Water scarcity assessments in the past, present and future

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Key Points

- We provide a comprehensive review of water scarcity indicators and reflect on their relevance in a rapidly changing world
- There is a need to incorporate green water, water quality and environmental flow requirements in water scarcity assessment
- Integrated approaches are required to capture the multi-faceted nature of water scarcity

Abstract

Water scarcity has become a major constraint to socio-economic development and a threat to livelihood in increasing parts of the world. Since the late 1980s, water scarcity research has attracted much political and public attention. We here review a variety of indicators that have been developed to capture different characteristics of water scarcity. Population, water availability and water use are the key elements of these indicators. Most of the progress made in the last few decades has been on the quantification of water availability and use by applying spatially explicit models. However, challenges remain on appropriate incorporation of green water (soil moisture), water quality, environmental flow requirements, globalization and virtual water trade in water scarcity assessment. Meanwhile, inter- and intra- annual variability of water availability and use also calls for assessing the temporal dimension of water scarcity. It requires concerted efforts of hydrologists, economists, social scientists, and environmental scientists to develop integrated approaches to capture the multi-faceted nature of water scarcity.

Keywords

Freshwater resources, green water, water quality, environmental flow requirements, virtual water, water footprint

1. Introduction

Population growth, economic development and dietary shift (towards more animal products) have resulted in ever increasing water demand, and consequently pressures on water resources. Many parts of the world are enduring water scarcity which generally refers to the condition wherein demand for water by all sectors, including the environment, cannot be satisfied fully due to the impact of water use on supply or quality of water [*Falkenmark* et al., 1989; *Alcamo*, et al., 2000; *Vörösmarty* et al., 2000]. In the *Global Risks 2015 Report* of the World Economic Forum, water supply crisis was identified as the top 1 high-impact risk for our current times [*World Economic Forum*, 2015].

Understanding water scarcity is important for formulating policies at global, regional, national and local scales. "Addressing water scarcity and quality" is one of the six themes of the 8th Phase of the International Hydrological Programme (IHP-VIII) that focuses on "Water Security: Responses to Local, Regional and Global Challenges (2014-2021)". Similarly, it is a key focus of the scientific decade 2013–2022 of the International Association of Hydrological Sciences (IAHS), named "*Panta Rhei* – Everything Flows", which is dedicated to research activities on changes in hydrology and society [*Montanari* et al., 2013]. A targeted working group on "Water Scarcity Assessment: methodology and application" was established in the *Panta Rhei* program to develop innovative methodology and conduct water scarcity assessment (http://iahs.info/Commissions--W-Groups/Working-Groups/Panta-Rhei/Working-Groups.do). "Substantially reduce the number of people suffering from water scarcity" is also one of the targets set in the Sustainable Development Goals recently adopted by the United Nations [*UN*, 2015].

Since the late 1980s, when water scarcity became an issue, many indicators have been developed to facilitate the assessment of status of water scarcity across the world (Table 1). Publications on water scarcity assessment have increased dramatically in the last two decades (Fig. 1) amid the intensification of the problem in increasing parts of the worlds. Rather straightforward water scarcity indicators were developed in the late 1980s throughout the beginning of the 2000s, which were criticized for their focus on surface water and groundwater (so called blue water) only, neglecting the important role of green water (soil moisture fed by rainfall) and spatial and temporal variations [*Savenije*, 2000; *Rijsberman*, 2006].

(Insert Fig. 1; Insert Table 1)

Entering the 2000s, more sophisticated approaches with high spatial resolution have been developed, attempting to incorporate more aspects of water, such as: water quality, green water (soil moisture), and environmental flow requirements. In recent years, explicit representation of water quality and environmental flow requirement have been taken into account, through a multiple-value water scarcity indicator [*Zeng* et al., 2013; *Liu* et al., 2016]. Although this development has increased understanding of the multi-faceted nature of water scarcity, these attempts usually focused on merely one aspect of water scarcity. In contrast to the wide use of the classical water scarcity indicators developed in the early years, the more integrated indicators have rarely been applied beyond the research groups where they were developed.

It is worth mentioning that most approaches for water scarcity assessment have used single indicators to quantify water scarcity. A few have combined two indicators. For example, *Falkenmark* [1997] assessed blue water scarcity with two indicators, water shortage and water stress (see Table 1), together using 'Falkenmark matrix'. *Kummu* et al. [2016] used similar approach to *Falkenmark* [1997] for water scarcity assessment on the global level for the whole 20th century. According to *Kummu* et al. [2016], areas under both water shortage and stress have very limited adaptation options to alleviate the scarcity compared to areas under sole stress or shortage.

In this paper, we provide a comprehensive review of existing water scarcity indicators and reflect on their relevance in a rapidly changing world. Based on which, we highlight some major challenges faced in the future research and propose ways forward.

2. An overview of classical water scarcity indicators

2.1. The Falkenmark indicator

The Falkenmark Indicator [*Falkenmark* et al., 1989], measuring water scarcity is a simple yet widely used method for calculating water scarcity. It requires: the number of people living within a given spatial domain and the volume of water (termed blue water by *Falkenmark*) available within that domain. The volume of water available per person is then calculated in m^3/cap/year. The indicator's reliance on population leads to the Water Crowding Index (WCI), which measures the number of people per unit of available water, e.g., persons/million m^3/year. A value of 1,700 m^3/cap/year of renewable freshwater was proposed as the threshold for *water scarcity*

[*Falkenmark* et al., 1989], below which social stress and a high level of competition for water emerges [*Falkenmark and Rockström*, 2004]. If water availability falls below 1,000 m^3/cap/year then the area experiences *high water scarcity*, and below 500 m^3/cap/year, *absolute scarcity*.

However, its ease of application is tempered by an important caveat: the index is only an indication of supply-side effects on global water scarcity [*Schewe* et al., 2014]. The indicator overlooks temporal variability and the important drivers of demand, related to economic growth, lifestyle, and technological developments [*Savenije*, 2000]. Management practices and infrastructure are not considered by the index and the simple threshold does not reflect the true spatial distribution of demand within and between the domains over which the index is calculated.

