used for the classification of climates, specifically the characterisation of (semi-)arid zones. Some more recently developed aridity indicators compare the actual rather than potential evaporation rate with precipitation (ER, HU-ER). These indicators reflect the actual availability of water at a given location (also from lateral fluxes) for meeting the evaporative demand of the atmosphere.

The SCMD by Wilhelmi et al. (2002) is somewhat different than the classical aridity indicators. It shows the probability of seasonal crop moisture deficiency based on a combination of long-term precipitation records and area-weighted evaporation of the mixture of crops grown in the study area. Wilhelmi and Wilhite (2002) apply the SCMD to assess agricultural drought vulnerability in Nebraska. We classify the SCMD here under the aridity indicators, because like most aridity indicators, it measures precipitation versus evaporation and is calculated for a historical time-period, thus representing a long-term average.

#### Agricultural drought indicators

According to the World Meteorological Organization (1975), agricultural drought indicators “indirectly express the degree to which growing plants have been adversely affected by an abnormal moisture deficiency”, which may be the result of an unusually small moisture supply or an unusually large moisture demand (World Meteorological Organization, 1975).

Formulated differently by Sivakumar (2010): “Agricultural drought depends on the crop evapotranspiration demand and the soil moisture availability to meet this demand.”

Therefore, the bulk of agricultural drought indicators measures crop available water compared to crop water needs for non-water limited growth (i.e. potential evaporation) and are usually applied on a daily, weekly, monthly or seasonal basis (Woli et al., 2012). Some indicators measure the plant water deficit more specifically by looking at the difference between actual and potential transpiration (e.g. DTx and WDI). Agricultural drought indicators can be influenced by soil management that affects the rates of infiltration and percolation and thus the water available to the crop.

Drought is typically a relative-to-normal phenomenon as will be discussed in Sect. 3.1.2. Agricultural drought indicators, which measure actual relative to potential evaporation, are ‘relative’ indicators in another way, though. They do not compare actual with ‘normal’ conditions. Instead, they compare moisture supply with a crop water demand in the ideal case of non-water limited growth. Therefore these indicators actually measure absolute green water availability (actual evaporation), set against this crop water demand. In fact, these indicators say more about the demand for blue water (irrigation) to ensure non-water limited crop growth than they do about green water availability. Some indicators do somehow compare the actual to potential evaporation ratio with a multi-year average (or median) of this ratio and are thus in essence relative indicators according to our classification. Examples are the CMI, DSI and GrWSI and anomalies of the ESI and WS. Nevertheless, they are classified as agricultural drought indicators because they, like most of the others, measure actual to potential evaporation.

A note is required on the GWSI by Nunez et al. (2013) of which the name suggests that it is a green water scarcity indicator. Nevertheless, we classify it as an agricultural drought indicator, because it measures actual moisture supply versus crop-specific reference evaporation, albeit on a larger time-scale (three-year crop rotation) than most other agricultural drought indicators.

### Absolute soil moisture indicators

Multiple indicators provide a measure of the absolute amount of soil moisture available at a given location and moment (or summed over a period), be it on the basis of field measurements (e.g. SMIX, SMI) and/or modelling of the soil water balance (e.g. Avg-GWS and SD-GWS) or remote sensing data (e.g. TVDI, MPDI). They can be used for monitoring spatial and/or temporal variations in soil moisture availability. Temporal analysis of soil moisture availability can warn for the onset of agricultural drought, or in contrast, the proneness to flash floods (Hunt et al., 2009). Several of these indicators have been introduced and applied as indicators of agricultural drought (e.g. ADD, SMDI, SMIX, SMI), analysing the correlation between soil moisture availability and crop yields. Therefore, they are typically calculated on intra-annual time-scales.

It should be noted that the soil moisture can partially be blue – also under rain-fed conditions – due to capillary rise or natural flooding (Sect. 2.3). This note also applies to the other indicators that are not purely based on climatic factors (Fig. 1).

#### Agricultural suitability under rain-fed conditions

Maps that classify land according to agricultural suitability under rain-fed conditions (green water only) are indirect measures of green water availability in the absolute sense. Up to date, two global studies have made such land suitability classifications for rain-fed crop production for climate-average temperature and precipitation conditions and taking into account crop-characteristics, various soil parameters and terrain slope: GAEZ (IIASA/FAO, 2012) and GLUES (Zabel et al., 2014). The GAEZ study additionally considers various levels of agricultural input/management. Both studies classify lands as ‘not suitable’, ‘marginally suitable’, ‘moderately suitable’ or ‘highly suitable’. This classification shows where the climate, soil and topographic conditions are more or less suitable for agricultural production with green water only. In other words, where aridity maps show the preconditions for vegetation in general (Falkenmark and Rockström, 2004), these maps show the preconditions for rain-fed crop production, therein considering crop, soil and terrain parameters in addition to climate.

### 3.1.2 Relative green water availability indicators

Indicators in this category measure green water availability relative to a ‘normal’ condition and are usually calculated on intra-annual scales. As opposed to aridity, drought is often defined as a condition relative to what is perceived as a ‘normal’ amount of precipitation or balance between precipitation and evaporation (World Meteorological Organization, 1975;Wilhite and Glantz, 1985). Droughts are often termed temporary, uncertain and difficult to predict features characterized by lower-than-average precipitation (Pereira et al., 2002;Heim, 2002;Kallis, 2008;Mishra and Singh, 2010;FAO, 2015). Therefore, indicators of meteorological drought and vegetation drought are classified into the category of relative green water availability indicators. Indicators that measure soil moisture in a relative sense are included in this category as well. Just like aridity indicators, meteorological drought indicators are solely based on climatic variables. The other two subcategories are also affected by the soil and vegetation and how they are managed. The three subcategories are sequentially discussed in the following.

#### Meteorological drought indicators

Meteorological drought indicators fall apart in indicators that are solely based on precipitation (e.g. SPI) and those that consider both precipitation and potential evaporation (e.g. PDSI, RDI, SPEI). These indicators show whether there is relatively little precipitation or whether the normal balance between precipitation and evaporation is distorted. Unlike aridity indicators, which are generally based on long-term annual averages reflecting climate, these indicators capture variations in the weather. They are applied for monitoring the intensity, duration and spatial extent of droughts and determining drought severity based on these characteristics. This is useful for recognizing droughts and comparing them with past drought, which serves as a basis for early warning systems and decision-support tools.

