# A Review of Continental-to-Global Sustainable Water Use Assessment

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Keywords: Sustainable Water Use, Water Scarcity, Water Demand, Water Withdrawal, Water Consumption, Environmental Flow

## Abstract

Freshwater scarcity and unsustainable water use are some of the growing concerns in many parts of the world. Increasing water demand accompanied by increasing climate change leads to the unsustainable use of freshwater resulting in water scarcity. Several studies have quantified sustainable water use and water scarcity at a global level in the past. This review focusses on such large-scale water resources assessments, and the methods by which sustainable water use and water scarcity are quantified. The review is structured based on a framework comprised of the main components of water demand and supply. Large-scale assessments have become an important tool to quantify the impacts of global climate

change and water use changes on water resources sustainability. The major components comprising the water demand and the supply are estimated by such assessments using global earth system models and national level census datasets. The selection of appropriate spatial and temporal scales for the major components of water demand and supply is critical. The grid-based global earth system models enable various spatial resampling of water information over the country/political boundaries. Recent studies observed that by refining temporal scale from annual (the most commonly used temporal scale of assessment) to monthly time steps, water scarcity is better captured due to the distinctive seasonality of water availability and demand. In addition, the major drivers of water scarcity are discussed as an important criterion. Although both changing climate and increase in water demand contribute to the sustainability of water use, the majority of the literature concludes that the magnitude of demand driven fresh water scarcity is much greater than that by climate. Further, many studies neglect the environmental flows in large-scale assessments which results in under estimation of water scarcity.

# 1. Introduction

Rapidly increasing population, urbanization and industrialization have paved the way for increasing water demand causing growing fresh water scarcity experienced across the world (Hoekstra et al., 2012). The amount of fresh water circulating through the global hydrological cycle exceeds the needs of 7.4 billion people in the world. Nonetheless, fresh water scarcity is experienced in many regions since the water is not evenly distributed in time or space (Postel, 2000). Fresh water scarcity and growing demand are serious threats to water resources sustainability (Water, 2007), which has been reflected in various large-scale studies on sustainable water use (Wahl, 1991; Gleick, 1998; Mason and Calow, 2012;

Gonzales and Ajami, 2015). These studies have tried to characterise and map water scarcity and sustainability at a global level using indicators such as the per capita water use (Islam et al., 2006; Kummu et al., 2010), the ratio of water withdrawals to available water supply (Vörösmarty et al., 2000; Oki et al., 2001; Alcamo et al., 2003; Oki and Kanae, 2006; Alcamo et al., 2007; Hanasaki et al., 2008), and the ratio of water consumption to available water supply (Wada et al., 2011a; Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016).

Several definitions are used throughout this review. The *water withdrawal* is "the amount of water diverted from a surface or groundwater source, part of which is consumed or retuned to the environment" (Cohen, 2002), whereas the *water consumption* is "the amount of surface and groundwater that is withdrawn and not returned because the water is evaporated or is incorporated into a product" (Mekonnen and Hoekstra, 2016). The *water demand* is "the amount of water that would be used by a given activity or sector if sufficient water were available" (Wada et al., 2011a). These definitions are adopted to compare various methods used by studies in quantifying sustainable water use and scarcity. The terms 'sustainable water use' and 'water scarcity' are used interchangeably in this review, as we focus on the studies that quantified water scarcity resulting from unsustainable water use at a global level.

Many global level water resources assessment studies (Oki et al., 2001; Alcamo et al., 2007; Hanasaki et al., 2008; Kummu et al., 2010) have assessed the water scarcity on an annual time scale. However, water shortage is highly seasonal owing to the large sub-annual variation of fresh water consumption and availability (Mekonnen and Hoekstra, 2016). Hence, an assessment carried out at the annual time scale may fail to quantify the seasonal fluctuations of water shortage during the year. Some studies  have attempted to overcome this limitation by assessing water scarcity at a monthly scale (Hanasaki et al., 2008; Wada et al., 2011a; Hoekstra et al., 2012; Wada et al., 2014; Mekonnen and Hoekstra, 2016). Supporting this view, the recent study by Mekonnen and Hoekstra (2016) reported that the assessments carried out at the annual time scale underestimated the water scarcity and the population experiencing water scarcity in many countries.

