

1 **Review and classification of indicators of green water**
2 **availability and scarcity**

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1 **Abstract**

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

13

1 **1 Introduction**

2 Freshwater is a renewable resource that is naturally replenished over time when moving
3 through the hydrological cycle (Oki and Kanae, 2006;Hoekstra, 2013). Precipitation forms the
4 input of freshwater on land. Subsequently, it takes the blue or the green pathway back to the
5 ocean and atmosphere before eventually returning as precipitation again (Falkenmark,
6 2003;Falkenmark and Rockström, 2006;Falkenmark and Rockström, 2010). The water that
7 runs off to the ocean via rivers and groundwater is called the blue water flow. The green water
8 flow is formed by the water that is temporarily stored in the soil and on top of vegetation and
9 returns to the atmosphere as evaporation instead of running off (Hoekstra et al., 2011). As
10 suggested by Savenije (2004), we use in this paper the term evaporation (instead of the often
11 used term evapotranspiration) to refer to the vapour flux from land to atmosphere, which
12 includes soil evaporation, evaporation of intercepted water, transpiration and in some cases
13 (e.g. rice or swamp vegetation) open-water evaporation. About three-fifth of the precipitation
14 over land takes the green path and two-fifth the blue path (Oki and Kanae, 2006).

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

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

26 Water scarcity is becoming increasingly important for multiple reasons. The growing world
27 population leads to rising demands for food, energy and other water-consuming goods and
28 services (Hejazi et al., 2014;WWAP, 2015). Moreover, people's diets are changing toward
29 more livestock-based products, due to rising incomes and continuing urbanization (Molden,
30 2007). Such diets are more water and land intensive (Erb et al., 2009;Kastner et al.,
31 2012;Odegard and van der Voet, 2014). Policies towards more energy production from
32 biomass create additional pressure on water and land (Hejazi et al., 2014). On top of this, a

1 changing climate with increased variability and more extremes (IPCC, 2013) amplifies water
2 scarcity (WWAP, 2014).

3 Given that green and blue water resources are limited and there are competing demands for
4 both, green water as well as blue water are scarce. Therefore, it is surprising that research and
5 debate on water scarcity have been, and still are, mainly focused on blue water (Vörösmarty et
6 al., 2000;Rijsberman, 2006;Vörösmarty et al., 2010;Wada et al., 2011;Hoekstra et al.,
7 2012;WWAP, 2014, 2015). Although the importance of green water has increasingly gained
8 acceptance since Falkenmark (1995) drew attention to it in the mid-1990s (Savenije,
9 2000;Rockström, 2001;Rijsberman, 2006;Liu et al., 2009;Hanasaki et al., 2010;Hoekstra and
10 Mekonnen, 2012), the notion of green water scarcity is only limitedly addressed in literature
11 (Falkenmark, 2013a, b;Falkenmark et al., 2007). While the need to incorporate green water in
12 water scarcity indicators and assessments has already been expressed since the beginning of
13 this millennium (Savenije, 2000;Rockström, 2001;Rijsberman, 2006;Falkenmark and
14 Rockström, 2006), only a few attempts have been made so far in the form of combined green-
15 blue water scarcity assessments (Rockström et al., 2009;Gerten et al., 2011;Kummu et al.,
16 2014) (discussed in detail in Sect. 3.2).

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

28 Therefore, it is due time that more attention is given to green water scarcity and how we can
29 measure it. In this review, we make an inventory of existing indicators of green water
30 availability and scarcity and classify them based on their scope and purpose of measurement.
31 The classification allows us to discuss similarities and differences between indicators and give
32 advice on how the various indicator classes could be used to measure different kinds of green

1 water availability or scarcity. This is useful in order to properly include limitations in green
2 water availability in water scarcity assessments.