#### Vegetation drought indicators

Vegetation drought indicators show the drought impact on vegetation by measuring the weather-related variations in greenness of vegetation. They reflect whether vegetation greenness is deviating from regular conditions. They can be used for studying the correlation between vegetation health and soil moisture availability, thermal conditions and crop yields (Kogan, 2001). Since the vegetation drought indicators we have identified are all based on remote-sensing observations, the indicators do not directly show whether deviations are caused by relatively dry weather (i.e. meteorological drought) or by other factors influencing vegetation growth (e.g. plant diseases or human interference such as pruning and clearing). Satellite-based vegetation drought indicators respond to subtle changes in vegetation canopy, which makes them suitable for early drought detection (Kogan, 2001).

#### Relative soil moisture indicators

In contrast to the absolute soil moisture indicators discussed in Sect. 3.1.1, these indicators measure the moisture conditions at a given location relative to a normal condition. Identified examples are the PZI, SMAI and SD. These indicators have similar uses as absolute soil moisture indicators. They are also used to correlate soil moisture conditions to crop yields and are considered suitable for measuring agricultural droughts (Keyantash and Dracup, 2002;Narasimhan and Srinivasan, 2005).

## 3.2 Green water scarcity indicators

As put forward in Sect. 2, water scarcity pertains to a situation with a high water demand compared to water availability, which is experienced by a community (numerous people) within a certain geographic area (e.g. catchment or country) over a significant period of time (months or years). We can then define green water scarcity as *the degree of competition over limited green water resources, whereby the demand for green water resources to sustain the production of a desirable level of biomass-based products within a certain geographic area is somehow compared to the available green water resources in space and time*.

Since production of biomass-based products (food, fibres, biofuels, timber) generally takes place in cycles of one year (or more in case of perennials and forestry), this definition of green water scarcity incorporates the ‘significant period of time’ element in the imbalance between green water demand and availability. Furthermore, limited production of biomass-based products affects numerous people, both producers and consumers.

As opposed to the indicators discussed in Sect. 3.1, indicators of green water scarcity thus need to include a measure of green water demand, associated with the production of biomass for human purposes, compared to green water availability. In other words, they should measure the green water demand related to crop production, grazing lands and forestry in relation to green water availability. Note that the term ‘green water availability’ here refers to the part of the green water flow available for biomass production for human purposes (in space and time); it thus excludes green water flows that are effectively unavailable, for instance green water flows in unsuitable areas (e.g. because of steep slopes) or green water flows in cold parts of the year unsuitable for growth.

We distinguish three different options to measure green water scarcity conceptually:

a. *Green water crowding*: per capita available green water resources in an area compared to a global average threshold representing the amount of green water required to sustain a person’s ‘standard consumption pattern of biomass-based products’.

b. *Green water requirements for self-sufficiency versus green water availability*: green water requirements for producing the consumed biomass-based products within a certain geographic area, assuming self-sufficiency within the geographic area, compared to the green water resources in the geographic area.

c. *Actual green water consumption versus green water availability*: actual green water consumption in a certain geographic area (associated with the actual production of biomass for human purposes) compared to green water availability in the area. This type of indicator thus acknowledges the possibility of virtual water trade as opposed to assuming self-sufficiency as in the previous two types of indicators.

In Sects. 3.2.1 and 3.2.2, we discuss existing indicators that measure overall green-blue water scarcity and reflect on how these indicators could be adapted to measure green water scarcity specifically, according to above-mentioned options a and b. In Sect. 3.2.3, we elaborate upon a third way of measuring green water scarcity that has yet to be brought into practice. The challenges for operationalization of these green water scarcity indicators are discussed in Sect. 3.2.4. Finally, in Sect. 3.2.5 we reflect on green water scarcity indicators versus indicators that measure overall green-blue water scarcity.

### 3.2.1 Green water crowding

Rockström et al. (2009) introduced a combined green-blue water shortage index, which compares the sum of green and blue water availability with a global average threshold of 1,300 $m^3$/cap/yr. This threshold represents the green and blue water requirements for sustaining a global average ‘standard diet’. When green-blue water availability drops below the threshold, this indicates a shortage of green-blue water resources in the study area and reflects the area’s dependency on external water resources. The green-blue water shortage index is an indicator of water crowding, similar to Falkenmark’s blue-water focused water crowding indicator (Falkenmark et al., 1989).

Similar to the indicator by Rockström et al. (2009), an indicator of green water crowding could be defined as the per capita available green water resources in an area compared to a global average threshold representing the amount of green water required to sustain a person’s ‘standard consumption pattern’. We intentionally speak here of a consumption pattern, because green water is not only required to produce food, but also to produce other biomass-based products humans consume, such as fibres, biofuels and forestry products. As such, the measure of green water requirements we propose here is broader than the definition of a ‘standard diet’ according to Rockström et al. (2009) (and Gerten et al. (2011) and Kummu et al. (2014)), which only pertains to water requirements for food production.

Rockström et al. (2009) define green water availability as “the soil moisture available for productive vapour flows from agricultural land”. Technically, they calculate green water availability as actual evaporation from existing cropland and permanent pasture, reduced by a factor 0.85 that accounts for minimum evaporation losses that are unavoidable in agricultural systems (Rockström et al., 2009). This definition is dependent on the extent of agricultural land and excludes available green water on lands that are currently uncultivated, but have potential to be used productively in a sustainable manner.

### 3.2.2 Green water requirements for self-sufficiency versus green water availability

Gerten et al. (2011) and Kummu et al. (2014) elaborated on the work by Rockström et al. (2009) by further developing and applying the overall green-blue water scarcity indicator. Instead of using a global average, Gerten et al. (2011) calculate the green-blue water requirements for sustaining a ‘standard diet’ on the national level based on local crop water productivities and compare this with the sum of green and blue availability in each country of the world. The resulting green-blue water scarcity indicator, computed for each country, is defined as the ratio between green-blue water availability and green-blue water requirements for producing the standard diet. They define green water availability similar to Rockström et al. (2009), but a bit more conservative: they do not assume year-round evaporation from areas covered with their category of ‘other’ crops that they parameterized as perennial grass, since this category includes non-food crops and crops that grow only during a part of the year (Gerten et al., 2011).

Whereas the studies by Rockström et al. (2009) and Gerten et al. (2011) are based on climate-averages, Kummu et al. (2014) apply the green-blue water scarcity indicator by Gerten et al. (2011) on a year-by-year basis to account for inter-annual climate variability on the scale of food producing units, the scale at which demand for water and food is assumed to be managed according to the authors. Kummu et al. (2014) measure the frequency of years in which green-blue water availability falls short of green-blue water requirements, on which they base their classification of green-blue scarcity: no scarcity; occasional scarcity (subdivided in four levels); or chronic scarcity.