2.2. Water use to availability ratio

The water use to availability ratio, or criticality ratio, is another widely used indicator to assess water scarcity. The advantage of this ratio is that it measures the amount of water used, and relates it to the available renewable water resources [*Alcamo and Henrichs*, 2002]. Over the past decades, the development of water use models has been fast, and water availability and use can now be modelled spatially explicitly on global scale with high spatial resolutions [*Alcamo* et al., 2003a; *Hanasaki* et al., 2008; *Flörke* et al., 2013; *Wada* et al., 2014].

Water use can refer to either water consumption or water withdrawals. Water consumption measures the amount that is removed from rivers, lakes or groundwater sources and evaporated to the atmosphere. Water withdrawal refers to the amount of water that is withdrawn from these sources, of which part returns to the system by leakage or return flows. The majority of the existing water scarcity studies use withdrawal to indicate water use [*Alcamo*, et al., 2003b; *Oki and Kanae*, 2006; *Wada* et al., 2011]. Recent work by *Munia* et al. [2016] uses consumption and withdrawals as a minimum and maximum levels of scarcity, respectively. However, since consumption is normally much smaller than withdrawal, the ratio of consumption to average available renewable water resources usually indicates an unrealistically low level of water scarcity.

Based on the water criticality ratio, high water stress occurs if water withdrawal exceeds 40% of the available water resources [*Alcamo and Henrichs*, 2002]. However, as part of the withdrawal water returns back to water bodies and the actual proportion of the return flow vary across regions depending on natural and social-economic and technical conditions, using 40% as a water scarcity threshold may not be consistent in reflecting the status of water scarcity across regions.

2.3. Physical and economic water scarcity – the IWMI Indicator

The International Water Management Institute (IWMI) developed a more complex indicator for assessing water scarcity [*Seckler* et al., 1998], combining the physical and economic water scarcities. Indicator takes into account the proportion of water supply, of a country in question, from renewable freshwater resource available for human requirements, while accounting for existing water infrastructure such as desalinization plants and water stored in reservoirs. A novel element of the index is that it considers an individual country's potential to develop water infrastructure and to improve irrigational water use efficiency.

Their analysis yielded five country groupings. The country groupings were in turn used to define whether countries are either "physically water scarce" or "economically water scarce" [*Rijsberman*, 2006]. The former is where countries are unable to meet estimated water demand in 2025, even after accounting for national adaptive capacity. The latter is where countries have a sufficient renewable water resource but would have to invest significantly in water infrastructure to make the resources available for consumption in 2025.

The index is available as a Microsoft Excel model [*Seckler* et al., 1998] yet it has not been used as much as other indicators to assess global water scarcity, with exception to an assessment conducted by *Cosgrove and Rijsberman* [2000]. One reason for this is that it is considerably more complex than many other indices reviewed here and thus more time-consuming to compute. Another is perhaps that its interpretation is less intuitive than other indices and therefore less attractive for presentation to the public and/or a policy audience [*Rijsberman*, 2006].

2.4. Water poverty index

The Water Poverty Index (WPI) proposes a relationship between the physical extent of water availability, its ease of abstraction, and the level of community welfare [*Sullivan*, 2001]. It considers five factors: resources or water availability; access to water for human use; effectiveness of people's ability to manage water; water use for different purposes; environmental integrity related to water and of ecosystem goods and services from aquatic habitats in the area. The WPI is mainly designed for assessing the situation facing poor water endowments and poor adaptive capacity.

The WPI is calculated with the weighted average of the five components, each of which is first standardized so that it falls in the range 0 to 100; thus the resulting WPI value is also between 0 and 100, representing the lowest and the highest level of water poverty [*Sullivan* et al., 2006]. The indicator has the advantage of comprehensiveness. However, its application is hampered by its complexity and lack of information for some of the factors required for building the indicator on large scale [*Rijsberman*, 2006]. It has so far only been applied at the community level for pilot sites in a few countries.

3. Progress in water scarcity assessment

Since the beginning of the 2000s, water scarcity assessment has entered an era characterized by the applications of more sophisticated models supported with spatial analytical tools. The water use to availability ratio has been the basis of many water scarcity assessment approaches developed during this period. The main efforts made in these assessments have been in the measurements of water "use" and "availability".

3.1. Green-blue water scarcity

Green water refers to soil moisture in the unsaturated zone recharged by precipitation. It is a crucial water resource for agricultural production, responsible for about 90% of total water use of agriculture and 60% of the global food is produced without additional irrigation (i.e., blue water use) [*Rockström* et al., 2009].

The development of the green-blue water indicator has attempted to incorporate green water in the assessment. The pioneer work was done by *Rockström* et al. [2009] who developed the first indicator to assess scarcity where both blue and green water resources are included. They measured the scarcity by comparing global average green-blue water consumption of 1300 m^3/cap/year for a healthy diet (3000 kcal/cap/day of which 20% originates from animal sources) and locally available green-blue water resources. The area is under scarcity if available water resources are less than the average requirement of 1300 m^3/cap/year. This was further developed by *Gerten* et al. [2011] who incorporated the local water requirements for a healthy diet to the calculations and thus taking into account spatial variations of the water needed to produce the actually grown food in different locations. These vary from less than 650 m^3/cap/year in Europe and North America to over 2000 m^3/cap/year in large parts of Africa [*Gerten* et al., 2011; *Kummu* et al., 2014].

Despite the merit of incorporating green water in water scarcity assessment, the attempts so far suffer from a drawback of inconsistency. The blue water resources are generally quantified as the total run-off of renewable freshwater on the earth surface or given geographical locations/river basins, regardless of their accessibility. The green water resources, on the other hand, are quantified as the evapotranspiration of vegetation on croplands (and grazing land). This greatly underrepresents the quantity of green water resources because a large (if not larger) amount of evapotranspiration occurs on non-croplands.