3 A review of green water scarcity indicators is new in its kind. Past reviews of water scarcity
4 indicators (Savenije, 2000;Rijsberman, 2006) date back a while and hence do not include
5 recent developments in the field, especially those related to the inclusion of green water.
6 There exist multiple reviews of indicators of aridity (Wallén, 1967;Walton, 1969;Stadler,
7 2005) and drought (World Meteorological Organization, 1975;Wilhite and Glantz,
8 1985;Maracchi, 2000;Tate and Gustard, 2000;Keyantash and Dracup, 2002;Heim,
9 2002;Hayes, 2007;Kallis, 2008;Mishra and Singh, 2010;Sivakumar et al., 2010). We classify
10 and discuss these indicators in an overarching way. First, we discuss the multiple dimensions
11 of water availability and scarcity and sharpen the scope of this review (Sect. 2). Next, we
12 classify and review green water availability and scarcity indicators (Sect. 3). Finally, we draw
13 conclusions and discuss future research directions (Sect. 4).

14 **2 Multiple aspects of water availability and scarcity**

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

18 **2.1 Water availability and scarcity**

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

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

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

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

5 The concept of scarcity describes a relation between humans and nature (Baumgärtner et al.,
6 2006). Nevertheless, we can distinguish water scarcity mainly caused by natural conditions of
7 low water availability from scarcity mainly induced by a large human demand relative to
8 natural availability. The latter can also occur in naturally water abundant areas (Pereira et al.,
9 2002).

10 Until now we have spoken about physical water scarcity, referring to the situation where there
11 is insufficient water to meet human demand. If human, institutional and financial capital limit
12 access to the water, the term economic water scarcity applies (Seckler et al., 1999; Molden,
13 2007). In a broader sense, Ohlsson (2000) defines social resource scarcity as the situation in
14 which social resources required to successfully adapt to physical water scarcity fall short.

15 **2.2 Relative and absolute water scarcity**

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

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

1 water scarcity turns into absolute scarcity when the boundaries of water exploitation are
2 approached.

3 **2.3 Blue and green water**

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

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

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

1 **2.4 Water quantity and quality**

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

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

13 **2.5 Scope of the review and classification**

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

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

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

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

9 Furthermore, the review and classification in this paper excludes indicators that measure
10 drought by combining multiple drought indicators (classified individually) and sometimes
11 other information such as land-use maps. Examples of such indicators are the U.S. Drought
12 Monitor (Svoboda et al., 2002) and the Vegetation Drought Response Index (Brown et al.,
13 2008).

14 **3 Green water availability and scarcity indicators**

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

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

27 Note that this distinction between absolute and relative indicators is unrelated to and
28 different from the concepts of relative and absolute scarcity earlier discussed in Sect.
29 2.2.

1 2. *Green water scarcity indicators* incorporate elements of both water availability and
2 demand and therefore respond – in contrast to green water availability indicators – to
3 changes in water demand as well. We distinguish three different options to measure
4 green water scarcity conceptually (explanation in Sect. 3.2):

5 a. *Green water crowding*

6 b. *Green water requirements for self-sufficiency versus green water availability*

7 c. *Actual green water consumption versus green water availability*

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

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

25 **3.1 Green water availability indicators**

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

1 3.1.1 Absolute green water availability indicators

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

7 **Aridity indicators**

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

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

27 **Agricultural drought indicators**

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

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

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

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

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

28 **Absolute soil moisture indicators**

29 Multiple indicators provide a measure of the absolute amount of soil moisture available at a
30 given location and moment (or summed over a period), be it on the basis of field
31 measurements (e.g. SMIX, SMI) and/or modelling of the soil water balance (e.g. Avg-GWS

1 and SD-GWS) or remote sensing data (e.g. TVDI, MPDI). They can be used for monitoring
2 spatial and/or temporal variations in soil moisture availability. Temporal analysis of soil
3 moisture availability can warn for the onset of agricultural drought, or in contrast, the
4 proneness to flash floods (Hunt et al., 2009). Several of these indicators have been introduced
5 and applied as indicators of agricultural drought (e.g. ADD, SMDI, SMIX, SMI), analysing
6 the correlation between soil moisture availability and crop yields. Therefore, they are
7 typically calculated on intra-annual time-scales.