The green-blue water scarcity indicator shows the potential of a geographic area (e.g. country or food producing unit) to reach food self-sufficiency and reflects its dependency on trade in agricultural commodities and associated virtual water (Kummu et al., 2014). A similar indicator for green water could show an area's green water demand (for self-sufficiency in biomass-based products, for sustaining the 'standard consumption pattern') compared to green water availability in the area. It would also reflect an area's dependency on internal blue water resources and virtual water trade.

For the potential green water scarcity indicators discussed in Sects. 3.2.1 and 3.2.2, a more comprehensive definition of green water availability is advised than the one applied by Rockström et al. (2009), Gerten et al. (2011) and Kummu et al. (2014). An example of a more comprehensive definition is discussed in the following section.

### 3.2.3 Actual green water consumption versus green water availability

The green water scarcity indicator by Hoekstra et al. (2011) compares the actual green water consumption in an area associated with the actual biomass production pattern (hence considering virtual water trade as opposed to assuming self-sufficiency) with green water availability in the area. Green water scarcity is defined as the ratio of the total green water footprint in a catchment in a period (e.g. a year) over green water availability.

The sum of green water footprints equals all actual evaporation ($E_{\mathrm{act}}$) related to biomass production for human purposes (i.e. agriculture and forestry) excluding the part of the vapour flow that originates from blue water resources (irrigation). Note that for cases where land use is partly natural and partly for human production (e.g. a semi-natural production forest), the green water demand related to human production would need to be expressed as a fraction of the total green water flow. Methods to do so for a production forest are discussed by van Oel and Hoekstra (2012). Green water availability is defined as total $E_{\mathrm{act}}$ over the catchment minus $E_{\mathrm{act}}$ from land reserved for natural vegetation (so called 'environmental green water requirement') and minus $E_{\mathrm{act}}$ from land that cannot be made productive, e.g. in areas or periods of the year that are unsuitable for crop growth (Hoekstra et al., 2011). In fact, green water availability defined like this, represents the maximum sustainable green water footprint in the catchment and period under consideration. Hence, the green water scarcity ratio shows the extent to which the green water footprint has reached its maximum sustainable level. Of course, this definition can also be applied to other geographical units than a catchment.

The definition of green water availability by Hoekstra et al. (2011) is more comprehensive than the one used by Rockström et al. (2009), Gerten et al. (2011) and Kummu et al. (2014). However, this is also the reason why the indicator has not been made operational yet. Difficulties remain in estimating the amount of land that needs to be reserved for nature and when and where the green water flow cannot be made productive (Hoekstra et al., 2011). These challenges are discussed in the following section.

Furthermore, the indicator does not deal with green water scarcity at a particular site as looked upon by Falkenmark et al. (2007) and Falkenmark (2013a). They describe green water scarcity as an issue of lower-than-potential plant-accessible water in the root zone and the occurrence of unproductive evaporation losses from the field, which results in lower yields than potentially achievable. First, blue water losses in the form of surface run-off and percolation decrease the plant-accessible water in the root zone (smaller green water flow) (Rockström and Falkenmark, 2000). Such losses are the result of a soil's low infiltration capacity (e.g. soil crusting) and poor soil water holding capacity, but can be caused or aggravated by human action through soil mismanagement (Falkenmark, 2013a). Second, low root/crop water uptake capacity leads to unproductive evaporation losses (green water flow not entirely productive) (Rockström and Falkenmark, 2000). Transpiration is a productive form of green water use, contributing to biomass production, while other components of the evaporative flow are regarded as unproductive (Rockström and Falkenmark, 2000;Rockström, 2001;Rockstrom et al., 2007;Savenije, 2004). Rockstrom et al. (2007) express the productivity of green water use as the ratio of transpiration to evaporation. Rockström et al. (2009) call this the transpiration efficiency. This transpiration efficiency is complementary to the green water scarcity indicator by Hoekstra et al. (2011). A green water scarcity assessment based on both will give insight into the *severity* of green water scarcity: areas that are considered highly green-water scarce, but have a low transpiration efficiency, may have options to improve the latter and thereby yields, which may lower the green water scarcity.

### 3.2.4 Challenges for operationalization of green water scarcity indicators

Operationalization of green water scarcity indicators faces three major challenges, particularly regarding the quantification of green water availability.

First, the determination of which areas and periods of the year the green water flow can be used productively is not straightforward. Absolute green water availability indicators, in particular land classifications of agricultural suitability, can provide insight in the availability of green water in the spatial dimension. Relative green water availability indicators can enrich the picture by showing which areas are prone to large inter- and intra-annual variations in green water availability, making these areas less suitable for (certain types of) biomass production. To estimate which part of the green water flow can be used productively in time, advanced crop growth models (like APSIM (McCown et al., 1995;Holzworth et al., 2014), AquaCrop (Steduto et al., 2009), CropSyst (Stöckle et al., 2003), EPIC (Jones et al., 1991) or SWAP/WOFOST (van Dam et al., 2008)) can be used to simulate water-limited yields and actual evaporation for various cropping periods and different types of soil, crop and agricultural water management (e.g. adding blue water in the form of deficit irrigation during a dry spell, might make it possible for the crop to survive and use the green water flow later in the year productively).

Second, estimating green water consumption of forestry is difficult, because it entails separation of production forest evaporation into green and blue parts. This is problematic, because trees generally root so deep that, by means of capillary rise, they directly take up water from groundwater (blue) in addition to the soil moisture (green) (Hoekstra, 2013).

Third, research is required to determine the environmental green water requirements, i.e. the green water flow that should be preserved for nature, similar to the environmental flow requirements for blue water. Key here is the identification of areas that need to be reserved for nature and biodiversity conservation. It is known that the current network of protected areas is insufficient to conserve biodiversity (Rodrigues et al., 2004a;Rodrigues et al., 2004b;Venter et al., 2014;Butchart et al., 2015) and that attention should be paid to conservation of biodiversity in production landscapes that are shared with humans (Baudron and Giller, 2014). The 11th Aichi Biodiversity Target is to expand the protected area network, which currently has a terrestrial coverage of about 14.6% (Butchart et al., 2015), to at least 17% terrestrial coverage by 2020 (Convention on Biological Diversity, 2010). However, to properly assess the limitations to green water availability, spatially explicit information on the additional areas to be preserved is required. The best-available data regarding this is recently published work by Montesino Pouzols et al. (2014). These authors have mapped global and national priority areas for expansion of the protected area network on 0.2 degrees spatial resolution and assessed associated conservation gains (Montesino Pouzols et al., 2014;Brooks, 2014).