3.2. Water footprint-based water scarcity assessment

The water footprint measures the amount of water used to produce the goods and services human uses [*Hoekstra* et al., 2011]. Noting the problem of ignoring the return flow in using water withdrawal to refer to water use in the water scarcity assessment, *Hoekstra* et al. [2012] developed a water footprint-based assessment for global blue water scarcity assessment. Three alternatives are used in measuring water use and availability. First, water use refers to consumptive use of ground- and surface water flows – i.e., the blue water footprint. Second, the flows needed to sustain critical ecological functions are subtracted from water availability. A presumptive standard of 20% depletion rate is used as a threshold, beyond which, risks to ecological health and ecosystem services increase. Third, water use and availability are measured on a monthly rather than annual basis to account for seasonal water scarcity. The water scarcity indicator derived from this approach provides a picture of where and when current levels of water use are likely to cause water shortages and ecological harm within river basins around the world [*Hoekstra* et al., 2012]. However, the assumption of EFR to be 80% of the total water resources across all the river basins in the assessment, as suggested by *Richter* et al. [2011], is too simplistic, as it did not consider the complexity of EFR in individual river regimes. This may also overestimate EFR as well as water scarcity because the 80% EFR is set unrealistically too high for most of the regions of the world [*Liu* et al., 2016]. Many studies found that appropriate levels of EFR vary across the river regimes considerably [*Pastor* et al., 2014].

3.3. Cumulative abstraction to demand ratio – considering temporal variations

In many areas of the world, water scarcity is seasonal, i.e., it only occurs in some months of the year, while there may be enough water on an annual basis. Given this situation, some water scarcity assessments have attempted to take the seasonality into consideration. For example, *Alcamo and Henrichs* [2002] took into account low river flows in computing a version of the criticality ratio. Another example is the Cumulative Abstraction to Demand (CAD) ratio devised by *Hanasaki* et al. [2008]. The index was intended to apply the results of global hydrological models, which are able to simulate river discharge and water abstraction at a daily time step. This index is expressed as the ratio of the cumulated daily water abstraction from rivers to the cumulated daily potential water demand (i.e. consumptive water requirement for agricultural, industrial, and domestic use) for a specific year. Recent studies have also been conducted on monthly scale [*Wada* et al., 2011; *Hoekstra* et al., 2012; *Brauman* et al., 2016]. It is assumed that if the ratio falls below unity, water scarcity can occur. *Hanasaki* et al. [2008] demonstrated that CAD is low in Southeast Asia and the Sahel due to periodic, severe water shortage in the dry season, which is often overlooked in the assessments adopting classical water scarcity indicators. CAD provides useful insights for assessing the impact of climate change on water resources. In some areas, annual total runoff is projected to increase due to global warming water scarcity may appear to diminish when the withdrawal to availability ratio is used, which may be misleading. In this case CAD presents a more realistic view of water scarcity because it takes into account the increase in water scarce conditions during the dry months [*Hanasaki* et al., 2013; *Haddeland* et al., 2014]. However, the high demand for data and complex computational tasks have limited the use of this water scarcity assessment approach.

3.4. LCA-based water stress indicators

Water scarcity assessment has been introduced in Life Cycle Assessment (LCA) to address water consumption and its environmental impact since 2008 [*Frischknecht* et al., 2009; *Pfister* et al., 2009; *Berger* et al., 2014] and is continuously expanded. The main methods used in LCA can be grouped into midpoint and endpoint indicators and address scarcity on watershed level [*Kounina* et al., 2013]. Midpoint indicators address water scarcity as a water resource problem, while endpoint methods try to quantify potential impacts on human health or ecosystem quality, which goes beyond scarcity but includes vulnerability and resilience. LCA methods address water scarcity at the midpoint level.

In LCA, water consumptive use to availability ratios are used to derive an indicator based on various functions, such as logistic or exponential [*Kounina* et al., 2013]. The most widely used indicator is the water stress index (WSI) [*Pfister* et al., 2009]. Recognizing that both monthly and annual variability of precipitation may lead to increased water stress during a specific period, a variation factor is introduced to calculate the ratio, which differentiates watersheds with strongly regulated flows. Considering water stress is not linear with regards to water consumptive use and water availability ratio, an adjusted water stress index is calculated with a logistic function to achieve continuous values between 0 and 1, while 0.1, 0.5 and 0.9 are assigned as thresholds for moderate, severe and extreme water scarcity. The water stress index is served as a general screening indicator or characterization factor for water consumption in Life Cycle Impact Assessment. As the LCA based water scarcity assessment focuses on impact assessment of water use, the indicator has not been separately used for water scarcity assessment.

3.5. Integrated water quantity-quality-environment flow in the water scarcity assessment

The water scarcity indicators developed have mainly considered water quantity. *Zeng* et al. [2013] developed an integrated indicator, which is expressed as the sum of a quantity-induced indicator and a quality-induced indicator. The quantity-induced water scarcity indicator follows the criticality ratio approach, and is defined as the ratio of the water withdrawal to freshwater resources in a specific region during a certain period. The quality-induced water scarcity indicator is defined as the ratio of grey water footprint to freshwater resources. Here, grey water footprint is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards [*Hoekstra* et al., 2011]. It does not have the same meaning as the terms used in urban water management, for which grey water refers to the water comes out of the shower or sink. This indicator combining quantity- and quality-induced water scarcity was illustrated by analyzing the water scarcity in China. The result shows that the northern parts of the country are suffering from both quantity- and quality-induced water scarcity (Fig. 2). In southeast, quality-induced water scarcity is dominant due to the heavy water pollution. The results imply that northern China has a much bigger burden to deal with the water scarcity problems, while for other provinces, quality-induced water scarcity is a grand challenge.

(Insert Fig. 2)

On the basis of *Zeng*'s indicator, EFR was further added in the water scarcity assessment, resulting in a quantity-quality-EFR (QQE) approach [*Liu* et al., 2016]. It is structured with multi-components in the indicator: $S_{quantity}(EFR)|S_{quality}$. The QQE approach was first used for the Huangqihai River Basin in Inner Mongolia, China. The QQE water scarcity indicator in this river basin is 1.3(26%)|14.2, indicating that the basin was suffering from scarcity problems related to both water quantity (1.3 is larger than the threshold of 1.0) and water quality (14.2 is far larger than the threshold of 1.0, indicating a serious water pollution condition) for a given rate of 26% of EFR.