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

11 **Agricultural suitability under rain-fed conditions**

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

25 **3.1.2 Relative green water availability indicators**

26 Indicators in this category measure green water availability relative to a ‘normal’ condition
27 and are usually calculated on intra-annual scales. As opposed to aridity, drought is often
28 defined as a condition relative to what is perceived as a ‘normal’ amount of precipitation or
29 balance between precipitation and evaporation (World Meteorological Organization,
30 1975; Wilhite and Glantz, 1985). Droughts are often termed temporary, uncertain and difficult
31 to predict features characterized by lower-than-average precipitation (Pereira et al.,

1 2002;Heim, 2002;Kallis, 2008;Mishra and Singh, 2010;FAO, 2015). Therefore, indicators of
2 meteorological drought and vegetation drought are classified into the category of relative
3 green water availability indicators. Indicators that measure soil moisture in a relative sense are
4 included in this category as well. Just like aridity indicators, meteorological drought
5 indicators are solely based on climatic variables. The other two subcategories are also affected
6 by the soil and vegetation and how they are managed. The three subcategories are sequentially
7 discussed in the following.

8 **Meteorological drought indicators**

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

18 **Vegetation drought indicators**

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

29 **Relative soil moisture indicators**

30 In contrast to the absolute soil moisture indicators discussed in Sect. 3.1.1, these indicators
31 measure the moisture conditions at a given location relative to a normal condition. Identified

1 examples are the PZI, SMAI and SD. These indicators have similar uses as absolute soil
2 moisture indicators. They are also used to correlate soil moisture conditions to crop yields and
3 are considered suitable for measuring agricultural droughts (Keyantash and Dracup,
4 2002;Narasimhan and Srinivasan, 2005).

5 **3.2 Green water scarcity indicators**

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

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

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

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

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

- 1 b. *Green water requirements for self-sufficiency versus green water availability*: green
2 water requirements for producing the consumed biomass-based products within a
3 certain geographic area, assuming self-sufficiency within the geographic area,
4 compared to the green water resources in the geographic area.
- 5 c. *Actual green water consumption versus green water availability*: actual green water
6 consumption in a certain geographic area (associated with the actual production of
7 biomass for human purposes) compared to green water availability in the area. This
8 type of indicator thus acknowledges the possibility of virtual water trade as opposed to
9 assuming self-sufficiency as in the previous two types of indicators.

10 In Sects. 3.2.1 and 3.2.2, we discuss existing indicators that measure overall green-blue water
11 scarcity and reflect on how these indicators could be adapted to measure green water scarcity
12 specifically, according to above-mentioned options a and b. In Sect. 3.2.3, we elaborate upon
13 a third way of measuring green water scarcity that has yet to be brought into practice. The
14 challenges for operationalization of these green water scarcity indicators are discussed in Sect.
15 3.2.4. Finally, in Sect. 3.2.5 we reflect on green water scarcity indicators versus indicators
16 that measure overall green-blue water scarcity.

17 3.2.1 Green water crowding

18 Rockström et al. (2009) introduced a combined green-blue water shortage index, which
19 compares the sum of green and blue water availability with a global average threshold of
20 1,300 m³/cap/yr. This threshold represents the green and blue water requirements for
21 sustaining a global average ‘standard diet’. When green-blue water availability drops below
22 the threshold, this indicates a shortage of green-blue water resources in the study area and
23 reflects the area’s dependency on external water resources. The green-blue water shortage
24 index is an indicator of water crowding, similar to Falkenmark’s blue-water focused water
25 crowding indicator (Falkenmark et al., 1989).

26 Similar to the indicator by Rockström et al. (2009), an indicator of green water crowding
27 could be defined as the per capita available green water resources in an area compared to a
28 global average threshold representing the amount of green water required to sustain a person’s
29 ‘standard consumption pattern’. We intentionally speak here of a consumption pattern,
30 because green water is not only required to produce food, but also to produce other biomass-
31 based products humans consume, such as fibres, biofuels and forestry products. As such, the

1 measure of green water requirements we propose here is broader than the definition of a
2 'standard diet' according to Rockström et al. (2009) (and Gerten et al. (2011) and Kummu et
3 al. (2014)), which only pertains to water requirements for food production.