To quantify the available water supply, most of these studies used large-scale earth system models at a coarser spatial resolution of $0.5^{\circ}$ (Oki et al., 2001; Oki and Kanae, 2006; Wada et al., 2011a; Wada et al., 2011b; Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016). Instead of relying solely on the data from water authorities/reservoirs, transfer of water between river basins and use of water occurring at small catchment scales, these assessments hydrologically redistributed water information derived from the major source of supply, such as precipitation and resulting runoff. Although the results from the large-scale assessments may not be ideally suited for catchment-level analysis, several aspects of fresh water resources assessment require analysis at a continental to global level. Firstly, the major environmental problems associated with fresh water scarcity can occur over a large portion of earth's geographical areas and hence large-scale assessments are required to capture the spatial context of the problems (Döll et al., 2003). Secondly, human induced climate change, which has important implications to local water scarcity issues, can be more fully comprehended when a better representation of the terrestrial water cycle is available (Sood and Smakhtin, 2015). Future climate projections based on various potential scenarios can be more readily integrated into the water resources analysis tools when a coupled earth system model is adopted for the large-scale assessments. Finally, international financing of fresh water projects focus on quantifying water use and water scarcity in developing countries and how they evolve with global changes in climate and water use (Döll et al., 2003).

When quantifying sustainable water use and water scarcity in global scale assessments, it is crucial to account for the variations in both the water demand and the water supply. Wahl (1991) focussed on the possible effect of climate on the water resources sustainability by quantifying the annual and seasonal runoff volume. On the other hand, Gleick (1998) parameterised sustainable water use based on human, ecosystem and water quality demands. It is sensible to include the water demand when assessing water scarcity, considering the critical influence of anthropogenic water demand on water scarcity. Hence, while quantifying sustainable water use and water scarcity, it is essential to include climate change and increase in water demand. Based on these observations, recent studies focus on quantifying both water demand and water available to assess water scarcity (Oki et al., 2001; Hanasaki et al., 2008; Hoekstra et al., 2012).

The major water uses such as irrigation, industrial and domestic water use are considered by most of the large-scale studies when quantifying water scarcity. Among these water uses, irrigation is the largest water use which constitutes 70% of the total water requirement (Döll et al., 2009; Wada et al., 2011a). Furthermore, a predicted doubling in food demand in the next 50 years (Tilman et al., 2002) poses serious challenges to sustainable water use and associated water services. On the other hand, industrial and domestic water uses are growing at a rapid rate, which is making them an important consideration in large-scale assessments.

Environmental water demand is often neglected by most of the large-scale assessments, resulting in an underestimation of water scarcity. Only a very few recent large-scale assessments have accounted for environmental water demand while quantifying water scarcity (Hanasaki et al., 2008; Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016). Some of these large-scale studies make provisions for environmental flow allocations greater than 60% – 80% of the natural runoff. However, this level of environmental water allocation may result in the overstated level of water scarcity and this implies an overstated population magnitude affected by water scarcity. By allocating greater than 50% of the total water available to meet the environmental flow demand, other demands such as irrigation, industrial and domestic water demand are unmet or partially met. Hence, there is clearly a need to improve the way in which environmental flows are quantified, to better understand how the increase in demand and climate change influences sustainable water use.

Based on these findings, this work aims to review various methods to quantify water scarcity at large-scales (continental to global). After outlining the components comprising the analysis of sustainable water use and water scarcity (see Figure 1), reviews of each individual component will follow. Finally, the significance of accounting for the impacts of increasing demand and changing climate on to the water scarcity and the limitations of the modelling approaches used in those assessments are discussed.

# 2. Methods to quantify sustainable water use

Sustainable water use and water scarcity are estimated as a function of total water available and total water use in most of the large-scale assessments as shown in Figure 1. However, majority of the large-scale assessments, as listed in Table 1, did not encompass this entire framework. In addition, the way in which total water available and total water use are defined in these studies is different (Table 1). In Figure 1, the green boxes represent the major components of water use and supply and the dashed lines represent the return flow, which is defined as the amount of water returning to the pool of 'available water' after demand is met. The methods by which the various water uses are estimated in large-scale assessments are shown in the violet boxes.