The QQE water scarcity indicator provides an easy to obtain and to understand measurement that contains the information of water quantity and quality status, as well as EFR. The procedure can be adapted to any other areas in the world to provide a comprehensive assessment on water scarcity. By specification, one can also use the percentage of EFR to indicate any other levels of ecological habitat status. However, the QQE indicator has some limitations. The indicator is not as straight forward as the existing indicators, which use a single value to indicate the status of water scarcity. It requires some professional knowledge to understand the indicator and interpret the information contained.

4. Where are we now?

Many global assessments of water scarcity have been conducted so far (Figure 3). The spatial resolution ranges from country, region to grid cell. In general, all the indicators pointed out that the areas in the middle to low latitudes of the northern hemisphere have a high level of water scarcity. It is noticed that the physical and economic water stress (Fig 3C) and water poverty index (Fig 3D) also identified the severe water scarcity problem in almost all African countries. This is attributed to the lack of economic capacity to build water infrastructure as well as poverty, which have hindered these countries to access their water resources that are often physically abundant. Despite the relevance of concerning economic factors in water scarcity assessment, the complexity such concern brought to the assessment increases greatly.

There is no consensus on which social and economic factors should be included, and for different countries and regions, these factors can be different. To keep the objectivity and simplicity, all the other water scarcity indicators developed so far have been based solely on physical quantity of water availability and use.

(Insert Fig. 3)

One of the main outcomes of water scarcity assessments is estimates of number of people affected by water scarcity. Results differ when different indicators are used, even for the same indicator from different reference sources (Figure 4). For example, estimates using the criticality ratio with a threshold of 40% tend to be higher than those based on the Falkenmark indicator with a threshold of 1000 m^3/person/year. Variations in number of people living in water scarcity with the same indicator are partially related to different spatial resolutions in the assessment. In general, the higher spatial resolution results in larger number of people suffering from water scarcity (Fig. 3). This is because the high spatial resolution can better reflect the water scarcity situation in urban areas with high population concentration [*Vörösmarty* et al., 2010]. However, high spatial resolution tends to underestimate human capacity to bring water from outside into cities. Also, including green water will enlarge the quantity of water availability for a geographical unit (e.g., country, region), resulting in smaller estimates of people living in water scarcity. Respecting the EFR by leaving sufficient water in steams, on the other hand, results in larger estimates, because it reduces the water resources available for humans. Furthermore, including water quality can lead to substantial increase in the magnitude of water scarcity, as the poor water quality can make available water not usable. Overall, the estimated numbers from different indicators suggest that between 1.5 and 2.5 billion people were living within areas exposed to water scarcity around the year 2000 (Fig. 4), but water footprint based water scarcity assessment increases the number to 4 billion [*Mekonnen and Hoekstra*, 2016]. When water stress and water shortage are assessed in a combined manner, altogether 3.8 billion lived under some degree of water scarcity in 2005 [*Kummu* et al., 2016]. The numbers are projected to increase substantially up to at least 2050 in association with the peak of world population. Current analyses suggest that thereafter the numbers may decline.

(Insert Fig. 4)

5. Future research challenges and directions

5. 1. Validating water scarcity indicators

The indicators presented in this paper have been used by scientists to compare their values in one region versus another in order to estimate the relative level of water scarcity. However, so far very little efforts have been made to prove how these indicators appropriately reflects the water scarcity quantitatively, and how the thresholds reasonably classify water scarcity. All the indicators and their thresholds have been determined based on expert judgments. The expression "to validate indicators" generally means to support or corroborate on a sound or authoritative basis [*Bockstaller and Girardin*, 2003; *Dauvin* et al., 2016]. An essential problem in validating these indicators has been the difficulty in identifying an independent variable for water scarcity. *Alcamo* et al. [2008] used the “frequency of occurrence of drought-related crises” in three large river basins as an independent variable. Values of this metric were determined from media-content analysis by *Taenzler* et al. [2008]. With estimates of this variable, it was possible to test the validity of various water scarcity indicators. Using modelling data from a 15-year period, it was found that 6 out of 14 different tested water scarcity indicators were statistically related to the occurrence of drought-related crises [*Alcamo* et al., 2008]. This initial work indicates that it may be possible to validate indicators, identify their appropriate range of application, and test scarcity thresholds. Research in this direction would strengthen the scientific basis of estimating water scarcity and perhaps accelerate the development of more useful indicators.

5.2. Incorporating water quality in water scarcity assessment

As poor water quality has intensified the pressure on water resources [*Bayart* et al., 2010], including more specific water quality classes for ecosystem and human uses is necessary to enhance the pertinence of water scarcity assessments. Water quality is typically expressed as concentration of certain pollutants. The most considered pollutants influencing water quality have been nutrient emissions, typically nitrogen and phosphorous, and to a lesser extent, COD [*Björklund* et al., 2009; *Liu* et al., 2012]. The assessment of water quality induced water scarcity is sensitive to the pollutant selected. In order to include water quality data in water scarcity assessments, suitable data need to be collected covering a range of water quality parameters. Often, the list of parameters to be considered may be guided by the objectives of a study, i.e. specific requirements for drinking water are different from that for irrigation water. For an aggregated water scarcity assessment, it would be ideal to use an aggregated water quality indicator that can reflect the overall water quality status. Building such an indicator with a broad applicability is a challenge faced in the future water scarcity assessment.