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

11 3.2.2 Green water requirements for self-sufficiency versus green water availability

12 Gerten et al. (2011) and Kummu et al. (2014) elaborated on the work by Rockström et al.
13 (2009) by further developing and applying the overall green-blue water scarcity indicator.
14 Instead of using a global average, Gerten et al. (2011) calculate the green-blue water
15 requirements for sustaining a 'standard diet' on the national level based on local crop water
16 productivities and compare this with the sum of green and blue availability in each country of
17 the world. The resulting green-blue water scarcity indicator, computed for each country, is
18 defined as the ratio between green-blue water availability and green-blue water requirements
19 for producing the standard diet. They define green water availability similar to Rockström et
20 al. (2009), but a bit more conservative: they do not assume year-round evaporation from areas
21 covered with their category of 'other' crops that they parameterized as perennial grass, since
22 this category includes non-food crops and crops that grow only during a part of the year
23 (Gerten et al., 2011).

24 Whereas the studies by Rockström et al. (2009) and Gerten et al. (2011) are based on climate-
25 averages, Kummu et al. (2014) apply the green-blue water scarcity indicator by Gerten et al.
26 (2011) on a year-by-year basis to account for inter-annual climate variability on the scale of
27 food producing units, the scale at which demand for water and food is assumed to be managed
28 according to the authors. Kummu et al. (2014) measure the frequency of years in which
29 green-blue water availability falls short of green-blue water requirements, on which they base
30 their classification of green-blue scarcity: no scarcity; occasional scarcity (subdivided in four
31 levels); or chronic scarcity.

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

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

12 3.2.3 Actual green water consumption versus green water availability

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

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

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

7 Furthermore, the indicator does not deal with green water scarcity at a particular site as
8 looked upon by Falkenmark et al. (2007) and Falkenmark (2013a). They describe green water
9 scarcity as an issue of lower-than-potential plant-accessible water in the root zone and the
10 occurrence of unproductive evaporation losses from the field, which results in lower yields
11 than potentially achievable. First, blue water losses in the form of surface run-off and
12 percolation decrease the plant-accessible water in the root zone (smaller green water flow)
13 (Rockström and Falkenmark, 2000). Such losses are the result of a soil's low infiltration
14 capacity (e.g. soil crusting) and poor soil water holding capacity, but can be caused or
15 aggravated by human action through soil mismanagement (Falkenmark, 2013a). Second, low
16 root/crop water uptake capacity leads to unproductive evaporation losses (green water flow
17 not entirely productive) (Rockström and Falkenmark, 2000). Transpiration is a productive
18 form of green water use, contributing to biomass production, while other components of the
19 evaporative flow are regarded as unproductive (Rockström and Falkenmark, 2000; Rockström,
20 2001; Rockstrom et al., 2007; Savenije, 2004). Rockstrom et al. (2007) express the productivity
21 of green water use as the ratio of transpiration to evaporation. Rockström et al. (2009) call this
22 the transpiration efficiency. This transpiration efficiency is complementary to the green water
23 scarcity indicator by Hoekstra et al. (2011). A green water scarcity assessment based on both
24 will give insight into the *severity* of green water scarcity: areas that are considered highly
25 green-water scarce, but have a low transpiration efficiency, may have options to improve the
26 latter and thereby yields, which may lower the green water scarcity.

27 3.2.4 Challenges for operationalization of green water scarcity indicators

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

30 First, the determination of which areas and periods of the year the green water flow can be
31 used productively is not straightforward. Absolute green water availability indicators, in
32 particular land classifications of agricultural suitability, can provide insight in the availability

1 of green water in the spatial dimension. Relative green water availability indicators can enrich
2 the picture by showing which areas are prone to large inter- and intra-annual variations in
3 green water availability, making these areas less suitable for (certain types of) biomass
4 production. To estimate which part of the green water flow can be used productively in time,
5 advanced crop growth models (like APSIM (McCown et al., 1995;Holzworth et al., 2014),
6 AquaCrop (Steduto et al., 2009), CropSyst (Stöckle et al., 2003), EPIC (Jones et al., 1991) or
7 SWAP/WOFOST (van Dam et al., 2008)) can be used to simulate water-limited yields and
8 actual evaporation for various cropping periods and different types of soil, crop and
9 agricultural water management (e.g. adding blue water in the form of deficit irrigation during
10 a dry spell, might make it possible for the crop to survive and use the green water flow later in
11 the year productively).