### 3.2.5 Measuring green water scarcity versus overall green-blue water scarcity

In Sects 3.2.1 and 3.2.2 we mentioned a few indicators that measure overall green-blue water scarcity (Rockström et al., 2009;Gerten et al., 2011;Kummu et al., 2014). Whereas useful for getting an overall picture of water scarcity, a disadvantage of these indicators is that a high degree of green water scarcity can be masked by a low degree of blue water scarcity and vice versa. Imagine for example a river basin where nearly all land is in use and natural forest is under pressure by conversion to cropland (high degree of green water scarcity), while there is enough blue water available to irrigate croplands if necessary (low degree of blue water scarcity). Measuring increasing green water scarcity could be relevant for instance for the Amazon basin in South America, where increasingly natural forest and associated green water flows are turned into use, where competition is essentially about land and associated green water resources, while blue water resources are abundant and blue water scarcity is low. Therefore, for studying green water scarcity, an indicator specifically comparing green water demand and green water availability can be more appropriate.

## 4 Conclusions and future research

In this paper we have reviewed and classified around eighty indicators of green water availability and scarcity. This list of indicators is extensive, but not exhaustive. Nevertheless, we are confident to have identified the most widely used and cited indicators.

The number of green water availability indicators by far outnumbers the existing green water scarcity indicators. This reflects that the concept of green water scarcity is still largely unexplored. Indicators of overall green-blue water crowding and scarcity have been developed by Rockström et al. (2009), Gerten et al. (2011) and Kummu et al. (2014). These have potential to be tailored to measure green water crowding and green water requirements for self-sufficiency versus green water availability. The green water scarcity indicator by Hoekstra et al. (2011) measures actual green water consumption versus green water availability, but has not yet been operationalized due to several challenges discussed in Sect. 3.2.4. The biggest challenge is to determine which part of the green water flow can be made productive in space and time. Application of both absolute and relative green water availability indicators will provide insight into where the green water flow can be made productive for human purposes. Simulations with crop growth models for different management strategies can be used to assess during which parts of the year the green water flow can be made productive.

Future research should be aimed at overcoming these challenges to make the green water scarcity indicators discussed in this paper operational. We also encourage the development of additional definitions of green water scarcity indicators to the ones discussed here. The conceptual definition of green water scarcity we introduced in Sect. 3.2 can be a starting point for this.

Despite scientific obstacles on the way, it is time that the scope of water scarcity assessments is broadened to include green water. We hope that this paper is a stepping stone towards this goal by bringing structure in the large pool of green water availability indicators and discussing the way forward to develop operational green water scarcity indicators. Practitioners and scholars might also find the classification of indicators provided in this paper insightful and helpful for choosing the indicator that suits their purpose.

## Appendix A: Absolute green water availability indicators

Absolute green water availability indicators are included in Tables A1 to A4. Often used symbols in this appendix: $E_{\mathrm{act}}$ = actual evaporation; $E_{\mathrm{pot}}$ = potential evaporation; $E_{\mathrm{pot,c}}$ = crop-specific potential evaporation; $E_{\mathrm{pot,ref}}$ = potential evaporation of FAO reference crop; $P$ = precipitation; $S$ = soil moisture; $T$ = air temperature; $Tr_{\mathrm{act}}$ = actual transpiration; $Tr_{\mathrm{pot}}$ = potential transpiration.

Table A1. Aridity indicators.

Table A2. Agricultural drought indicators.

Table A3. Absolute soil moisture indicators.

Table A4. Agricultural suitability under rain-fed conditions.

## Appendix B: Relative green water availability indicators

Relative green water availability indicators are included in Tables B1 to B4. Often used symbols in this appendix: $E_{\mathrm{pot}}$ = potential evaporation; $E_{\mathrm{pot,ref}}$ = potential evaporation of FAO reference crop; $P$ = precipitation; $NDVI$ = Normalized Difference Vegetation Index.

Table B1. Meteorological drought indicators based on precipitation only.

Table B2. Meteorological drought indicators based on precipitation and a measure of potential evaporation.

Table B3. Vegetation drought indicators.

Table B4. Relative soil moisture availability indicators.

## Author contribution

Conceived and designed the study: A. Y. Hoekstra, J. F. Schyns and M. J. Booij. Executed the study: J. F. Schyns. Wrote the paper: J. F. Schyns, A. Y. Hoekstra and M. J. Booij.

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Table 1. Overview of indicator categories.

| Indicator category (parent category) | Measures | Human factors of direct influence | Purposes |
|---|---|---|---|
| Aridity (absolute green water availability) | Long-term annual climatic balance between precipitation and evaporation. | - | Classification of climates; characterisation of (semi)-arid zones. |
| Agricultural drought (absolute green water availability) | Actual soil moisture availability versus crop water demand for non-water limited growth. | Soil management affecting infiltration and groundwater recharge (percolation); crop management. | Assessing the extent to which crop growth is adversely affected by limiting soil moisture conditions; linking drought conditions to yield losses. |
| Absolute soil moisture (absolute green water availability) | Actual soil moisture availability. | Soil management affecting infiltration and groundwater recharge (percolation). | Monitoring spatial and temporal variation in soil moisture availability; analysing the correlation between soil moisture availability and crop evaporation and yields; warning for onset of agricultural drought. |
| Agricultural suitability under rain-fed conditions (absolute green water | Land suitability for rain-fed crop production based on climate-average temperature and precipitation | Level of agricultural inputs and management. | Agro-ecological zoning; determining a location’s potential for rain-fed agriculture (yield gap analysis). |

| | | | |
|---|---|---|---|
| availability) | conditions, crop and soil characteristics, terrain slope. | | |
| Meteorological drought (relative green water availability) | Whether there is relatively little precipitation or whether the normal balance between precipitation and potential evaporation is distorted. | - | Drought monitoring as a basis for early warning systems and decision-support tools; assessing drought severity based on intensity, duration and spatial extent; comparison of historic drought events. |
| Vegetation drought (relative green water availability) | Greenness of vegetation relative to historical observations of greenness. | Pruning or clearing; prevention of plant disease. | Assessment of drought impact on vegetation; early drought detection; studying the correlation between vegetation health and soil moisture availability, thermal conditions and crop yields. |
| Relative soil moisture (relative green water availability) | Whether the soil is dryer or wetter than normal. | Soil management affecting infiltration and groundwater recharge (percolation). | Monitoring spatial and temporal variation in relative soil moisture availability; analysing the correlation between soil moisture availability and crop yields. |