Another challenge in incorporating water quality is that the availability of water quality data is very heterogeneously distributed over the world and varies tremendously between regions with huge data gaps in developing countries. The United Nations Environment Programme Global Environment Monitoring System (GEMS) Water Programme is a multi-faceted water science centre oriented towards building knowledge on inland quality issues worldwide (http://www.unep.org/gemswater/), which is still very limited considering the large surface of the earth. The GEMS/Water Programme, established in 1978, is the primary source for global water quality data. The related water quality database, GEMStat, is designed to share surface and ground water quality data sets collected from the GEMS/Water Global Network, so far including more than 3,000 stations (http://gemstat.org/). For Africa, data found in scientific literature were very dissimilar and disparate, most published data were aggregated over long time periods and/or over several sampling stations [*UNEP*, 2016]. Furthermore, specific locations of sampling stations were usually not available and the selection of parameters was restricted. In this context, global scale water quality models could be used as a complementary approach to fill data gaps of relevant parameters in time series and in regions where no reliable data exist. Since a model is a simplified representation of the real world system, its credibility is ensured by its model performance in terms of validation and testing against measured data. It is worth mentioning that the WaterGAP3 modeling framework has been enhanced by a large-scale water quality model WorldQual in order to estimate pollution loadings and in-stream concentration for a variety of parameters (e.g. *Voß* et al., [2012]; *Reder* et al., [2013, 2015]). Many crop models, such as GEPIC, have both components of hydrology and pollution loading [*Liu and Yang*, 2010; *Liu* et al., 2013a]. With their ability to calculate water availability, water use, and water quality parameters, the modeling framework is promising for simultaneously considering water quantity and water quality in water scarcity assessment.

5.3. Incorporating environmental flow requirements in water scarcity assessment

Rudimentarily, EFRs has been incorporated in water scarcity assessment by assuming a fixed percentage of river flow for EFR, ranging from 80% of the annual flow uniformly all over the globe [*Hoekstra* et al., 2012] to specific proportions in given locations [*Smakhtin* et al., 2004; *Rockström* et al., 2009; *Gerten* et al., 2011; *Liu* et al., 2016]. However, in the natural system, EFRs vary across flow regimes and seasons. E.g., *Pastor* et al. [2014] found that EFRs ranged between 25% and 46% of mean annual flow. This suggests an importance to incorporate locally pertinent EFR for a proper assessment of water scarcity status.

The future studies that estimate EFRs should consider a range of methodologies that account for seasonal variations and flow regimes in different parts of the globe [*Gerten* et al., 2013]. Different approaches have been developed for assessing the EFRs for different river regimes. E.g., *Laize* et al. [2014] and *Schneider* et al. [2013] presented a comprehensive approach to quantify ecological risk as a result of flow alterations in terms of the deviation from natural flow conditions. They assessed hydrological alterations from natural flow dynamics caused by anthropogenic water use and dam operations and by using a subset of 12 different parameters chosen from the list of Indicators of Hydrological Alteration [*Richter* et al., 1996, 1997]. This approach considers different flow characteristics and describes non-redundant departures from the natural flow regime. In addition, changes in average magnitude and variability of each parameter are considered, and therefore, in total 24 sub-indicators are taken into account. This indicator system could be used to account for EFRs across regions in water scarcity assessment.

5.4. Temporal and spatial scales of water scarcity with consideration of green water and virtual water

In water scarcity assessments, the selection of spatial scale (or unit of analysis) is important, and difficult too. It has considerable impacts on results, as shown earlier (Fig. 3) and by other studies [*Salmivaara* et al., 2015; *Perveen* et al., 2011]. Most of the water scarcity assessments are conducted on a grid scale (30 arc-min, i.e. 50 km resolution near the equator), while for addressing water scarcity, country, basin or sub-basin (e.g. food production unit) scales are more policy relevant. A detailed study of the impact of different spatial scale on water scarcity assessment would be needed.

Most water scarcity indicators are measured on annual time scale. With significant intra-annual variations in water use and availability, it is important to understand when water is available and when it is needed within a year. Thus, the introduction of a monthly scale assessment could provide information whether there is enough water for each month to fulfill the requirements.

Other relevant aspect to temporal scale is the impact of inter-annual variability of water availability and water requirements on scarcity measures. *Veldkamp* et al [2015] found that on the shorter time scales (up to 6-10 years) the climate variability is the dominant factor influencing water scarcity while on the longer time scales the socio-economic development is more important factor. *Brauman* et al. [2016] found that watersheds that appear to be moderately depleted on an annual time scale are almost uniformly heavily depleted at seasonal time scales or in dry years. Hence, the assessment of inter-annual variability adds important insights on the understanding of water scarcity.

It also needs to be pointed out that the whole population living in a region (e.g. country, watershed) are often not equally been impacted by water scarcity. For example, people with a higher income may be less affected by water scarcity than people with a lower income. Also the rural and urban population may be affected differently. For this reason, it would be more indicative to consider the possibly different effects of socio-economic conditions on the people residing in a water scarcity region. Adopting a probabilistic approach could reduce the scaling effects. This, however, requires more detailed information on the socio-economic conditions of people in the region.

Green water is an important component of water resources. However, in the water scarcity assessment, it has been rarely considered due mainly to different measurements of green and blue water resources, the former is in storage (in unsaturated soil) and the latter is flow measured on annual basis. The work which did consider green water only accounted for the portion that has been actually used by crops [*Rockström* et al., 2009; *Gerten* et al., 2011]. This greatly underestimates green water resources. One possible approach to remedy the problem is to count for accumulated soil moisture on an annual basis on the land surface regardless of if it is used or not by crops or other plants. It needs to be pointed out that the validity to incorporate green water is sometime questioned in water resources management [*Bogardi* et al., 2013]. One major reason is that green water is not part of the water budget that could be easily reallocated to other use. Our opinion is that soil moisture (green water) is an important resource which should be appropriately incorporated in the water availability accounting.

Most of the water scarcity indicators previously developed only account for local water resources and local water demand. But recent research advances have revealed that previously unrecognized global forces may drive local-scale water problems [*Vörösmarty* et al., 2015]. Much of the global water use and pollution is from the production of commodities for global and regional trade, which embodies a large amount of virtual water flows and influences local water scarcity [*Zhao et al.*, 2015; *Hoekstra and Mekonnen*, 2016; *Vörösmarty* et al., 2015; *Zhao* et al., 2016]. Long distance water transfer systems also impact the local water scarcity situations in both the sourcing and destination regions [*Liu* et al., 2013b]. There is a need to integrate virtual water flows and water transfers in the water scarcity analysis.