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

16 Third, research is required to determine the environmental green water requirements, i.e. the
17 green water flow that should be preserved for nature, similar to the environmental flow
18 requirements for blue water. Key here is the identification of areas that need to be reserved for
19 nature and biodiversity conservation. It is known that the current network of protected areas is
20 insufficient to conserve biodiversity (Rodrigues et al., 2004a;Rodrigues et al., 2004b;Venter
21 et al., 2014;Butchart et al., 2015) and that attention should be paid to conservation of
22 biodiversity in production landscapes that are shared with humans (Baudron and Giller,
23 2014). The 11th Aichi Biodiversity Target is to expand the protected area network, which
24 currently has a terrestrial coverage of about 14.6% (Butchart et al., 2015), to at least 17%
25 terrestrial coverage by 2020 (Convention on Biological Diversity, 2010). However, to
26 properly assess the limitations to green water availability, spatially explicit information on the
27 additional areas to be preserved is required. The best-available data regarding this is recently
28 published work by Montesino Pouzols et al. (2014). These authors have mapped global and
29 national priority areas for expansion of the protected area network on 0.2 degrees spatial
30 resolution and assessed associated conservation gains (Montesino Pouzols et al.,
31 2014;Brooks, 2014).

1 3.2.5 Measuring green water scarcity versus overall green-blue water scarcity

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

15 **4 Conclusions and future research**

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

19 The number of green water availability indicators by far outnumbers the existing green water
20 scarcity indicators. This reflects that the concept of green water scarcity is still largely
21 unexplored. Indicators of overall green-blue water crowding and scarcity have been
22 developed by Rockström et al. (2009), Gerten et al. (2011) and Kummu et al. (2014). These
23 have potential to be tailored to measure green water crowding and green water requirements
24 for self-sufficiency versus green water availability. The green water scarcity indicator by
25 Hoekstra et al. (2011) measures actual green water consumption versus green water
26 availability, but has not yet been operationalized due to several challenges discussed in Sect.
27 3.2.4. The biggest challenge is to determine which part of the green water flow can be made
28 productive in space and time. Application of both absolute and relative green water
29 availability indicators will provide insight into where the green water flow can be made
30 productive for human purposes. Simulations with crop growth models for different
31 management strategies can be used to assess during which parts of the year the green water
32 flow can be made productive.

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

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

12

1 **Appendix A: Absolute green water availability indicators**

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

7 Table A1. Aridity indicators.

8 Table A2. Agricultural drought indicators.

9 Table A3. Absolute soil moisture indicators.

10 Table A4. Agricultural suitability under rain-fed conditions.

11

1 **Appendix B: Relative green water availability indicators**

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

5 Table B1. Meteorological drought indicators based on precipitation only.

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

8 Table B3. Vegetation drought indicators.

9 Table B4. Relative soil moisture availability indicators.

10

1 **Author contribution**

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

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42

1 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.

1

1 Table A1. Aridity indicators.

Name	Acronym	Formula/Description	Reference
Rainfall- evaporation ratio	RER	$\frac{P}{E_{ow}}$ E_{ow} = open water evaporation	Transeau (1905)
Rain Factor	RF	$\frac{P}{T}$	Lang (1920)
Koloskov Index	KI	$\frac{P}{\sum T}$ 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	$\frac{P}{D}$ D = mean annual atmospheric saturation deficit	Meyer (1926) as cited by Thornthwaite (1931) and Budyko (1958)
Reichel's Aridity Index	R-AI	$\frac{N \times P}{T + 10}$ N = number of rainy days	Reichel (1928) as cited by Perez-Mendoza

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

$$P = 2(T + 14) \text{ (summer rainfall)}$$

$$P = 2T \text{ (winter rainfall)}$$

Threshold for classifying area as arid:

$$P = T + 14 \text{ (summer rainfall)}$$

$$P = T \text{ (winter rainfall)}$$

P = annual precipitation amount in cm yr⁻¹; T = mean annual temperature in °C.