| | | | |
|---|---|---|---|
| Green water crowding (green water scarcity) | The potential of a geographic area to reach self-sufficiency based on its available green water resources. | Consumption pattern (diet composition); population growth; land-use changes. | Studying green water availability in relation to hypothetical green water requirements for self-sufficiency; identifying geographic areas that have too limited green water availability for self-sufficiency and are dependent on blue water resources and virtual water import (assessing food security). |
| Green water requirements for self-sufficiency versus green water availability (green water scarcity) | Idem to green water crowding indicators. | Consumption pattern (diet composition); population growth; crop and soil management affecting water productivities; land-use changes. | Idem to green water crowding indicators. |
| Actual green water consumption versus green water availability (green water scarcity) | The degree to which the available green water resources in a geographic area have been appropriated, i.e. the extent to which the green water footprint has reached its | Consumption pattern (diet composition); population growth; production pattern; crop and soil management affecting water productivities; land-use changes. | Studying the competition over limited green water resources and allocation over competing demands. |

| | |
|---|---|
| | maximum sustainable level. |

Table A1. Aridity indicators.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| Rainfall-evaporation ratio | RER | $\frac{P}{E_{ow}}$<br>$E_{\mathrm{ow}}$ = open water evaporation | Transeau (1905) |
| Rain Factor | RF | $\frac{P}{T}$ | Lang (1920) |
| Koloskov Index | KI | $\frac{P}{\sum T}$<br>Sum over vegetative period | Koloskov (1925) as cited by World Meteorological Organization (1975) |
| de Martonne's Aridity Index | dM-AI | $\frac{P}{T+10}$ | de Martonne (1926) as cited by Thornthwaite (1931), Budyko (1958) and de Martonne (1942) |
| Precipitation-Saturation deficit ratio | PDR | $\frac{P}{D}$<br>$D$ = mean annual atmospheric saturation deficit | Meyer (1926) as cited by Thornthwaite (1931) and Budyko (1958) |
| Reichel's Aridity Index | R-AI | $\frac{N \times P}{T+10}$<br>$N$ = number of rainy days | Reichel (1928) as cited by Perez-Mendoza |

|  |  |  |  |
|---|---|---|---|
|  |  |  | et al. (2013) |
| Marcovitch's Index | MI | $0.5L^2 \times \left(\frac{100}{P}\right)^2$<br>$L$ = the total number of two or more consecutive days above 90° Fahrenheit for the months of June, July, August, and September; Total $P$ for those months. | Marcovitch (1930) |
| Shostakovich Index | SI | $\frac{P}{T}$<br>$P$ during vegetative period; mean $T$ over this period | Shostakovich (1932) as cited by Jenny (1941) |
| Emberger's Aridity Index | E-AI | $\frac{100P}{(M+m)(M-m)}$<br>$M$ = mean temperature of the warmest month; $m$ = mean temperature of the coldest month | Emberger (1932) as cited by Wallén (1967) |
| Precipitation Effectiveness Index | PE | $\sum_{n=1}^{12} 10 \frac{P_n}{E_{pot_n}}$ | Thornthwaite (1931) |
| Hydrothermal coefficient | HC | $\frac{P}{\sum T\big\|_{T>10^o C}}$ | Selianinov (1930; 1937) as cited by Budyko (1958) and World Meteorological Organization (1975) |
| Köppen classification | KC | Threshold for classifying area as semi-arid: | Köppen (1931) |

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| | | $P = 2(T + 14)$ (summer rainfall)<br>$P = 2T$ (winter rainfall)<br>Threshold for classifying area as arid:<br>$P = T + 14$ (summer rainfall)<br>$P = T$ (winter rainfall)<br>$P$ = annual precipitation amount in cm yr$^{-1}$; $T$ = mean annual temperature in °C. | |
| Aridity Coefficient | AC | $f_{lat} \times (T_{\max} - T_{\min}) \times (\frac{P_{\max} - P_{\min}}{P_{avg}})$<br>$f_{\text{lat}}$ = latitude factor; $T_{\max}$ = temperature of the long-term mean warmest month; $T_{\min}$ = temperature of the long-term mean coldest month; $P_{\max}$ = largest annual precipitation amount on record; $P_{\min}$ = smallest annual precipitation amount on record; $P_{\text{avg}}$ = average annual precipitation amount on record | Gorczynski (1940) |
| Modified de Martonne Aridity Index | MdM-AI | $\frac{1}{2}\left(\frac{P}{T+10} + \frac{12P_d}{T_d + 10}\right)$<br>$P_d$ = precipitation in the driest month; $T_d$ = temperature in the driest month | de Martonne (1942) |
| Popov's Aridity Index | P-AI | $\frac{P_{eff}}{2.4(t - t')r}$<br>$P_{\text{eff}}$ = annual amount of precipitation available to plants; $r$ = factor depending on day length; $t$-$t'$ = annual mean wet bulb depression in °C. | Popov (1948) as cited by World Meteorological Organization (1975) |

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| Moisture Index; Aridity Index; Humidity Index | $I_m$; $I_a$; $I_h$ | $I_a = \frac{100d}{E_{pot}}$<br>$I_h = \frac{100s}{E_{pot}}$<br>$I_m = I_h - 0.6I_a$<br>where $d$ is a water deficiency when $P < E_{pot}$ and $s$ is a water surplus when $P > E_{pot}$.<br>$I_m$ is an overall measure of the moisture conditions of a region, giving more weight to $I_h$, since $s$ in one season can partially compensate for $d$ in another season. | Thornthwaite (1948) |
| Capot-Rey's Aridity Index | CR-AI | $\frac{1}{2}\left(\frac{100P}{E_{pot}} + \frac{12P_w}{E_{pot,w}}\right)$<br>$P_w$ = precipitation of the wettest month of the year (in cm month$^{-1}$); $E_{pot,w}$ = potential evaporation of the wettest month of the year (in cm month$^{-1}$) | Capot-Rey (1951) |
| Radiational Index of Dryness | RID | $\frac{R}{L \times P}$<br>$R$ = mean annual net radiation; $L$ = latent heat of vaporization of water | Budyko (1958) |
| Gaussen Classification | GC | $P \leq 2T$ | UNESCO (1963) |
| Sly's Climatic Moisture Index | SCMI | $\frac{P}{P + S + I}$<br>$I$ = irrigation requirement for non- | Sly (1970) |