5.5. Need for collaboration between hydrological, water quality, aquatic ecosystem science and social science communities in water scarcity assessment

There are crucial connections between water availability and water quality [*Jury and Vaux*, 2005] and both have been associated with human health [*Myers and Patz*, 2009], food security [*Rockström* et al., 2009; *Simelton* et al., 2012] and for sustaining native biodiversity and integrity of aquatic ecosystems [*Poff* et al., 1997; *Richter* et al., 1997]. This means that assessments of water availability and quality should be conducted in a consistent way so that relevant dependencies between availability and quality are accounted for. This will require the integration of water quality and ecological parameters, and processes (and feedbacks between them) into water availability assessment models. This can only be achieved through sustained integration of the water availability modelling community with the water quality and ecological modelling communities.

Integrating these communities represents the first, and an important step, towards developing a comprehensive understanding of the susceptibility of global water availability and quality to change. Beyond this, the relevant communities will need to develop improved hydrological models at the global scale that consider both water quantity and quality. Reliable observations of water quality at sufficient spatial resolution across the globe will also be needed to validate the models.

As noted above, water scarcity indicator thresholds are artificial and 'best guess' rather than evidence-based. There are limitations about the utility of indicators [*Fekete and Stakhiv*, 2014] given the complexity of water management challenges that these indicators intend to support. These indicators are generally insufficient to incorporate the complex socio-economic backdrop driving water demands and they do not address the alternative pathways such as the choices of water produced. Fostering interdisciplinary or even trans-disciplinary research in water scarcity studies as well as the integration of stakeholders offers the possibility of clear frameworks and hence the improvement of systems' understanding. For example, factors affecting water demand, such as changes in lifestyle, perceptions of water scarcity, and attitudes towards water use, are routed in social science understandings of how these factors can be influenced by government policy and social norms [*Wolters*, 2014]. Moreover, a novel opportunity exists to make social science more effective in improving water management and understanding the drivers of water scarcity [*Lund*, 2015].

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Figure legends

Figure 1: The number of publications based on the keyword "water scarcity" from Scopus as of 17 January 2016. The years of publication of specific water scarcity indicators are marked.

Figure 2: Water scarcity assessment for different provinces with the quantity-quality indicator approach. This map was generated by *J Liu* based on the approach of *Zeng* et al. [2013].

Figure 3: Spatial distribution of water scarcity from different assessments. Below is a list of references for Fig. 3 A-H and the indicator used in relation to Table 1. A: Water shortage (modified from *Kummu* et al., [2010]); B: Water stress (modified from *Wada* et al., [2011]); C: Physical and economic water scarcity (modified from *Seckler* et al., [1998]); D: Water poverty index (modified from *World Resources Institute* [2006]; *Sullivan* et al., [2002]); E: Green-blue water scarcity (modified from *Kummu* et al., [2014]); F: Monthly blue water stress (modified from *Mekonnen and Hoekstra*, [2016]); G: Cumulative abstraction to demand ratio (modified from *Hanasaki* et al., [2013]); H: LCA-based water stress indicator (modified from *Pfister* et al. [2009]). Note: all maps were redrawn by authors based on original data from the sources given above, except water poverty index, which was modified from a softcopy map. Further, legend colors in some maps are modified for consistency.

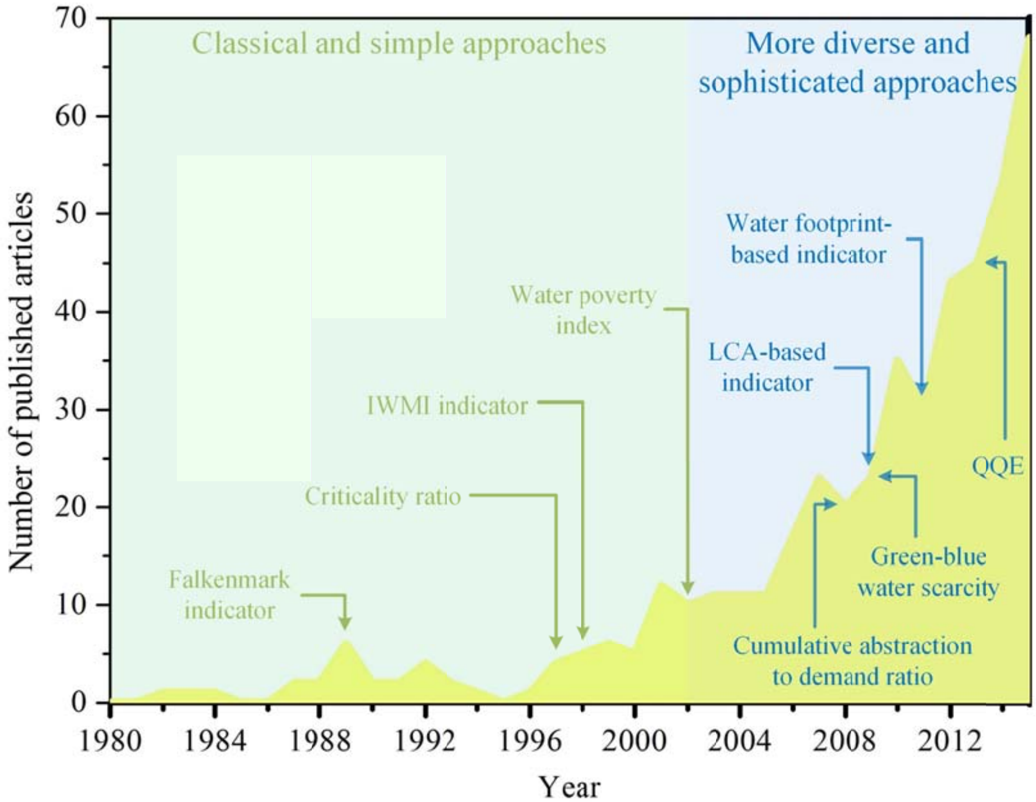
Figure 4: Number of people suffering from water scarcity assessed with the average annual water availability per capita (1000m^3/capita/year) and water use to availability ratio (40%). The marks show the estimates from different studies. Specific estimates include: 1.2 billion [*Hayashi* et al., 2010], 1.4 billion [*Arnell*, 2004], 1.6 billion [*Alcamo* et al., 2007; *Arnell* et al., 2011; *Gosling and Arnell*, 2016], 1.7 billion [*Revenga* et al., 2000], and 2.3 billion [*Kummu* et al., 2010]. But the number may be quite different when other indicators are used, e.g. *Mekonnen and Hoekstra* [2016] estimated that 4 billion people live under conditions of severe water scarcity at least 1 month of the year between 1996 and 2005.