Aridity
Coefficient

AC

$$f_{lat} \times (T_{max} - T_{min}) \times \left(\frac{P_{max} - P_{min}}{P_{avg}} \right)$$

Gorczynski
(1940)

f_{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_{avg} = average annual precipitation amount on record

Modified de
Martonne
Aridity Index

MdM-AI

$$\frac{1}{2} \left(\frac{P}{T + 10} + \frac{12P_d}{T_d + 10} \right)$$

de Martonne
(1942)

P_d = precipitation in the driest month;
 T_d = temperature in the driest month

Popov's Aridity
Index

P-AI

$$\frac{P_{eff}}{2.4(t - t')r}$$

Popov (1948)
as cited by

P_{eff} = annual amount of precipitation available to plants; r = factor depending on day length; $t - t'$ = annual mean wet bulb depression in °C.

World
Meteorological
Organization
(1975)

Moisture Index; Aridity Index; Humidity Index	I _m ; I _a ; I _h	$I_a = \frac{100d}{E_{pot}}$ $I_h = \frac{100s}{E_{pot}}$ $I_m = I_h - 0.6I_a$	Thornthwaite (1948)
<p>where d is a water deficiency when $P < E_{pot}$ and s is a water surplus when $P > E_{pot}$.</p> <p>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.</p>			
Capot-Rey's Aridity Index	CR-AI	$\frac{1}{2} \left(\frac{100P}{E_{pot}} + \frac{12P_w}{E_{pot,w}} \right)$	Capot-Rey (1951)
<p>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)</p>			
Radiational Index of Dryness	RID	$\frac{R}{L \times P}$	Budyko (1958)
<p>R = mean annual net radiation; L = latent heat of vaporization of water</p>			
Gausse Classification	GC	$P \leq 2T$	UNESCO (1963)
Sly's Climatic Moisture Index	SCMI	$\frac{P}{P + S + I}$	Sly (1970)
<p>I = irrigation requirement for non-</p>			

		water limited growth.	
		<i>P</i> and <i>I</i> during growing season. <i>S</i> at start of growing season. The index is made purely climatic by fixed assumptions on the non-climatic factors.	
Moisture Availability Index	MAI-H	$\frac{P_{dep}}{E_{pot}}$ <i>P</i> _{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 <i>E</i> _{act} of the mixture of crops grown in the study area. Although most crops studied by Wilhelmi et al. (2002) are considered well-watered (<i>E</i> _{act} = <i>E</i> _{pot,c}), for wheat and grasses <i>E</i> _{act} is estimated as the <i>E</i> _{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)

Climatic Moisture Index	CliMI	$\frac{P}{E_{pot}} - 1 \text{ when } P < E_{pot}$ $1 - \frac{E_{pot}}{P} \text{ when } P \geq E_{pot}$	Vörösmarty et al. (2005)
Hydrologic unit evaporation ratio	HU-ER	$\frac{E_{act}}{P}$ <p>Theoretically equivalent to ER (above), but applied to the level of a hydrologic unit.</p>	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)

1

1 Table A2. Agricultural drought indicators.

Name	Acronym	Formula/Description	Reference
Bova's Drought Index	BDI	$\frac{10(S + P)}{\sum T}$ <p>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.</p>	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	$\frac{E_{act}}{E_{pot} \times K_c}$ <p>K_c = crop coefficient that accounts for the difference in evaporation between the considered crop and a reference grass surface.</p> <p><i>WRSI</i> is usually evaluated as sum over the growing season.</p>	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 <i>CWSI</i> .	Anderson et al. (2007a, 2007b); Yao et al. (2010)
Water Stress ratio	WS	$\frac{E_{pot} - E_{act}}{E_{pot}}$ <p>In fact, idem to <i>CWSI</i>.</p>	Narasimhan and Srinivasan (2005)
Crop Moisture	CMI	Abnormal evaporation deficit, defined	Palmer (1968)

Index		as the difference between E_{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_{act} and Tr_{pot} and/or leaf and soil water potential.	Hiler and Clark (1971)
Crop-Specific Drought Index	CSDI	$\prod_{i=1}^n \left(\frac{\sum E_{act}}{\sum E_{pot,c}} \right)_i^{\lambda_i}$ <p>Index i depicts the crop growth stage. Exponent λ_i expresses the relative sensitivity of the crop to moisture stress during stage i.</p> <p>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).</p>	Meyer et al. (1993)
Integrated transpiration deficit	DTx	$\sum_{i=1}^x (Tr_{pot} - Tr_{act})$ <p>Transpiration deficit that has been</p>	Marletto et al. (2005)