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| | | water limited growth.<br>$P$ and $I$ during growing season. $S$ at start of growing season. The index is made purely climatic by fixed assumptions on the non-climatic factors. | |
| Moisture Availability Index | MAI-H | $\frac{P_{dep}}{E_{pot}}$<br>$P_{\mathrm{dep}}$ = dependable precipitation, which is the precipitation amount with a specified probability of occurrence | Hargreaves (1972) |
| Evaporation ratio | ER | $\frac{E_{act}}{P}$ | Peixoto and Oort (1992) |
| UNEP's Aridity Index | AI | $\frac{P}{E_{pot}}$ | Middleton and Thomas (1992, 1997) |
| Seasonal Crop Moisture Deficiency | SCMD | Probability of seasonal crop moisture deficiency based on a combination of long-term precipitation records and area-weighted $E_{\mathrm{act}}$ of the mixture of crops grown in the study area.<br>Although most crops studied by Wilhelmi et al. (2002) are considered well-watered ($E_{\mathrm{act}} = E_{\mathrm{pot,c}}$), for wheat and grasses $E_{\mathrm{act}}$ is estimated as the $E_{\mathrm{act}}$ associated with a certain threshold yield, representing so called critical crop water requirements (Wilhelmi et al., 2002). | Wilhelmi et al. (2002);Wilhelmi and Wilhite (2002) |

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| Climatic Moisture Index | CliMI | $\frac{P}{E_{pot}} - 1$ when $P < E_{pot}$<br>$1 - \frac{E_{pot}}{P}$ when $P \geq E_{pot}$ | Vörösmarty et al. (2005) |
| Hydrologic unit evaporation ratio | HU-ER | $\frac{E_{act}}{P}$<br>Theoretically equivalent to ER (above), but applied to the level of a hydrologic unit. | Weiskel et al. (2014) |
| Green-blue index | GBI | Indicates whether vertical precipitation and evaporation fluxes dominate in a hydrologic unit (compared to lateral blue water flows) during a period of interest. Distinction between semi-arid and arid areas can be made when combined with a precipitation map. | Weiskel et al. (2014) |

Table A2. Agricultural drought indicators.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| Bova's Drought Index | BDI | $\frac{10(S+P)}{\sum T}$<br>*S* (in mm) of the top 100 cm of soil at the beginning of the growing season; *P* during growing season; sum of *T* from the first day *T* is above 0 °C. | Bova (1941) as cited by World Meteorological Organization (1975) |
| Moisture Adequacy Index | MAI | $\frac{P+S}{E_{pot}}$ | McGuire and Palmer (1957) |
| Water Requirement Satisfaction Index | WRSI | $\frac{E_{act}}{E_{pot} \times K_c}$<br>$K_c$ = crop coefficient that accounts for the difference in evaporation between the considered crop and a reference grass surface.<br>*WRSI* is usually evaluated as sum over the growing season. | FAO (1986);Verdin and Klaver (2002) |
| Crop Water Stress Index | CWSI | $1-\frac{E_{act}}{E_{pot}}$ | Jackson et al. (1981);Moran et al. (1994) |
| Evaporative Stress Index | ESI | Idem to *CWSI.* | Anderson et al. (2007a, 2007b);Yao et al. (2010) |
| Water Stress ratio | WS | $\frac{E_{pot}-E_{act}}{E_{pot}}$<br>In fact, idem to *CWSI.* | Narasimhan and Srinivasan (2005) |
| Crop Moisture | CMI | Abnormal evaporation deficit, defined | Palmer (1968) |

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| Index | | as the difference between $E_{\mathrm{act}}$ and climatologically expected weekly evaporation. Whereby the latter is the normal value adjusted up or down according to the departure of the week's temperature from normal (Wilhite and Glantz, 1985). | |
| Stress Day Index | SDI | Product of a stress day factor (*SD*) that measures the degree and duration of plant water deficit and a crop susceptibility factor (*CS*), which is specific for the crop species and growth stage, indicating a crop's susceptibility to water deficit. Various definitions of *SD* are proposed based on $Tr_{\mathrm{act}}$ and $Tr_{\mathrm{pot}}$ and/or leaf and soil water potential. | Hiler and Clark (1971) |
| Crop-Specific Drought Index | CSDI | $\prod_{i=1}^{n}\left(\frac{\sum E_{act}}{\sum E_{pot,c}}\right)_{i}^{\lambda_i}$<br>Index *i* depicts the crop growth stage. Exponent $\lambda_{\mathrm{i}}$ expresses the relative sensitivity of the crop to moisture stress during stage *i*.<br>Meyer et al. (1993) initially developed the *CSDI* for corn. Later on, the index was also applied for soybean, wheat and sorghum (Wu et al., 2004). | Meyer et al. (1993) |
| Integrated transpiration deficit | DTx | $\sum_{i=1}^{x}\left(Tr_{pot} - Tr_{act}\right)$<br>Transpiration deficit that has been | Marletto et al. (2005) |

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| | | built up during a period of *x* days before. | |
| Actual to potential canopy conductance | LTA | $\frac{g_{act}}{g_{pot}}$<br>Ratio of actual to potential canopy conductance. It describes the extent to which transpiration and photosynthesis are co-limited by soil water deficits (Gerten et al., 2007). | Gerten et al. (2005) |
| Water Deficit Index | WDI | $1-\frac{Tr_{act}}{Tr_{pot}}$ | Woli et al. (2012) |
| Agricultural Reference Index for Drought | ARID | $1-\frac{Tr_{act}}{E_{pot,ref}}$ | Woli et al. (2012) |
| MODIS Global Terrestrial Drought Severity Index | DSI | Standardized sum of the standardized ratio of $E_{\mathrm{act}}$ to $E_{\mathrm{pot}}$ and the standardized Normalized Difference Vegetation Index (*NDVI*). The latter only during the snow-free growing season. | Mu et al. (2013) |
| Green Water Scarcity Index | GWSI | $\frac{\min(P_{eff}, E_{pot,c})}{P_{eff}}$<br>Ratio of the green water consumption of a three-years crop rotation (in $m^3$ $m^{-2}$ $rotation^{-1}$) over the effective precipitation during the same period ($P_{\mathrm{eff}}$ in $m^3/m^2$/rotation). $P_{\mathrm{eff}}$ represents infiltrated precipitation as a proxy for crop-available green water. Green water consumption is defined as the | Nunez et al. (2013) |

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|  |  | minimum of $P_{\mathrm{eff}}$ and $E_{\mathrm{pot,c}}$. Therefore, the index is 1 if $P_{\mathrm{eff}} \leq E_{\mathrm{pot,c}}$ and ranges from 0 to 1 if $P_{\mathrm{eff}} > E_{\mathrm{pot,c}}$. It measures to which extent available green water during the three-year period was sufficient to meet the evaporative demand of the crop rotation during that period. |  |
| Green Water Stress Index | GrWSI | $\frac{E_{act} / E_{pot}}{\overline{E_{act}} / \overline{E_{pot}}}$ | Wada (2013) |