Table 1. Summary of the characteristics of water scarcity indicators. EFR stands for Environmental Flow Requirements.

Indicator name	Measurement	Water quantity (Blue water)	Green water	Water quality	EFR	Main references
Falkenmark indicator (Water shortage)	Per capita water availability	Y	N	N	N	[Falkenmark et al., 1989; Ohlsson and Appelgren, 1998; Falkenmark et al., 2009]
Criticality ratio (Water stress)	Ratio of water use to availability	Y	N	N	Y*	[Falkenmark, 1997; Raskin et al., 1997; Alcamo, et al., 2000; Vörösmarty et al., 2000; Oki and Kanae, 2006]
IWMI indicator (Physical and economic water scarcity)	Proportion of water supply that is water availability, accounting for water infrastructure	Y	N	N	N	[Seckler et al., 1998]
Water poverty index	Weighted average of 5 components (water availability, access, capacity, use, and environment)	Y	N	N	Y	[Sullivan, 2002, 2003]
Green-blue water scarcity	Requirement vs. availability of green-blue water resources	Y	Y	N	Y*	[Rockström et al., 2009; Gerten et al., 2011]
Water footprint-based assessment	The ratio of water footprint to water availability	Y	Y	N	Y	[Hoekstra et al., 2011]
Cumulative abstraction to demand ratio	Cumulative abstraction to demand ratio	Y	N	N	N	[Hanasaki et al., 2008]
LCA-based water stress indicator	The ratio of water use of water footprint to availability	Y	Y	Y	N	[Frischknecht et al., 2009; Pfister et al., 2009]
Quantity-quality-environmental flow requirement (QQE) indicator	Incorporating water quantity, quality and EFR	Y	N	Y	Y	[Zeng et al., 2013; Liu et al., 2016]

** EFR is included but constant 30% requirement assumed.*

Figure 1



Classical and simple approaches
More diverse and sophisticated approaches
Number of published articles
Year
Falkenmark indicator
Criticality ratio
IWMI indicator
Water poverty index
LCA-based indicator
Water footprint-based indicator
QQE
Green-blue water scarcity
Cumulative abstraction to demand ratio

Figure 2


Heilongjiang
Jilin
Xinjiang
Liaoning
Inner Mongolia
Beijing
Tianjin
Hebei
Shanxi
Shandong
Qinghai
Gansu
Shaanxi
Henan
Jiangsu
Xizang
Anhui
Shanghai
Hubei
Sichuan
Chongqing
Zhejiang
Hunan
Jiangxi
Guizhou
Fujian
Yunnan
Guangxi
Guangdong
Hainan
N
Kilometers
0
250
500
1,000
Water scarcity classification
Both quantity- and quality- induced water scarcity
Quality-induced water scarcity
Quantity-induced water scarcity
No water scarcity
No data