			built up during a period of x days before.	
Actual to potential canopy conductance	L_{TA}	$\frac{g_{act}}{g_{pot}}$	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_{act} to E_{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	$\frac{\min(P_{eff}, E_{pot,c})}{P_{eff}}$	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_{eff} in $m^3/m^2/rotation$). P_{eff} represents infiltrated precipitation as a proxy for crop-available green water. Green water consumption is defined as the	Nunez et al. (2013)

minimum of P_{eff} and $E_{\text{pot,c}}$. Therefore, the index is 1 if $P_{\text{eff}} \leq E_{\text{pot,c}}$ and ranges from 0 to 1 if $P_{\text{eff}} > E_{\text{pot,c}}$. 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	GrWSI	$\frac{E_{act} / E_{pot}}{E_{act} / E_{pot}}$	Wada (2013)
Stress Index			

1

1 Table A3. Absolute soil moisture indicators.

Name	Acronym	Formula/Description	Reference
Antecedent Precipitation Index	API	$k \times API_{i-1} + P_i$ <p><i>API</i> on day <i>i</i> is calculated by multiplying <i>API</i> of the previous day with a factor <i>k</i> (e.g. 0.9) and adding the <i>P</i> during day <i>i</i>. By combining the amount and timing of precipitation, the index is a proxy for available soil moisture.</p>	McQuigg (1954)
Agricultural Drought Day	ADD	$\sum_{i=1}^L \text{day} \Big _{\theta \leq \theta_{wp}}$ <p><i>L</i> = length of the period considered</p>	Rickard (1960)
Kulik's drought indicator	KU	$\sum \text{day} \Big _{S < S_{thres}}$ <p><i>S</i> in tilled layer of soil (top 20 cm).</p>	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	$\int_{t1}^{t2} \int_{l1}^{l2} S \, dldt$ <p><i>t1</i> and <i>t2</i> are usually start and end of</p>	Isard et al. (1995)

		growing seasons (authors also take t_2 somewhat before end of the cropping period); l_1 and l_2 are the soil depths over which integration takes place; l_1 is the soil surface and l_2 represents the rooting depth, which depends on the crop type and stage of growth.	
Water stress coefficient	K_s	$\frac{S_{tot} - S_{depl}}{(1 - p) \times S_{tot}}$ <p>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.</p>	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 $S > 1 \text{ mm m}^{-1}$.	Schuol et al. (2008)
Standard deviation of	SD-GWS	Standard deviation of the number of months in which $S > 1 \text{ mm m}^{-1}$.	Schuol et al. (2008)

green water
storage
availability

Soil Moisture SMI
Index

$$-5 + 10 \frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}}$$

Hunt et al.
(2009)

θ = volumetric soil moisture content
(cm m⁻¹); θ_{WP} = volumetric soil
moisture content at wilting point (cm
m⁻¹); θ_{FC} = volumetric soil moisture
content at field capacity (cm m⁻¹).

1

1 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)

2

1 Table B1. Meteorological drought indicators based on precipitation only.

Name	Acronym	Formula/Description	Reference
Days of rain	DoR	$\sum day _{P < P_{thres}}$	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	$\pm 3 \frac{P - \overline{P}}{\overline{P_{ext}} - \overline{P}}$ $\overline{P_{ext}}$ = 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 (<i>EP</i> , 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	$\frac{P - P_{\min}}{P_{\max} - P_{\min}}$	Du et al. (2013)

P inputs refer to monthly amounts.

1 Table B2. Meteorological drought indicators based on precipitation and a measure of potential
 2 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)

3

1 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	$\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}$ $NDVI_{\min}$ = multiyear minimum of smoothed weekly NDVI $NDVI_{\max}$ = multiyear maximum of smoothed weekly NDVI	Kogan (1990, 1995)
Vegetation Health Index	VHI	$a \cdot VCI + b \cdot TCI$ 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)