Table A3. Absolute soil moisture indicators.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| Antecedent Precipitation Index | API | $k \times API_{i-1} + P_i$<br>*API* on day *i* is calculated by multiplying *API* of the previous day with a factor *k* (e.g. 0.9) and adding the *P* during day *i*. By combining the amount and timing of precipitation, the index is a proxy for available soil moisture. | McQuigg (1954) |
| Agricultural Drought Day | ADD | $\sum_{i=1}^{L} day \Big\rvert_{\theta \leq \theta_{wp}}$<br>*L* = length of the period considered | Rickard (1960) |
| Kulik's drought indicator | KU | $\sum day \big\rvert_{S<S_{thres}}$<br>*S* in tilled layer of soil (top 20 cm). | Kulik (1958) as cited by World Meteorological Organization (1975) |
| Keetch-Byram drought index | KBDI | The amount of net precipitation (precipitation minus evaporation) that is required to fill up the soil moisture to field capacity. | Keetch and Byram (1968) |
| Soil Moisture Drought Index | SMDI | $\sum_{i=1}^{365} S$ | Hollinger et al. (1993) as cited by Byun and Wilhite (1999) |
| Soil Moisture Index | SMIX | $\int_{t1}^{t2} \int_{l1}^{l2} S \ dldt$<br>*t1* and *t2* are usually start and end of | Isard et al. (1995) |

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|  |  | growing seasons (authors also take *t2* somewhat before end of the cropping period); *l1* and *l2* are the soil depths over which integration takes place; *l1* is the soil surface and *l2* represents the rooting depth, which depends on the crop type and stage of growth. |  |
| Water stress coefficient | $K_s$ | $\frac{S_{tot} - S_{depl}}{(1-p) \times S_{tot}}$<br>$S_{tot}$ = total available soil water in the root zone (mm); $S_{depl}$ = root zone depletion (mm); $p$ = part of total available soil water in the root zone that a crop can extract from the root zone without suffering from water stress. | Allen et al. (1998) |
| Temperature - Vegetation Dryness Index | TVDI | Surface soil moisture availability based on an empirical parameterisation of the relationship between *NDVI* and land surface temperature (*LST*) derived from satellite observations. | Sandholt et al. (2002) |
| Modified Perpendicular Drought Index | MPDI | Soil moisture and vegetation status on the basis of near-infrared and red spectral reflectance space. | Ghulam et al. (2007a);Ghulam et al. (2007b) |
| Average green water storage availability | Avg-GWS | Long-term average number of months in which $S > 1$ mm m$^{-1}$. | Schuol et al. (2008) |
| Standard deviation of | SD-GWS | Standard deviation of the number of months in which $S > 1$ mm m$^{-1}$. | Schuol et al. (2008) |

| | | | |
|---|---|---|---|
| green water storage availability | | | |
| Soil Moisture Index | SMI | $-5+10\frac{\theta-\theta_{WP}}{\theta_{FC}-\theta_{WP}}$<br>$\theta$ = volumetric soil moisture content (cm $m^{-1}$); $\theta_{WP}$ = volumetric soil moisture content at wilting point (cm $m^{-1}$); $\theta_{FC}$ = volumetric soil moisture content at field capacity (cm $m^{-1}$). | Hunt et al. (2009) |

Table A4. Agricultural suitability under rain-fed conditions.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| GAEZ crop-specific suitability under rain-fed conditions | GAEZ | Crop-specific suitability under rain-fed conditions is based on estimates of agro-ecologically attainable yields. First, agro-climatically attainable yields are determined based on a water balance approach that calculates $E_{act}$ and additionally considers crop water requirements and a crop's sensitivity to water stress during the various stages of growth to calculate a yield reduction factor due to water limitations. Second, agro-climatically attainable yields are further reduced by agro-edaphic constraints. | IIASA/FAO (2012) |
| GLUES crop-specific suitability under rain-fed conditions | GLUES | Crop-specific suitability under rain-fed conditions is based on a fuzzy logic approach with crop-specific membership functions for climatic, soil and topographic conditions. Yield estimates are not provided by the GLUES methodology. | Zabel et al. (2014) |

Table B1. Meteorological drought indicators based on precipitation only.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| Days of rain | DoR | $\sum day\big\|_{P<P_{thres}}$ | Munger (1916);Kincer (1919);Blumenstock (1942) |
| Percent of average precipitation | PoAP | $\frac{P}{\overline{P}}$ | Bates (1935);Hoyt (1936) as cited by World Meteorological Organization (1975) |
| Foley Drought Index | FDI | Cumulative deficiency (excess) of *P* in certain month (period) compared to the long-term average *P* for that month (period), expressed in thousands of annual *P*. | Foley (1957) as cited by World Meteorological Organization (1975) and Keyantash and Dracup (2002) |
| Rainfall Anomaly Index | RAI | $\pm 3\frac{P-\overline{P}}{\overline{P_{ext}}-\overline{P}}$<br>$\overline{P_{ext}}$ = average of the 10 most extreme precipitation amounts on record (largest for positive and smallest for negative anomalies). Can be calculated on weekly, monthly or annual time scale (Wanders et al., 2010). | Van Rooy (1965) as cited by Keyantash and Dracup (2002) |
| Deciles | - | In which decile of a long-term record of precipitation events a certain | Gibbs and Maher (1967) |

|  |  |  |  |
|---|---|---|---|
|  |  | precipitation event falls. | as cited by Wilhite and Glantz (1985) |
| Bhalme and Mooley Drought Index | BMDI | The percentage departure of monthly rainfall from the long-term mean weighted by the reciprocal of the coefficient of variation. | Bhalme and Mooley (1980) |
| Standardized Precipitation Index | SPI | Precipitation deviation for a normally distributed probability density with a mean of zero and standard deviation of one. | McKee et al. (1993) |
| National Rainfall Index | NRI | National average of annual precipitation weighed according to the long-term average precipitation of all individual stations in a country. | Gommes and Petrassi (1994) |
| Effective Drought Index | EDI | Ratio of the difference between effective precipitation (*EP*, calculated from equations based on precipitation) and its 5-day running mean over the standard deviation of this difference. | Byun and Wilhite (1999) |
| Precipitation Condition Index | PCI | $\frac{P - P_{\min}}{P_{\max} - P_{\min}}$<br>$P$ inputs refer to monthly amounts. | Du et al. (2013) |

Table B2. Meteorological drought indicators based on precipitation and a measure of potential evaporation.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| Palmer Drought Severity Index | PDSI | Accumulated weighted differences between actual precipitation and precipitation requirement of evaporation (Wilhite and Glantz, 1985). | Palmer (1965);Alley (1984) |
| Reconnaissance Drought Index | RDI | Standardized ratio of $P$ to $E_{pot}$ based on a lognormal distribution. | Tsakiris and Vangelis (2005);Tsakiris et al. (2007) |
| Standardized Precipitation Evapotranspiration Index | SPEI | Standardized difference between $P$ and $E_{pot}$ based on a log-logistic distribution. | Vicente-Serrano et al. (2009) |
| Water Surplus Variability Index | WSVI | Standardized difference between $P$ and $E_{pot,ref}$ based on a logistic distribution. | Gocic and Trajkovic (2014) |