Figure 3

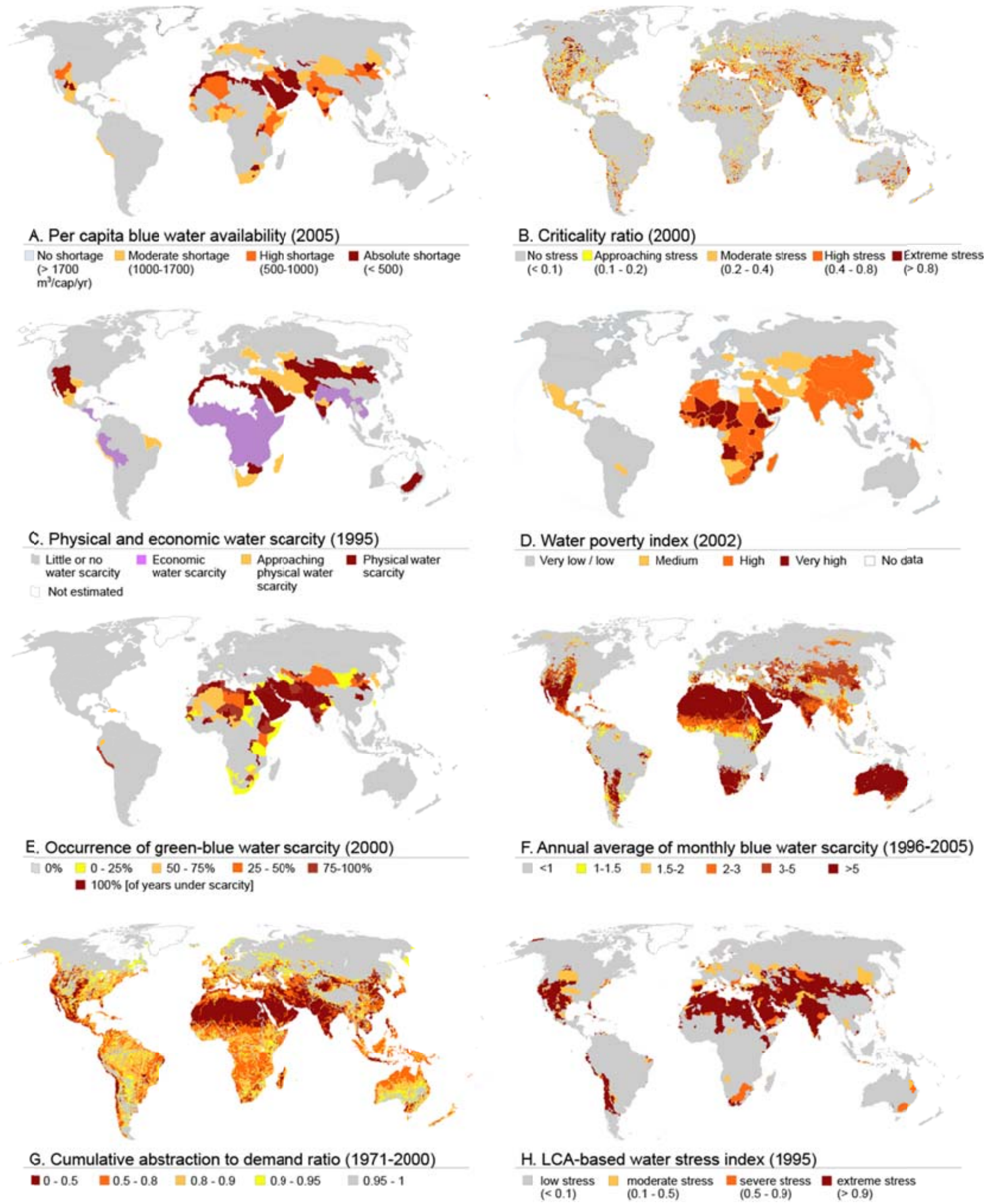
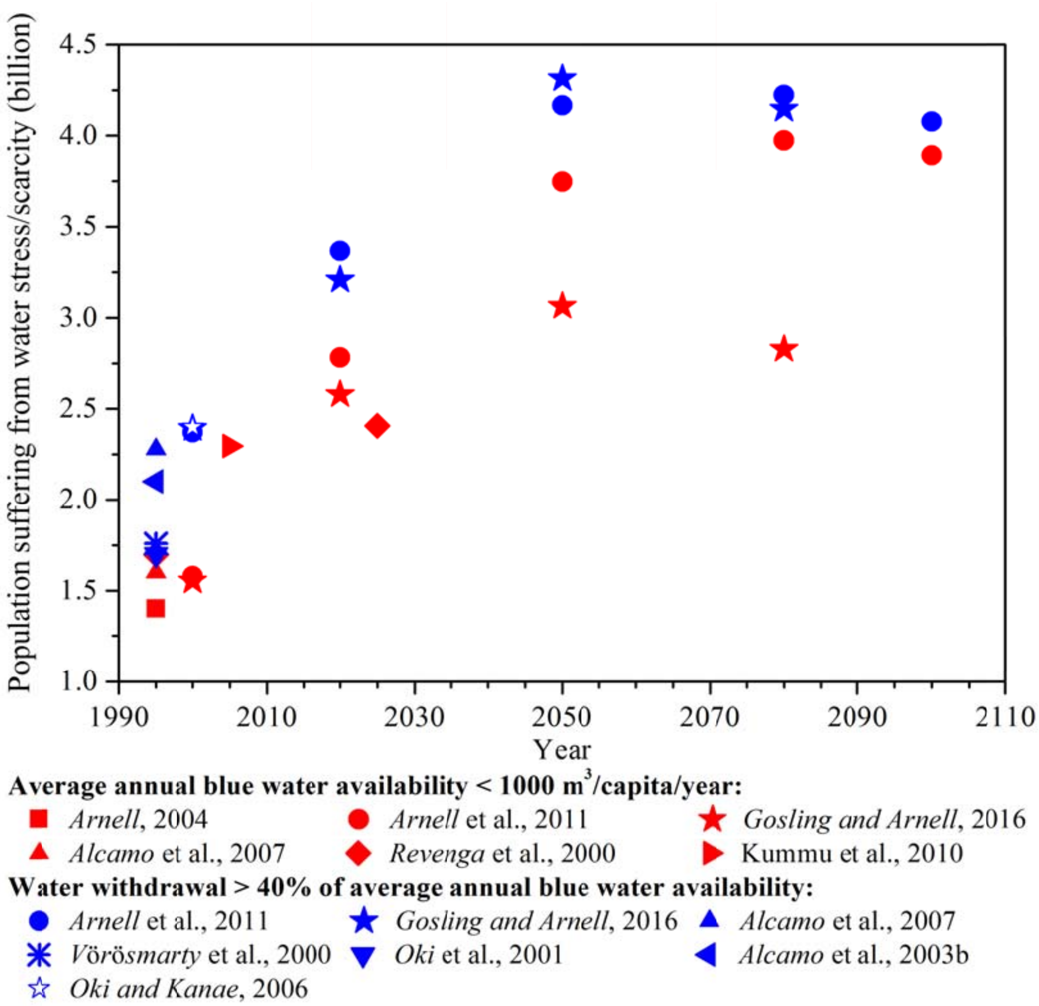

A. Per capita blue water availability (2005)
No shortage (> 1700 m³/cap/yr)
Moderate shortage (1000-1700)
High shortage (500-1000)
Absolute shortage (< 500)
B. Criticality ratio (2000)
No stress (< 0.1)
Approaching stress (0.1 - 0.2)
Moderate stress (0.2 - 0.4)
High stress (0.4 - 0.8)
Extreme stress (> 0.8)
C. Physical and economic water scarcity (1995)
Little or no water scarcity
Economic water scarcity
Approaching physical water scarcity
Physical water scarcity
Not estimated
D. Water poverty index (2002)
Very low / low
Medium
High
Very high
No data
E. Occurrence of green-blue water scarcity (2000)
0%
0 - 25%
50 - 75%
25 - 50%
75-100%
100% [of years under scarcity]
F. Annual average of monthly blue water scarcity (1996-2005)
<1
1-1.5
1.5-2
2-3
3-5
>5
G. Cumulative abstraction to demand ratio (1971-2000)
0 - 0.5
0.5 - 0.8
0.8 - 0.9
0.9 - 0.95
0.95 - 1
H. LCA-based water stress index (1995)
low stress (< 0.1)
moderate stress (0.1 - 0.5)
severe stress (0.5 - 0.9)
extreme stress (> 0.9)

Figure 4



Population suffering from water stress/scarcity (billion)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1990
2010
2030
2050
2070
2090
2110
Year
Average annual blue water availability < 1000 m3/capita/year:
Arnell, 2004
Arnell et al., 2011
Gosling and Arnell, 2016
Alcamo et al., 2007
Revenga et al., 2000
Kummu et al., 2010
Water withdrawal > 40% of average annual blue water availability:
Arnell et al., 2011
Gosling and Arnell, 2016
Alcamo et al., 2007
Vörösmarty et al., 2000
Oki et al., 2001
Alcamo et al., 2003b
Oki and Kanae, 2006