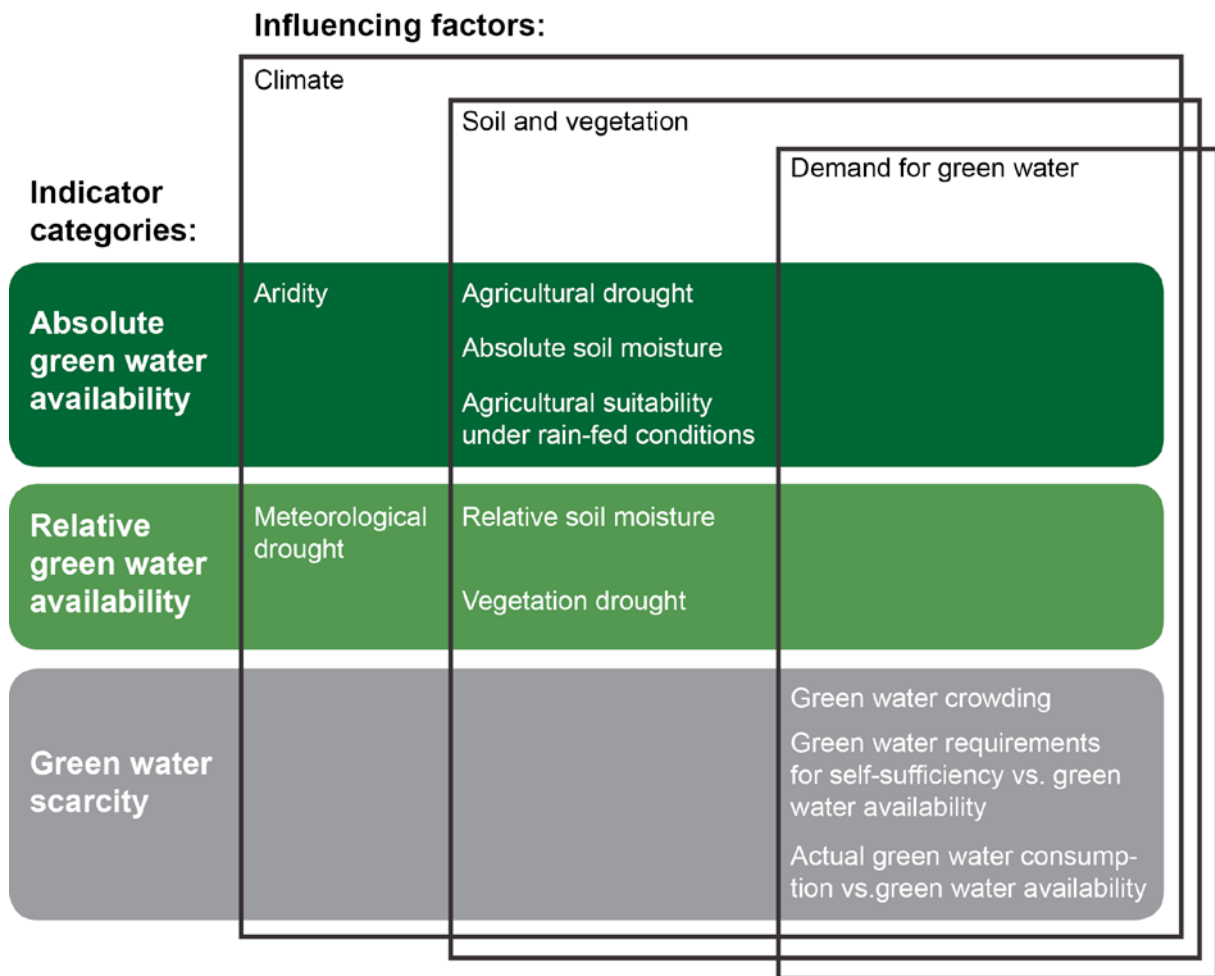
Enhanced Vegetation Index Anomaly	EVIA	<i>EVI</i> anomaly. <i>EVI</i> is an improvement over <i>NDVI</i> , which keeps sensitivity over densely vegetated areas (Huete et al., 1994).	Saleska et al. (2007)
Percent of Average Seasonal Greenness	PASG	$\frac{SG}{\overline{SG}} \times 100\%$ <i>SG</i> = seasonal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

1

1 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	$\frac{\theta - \bar{\theta}}{\bar{\theta}} \times 100\%$ $\theta = \text{volumetric soil moisture content}$	Bergman et al. (1988)

2



1

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