Table B3. Vegetation drought indicators.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| Normalized Difference Vegetation Index Anomaly | NDVIA | $NDVI - \overline{NDVI}$ | Tucker (1979);Myneni et al. (1998) |
| Vegetation Condition Index | VCI | $\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}$<br>$NDVI_{\min}$ = multiyear minimum of smoothed weekly NDVI<br>$NDVI_{\max}$ = multiyear maximum of smoothed weekly NDVI | Kogan (1990, 1995) |
| Vegetation Health Index | VHI | $a \cdot VCI + b \cdot TCI$<br>$a$ = coefficient quantifying share of $VCI$ contribution in the combined condition; $b$ = coefficient quantifying share of $TCI$ contribution in the combined condition; $TCI$ = Temperature Condition Index; $VCI$ = Vegetation Condition Index | Kogan (2001) |
| Standardized Vegetation Index | SVI | *NDVI* deviation for a normally distributed probability density with a mean of zero and standard deviation of one. | Peters et al. (2002) |
| Normalized Difference Water Index Anomaly | NDWIA | Adaptation of *NDVI* (Gao, 1996) compared to its multi-year mean. | Gu et al. (2007) |

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|---|---|---|---|
| Enhanced Vegetation Index Anomaly | EVIA | *EVI* anomaly. *EVI* is an improvement over *NDVI*, which keeps sensitivity over densely vegetated areas (Huete et al., 1994). | Saleska et al. (2007) |
| Percent of Average Seasonal Greenness | PASG | $\frac{SG}{\overline{SG}}\times 100\%$<br>*SG* = seasonal greenness, defined as accumulated *NDVI* above background *NDVI* during a specified period. | Brown et al. (2008) |

Table B4. Relative soil moisture availability indicators.

| Name | Acronym | Formula/Description | Reference |
|---|---|---|---|
| Soil water Deficit | SD (& SMDI) | Difference between mean weekly and long-term median *S*, divided by the difference between long-term minimum (maximum) and median *S*. | Narasimhan and Srinivasan (2005) |
| Palmer Z-index (a.k.a. Palmer moisture anomaly index) | PZI | Moisture anomaly for the current period from the climate-average moisture conditions for that period. | Palmer (1965);Alley (1984) |
| Soil Moisture Anomaly Index | SMAI | $\frac{\theta-\bar{\theta}}{\bar{\theta}}\times 100\%$<br>$\theta$ = volumetric soil moisture content | Bergman et al. (1988) |

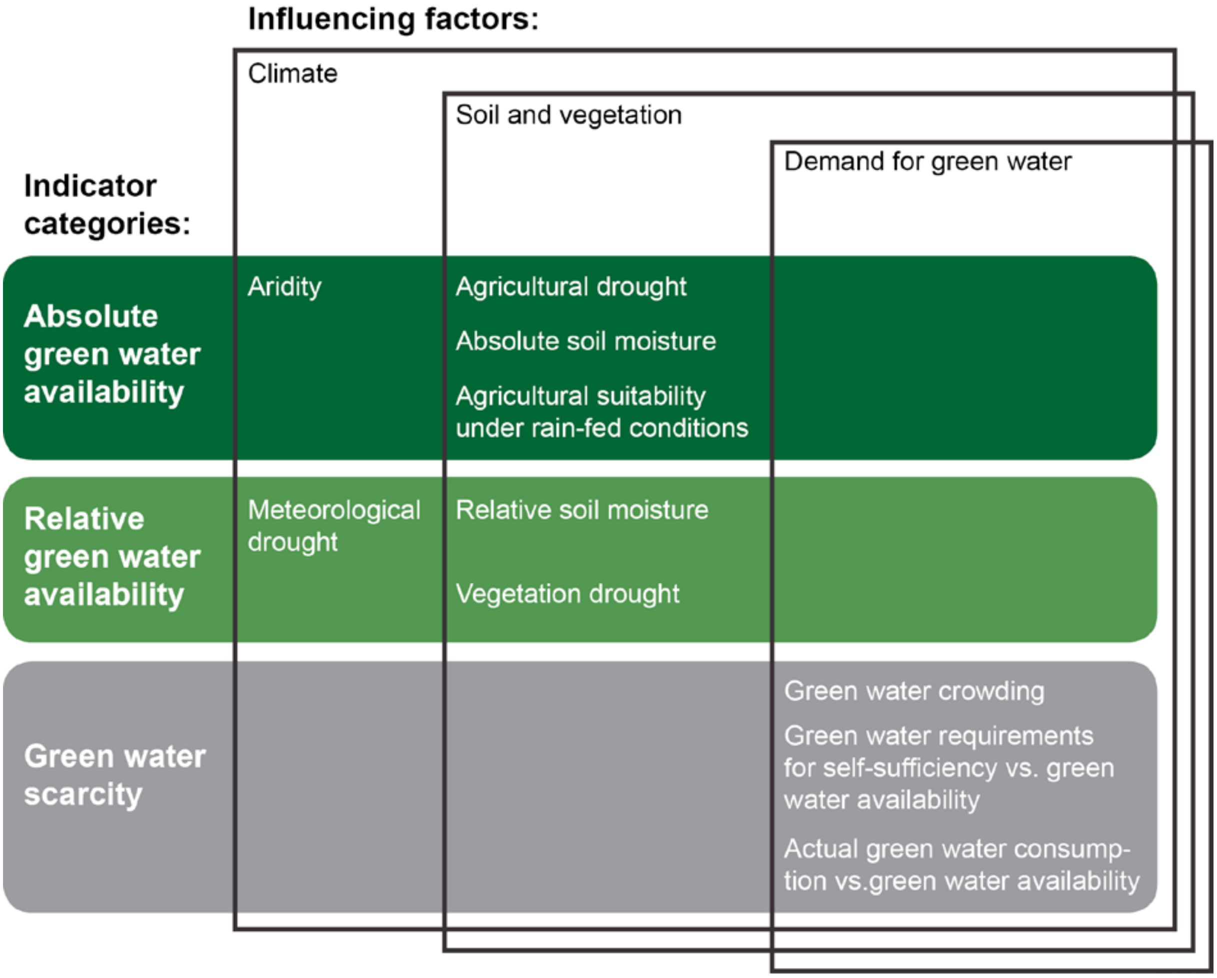

Figure 1. Conceptual diagram of indicator categories and the factors that influence them.