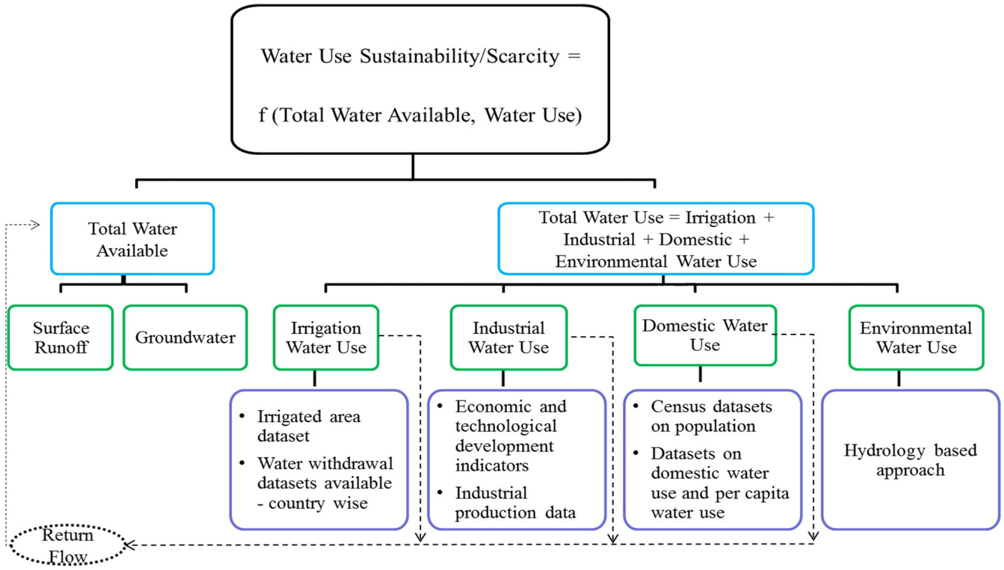


Figure 1. Sustainable water use and water scarcity modelling framework summary

At a global level, there are many studies undertaken to assess the sustainable water use, some of which are listed in Table 1 (extended from Mekonnen and Hoekstra (2016)). The major focus of such assessments is to estimate the water availability and water demand as realistically as possible (Veldkamp et al., 2015). The majority of these studies characterize water scarcity as *a function of the total water available to total water demand/withdrawal*, as depicted in Figure 1. However, the methods used to estimate each of the major components of sustainable water use differ between existing studies. The total water use is estimated based on population size in some studies (Islam et al., 2006; Kummu et al., 2010), while other studies use water withdrawals by various sectors to estimate water use (e.g., Alcamo et al. (2000), Oki et al. (2001)). On the other hand, some recent studies re-defined 'water use' based on the concept of the "blue water footprint" as "the net water withdrawal that is not returned to the environment because either the water is evaporated or is incorporated into a product" (Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016). Moreover, environmental water use is another important water use, which needs to be considered in sustainable water use quantification as shown in Figure 1.

Table 1. List of studies on global water resources scarcity assessment [modified from Mekonnen and Hoekstra (2016)]

| Study | Modelling Platform | Water Use Measure | Total Water Availability Measure | Space | Time | Sustainable Water Use Measure | Population affected (billion) | Remarks |
|---|---|---|---|---|---|---|---|---|
| Alcamo et al. (2000) | Water GAP “Global hydrological model with modules of water use and water availability” | Withdrawal | Natural Runoff | Basin | Annual | Water Withdrawal/ Availability > 0.4 | 2.1 | Future scenarios: business as usual scenarios considered and observed that in developing countries, severe water stress and water shortages may be experienced |
| Vörösmarty et al. (2000) | Water Balance Model (WBM) | Withdrawal | Actual Runoff | 30 arc minute | Annual | Water Withdrawal/ Availability > 0.4 | 1.8 | Large-scale assessments at continent level masks the water scarcity at regional level almost accounting for another 1.3 billion population experiencing water scarcity at the regional level |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Oki et al. (2001) | 11 Land Surface models using TRIP (Total Runoff Integrating Pathways) | Withdrawal | Actual Runoff | 30 arc min and basin | Annual | Water Withdrawal/ Availability > 0.4 | 1.7 - 2.7 | Water use highest in Asian countries and water availability was underestimated which exaggerate the water scarcity |
| Oki and Kanae (2006) | | Withdrawal | Actual Runoff | 30 arc minute | Annual | Water Withdrawal/ Availability > 0.4 | 2.4 | Climate change increase the availability of fresh water; but seasonal variations offset it |
| Islam et al. (2006) | | Population Size | Natural and Actual Runoff | 30 arc min | Annual | Water use < 1000 $m^3$/person/year | 1.8 - 3.1 | Natural water availability + virtual water trade is considered |
| Hanasaki et al. (2008) | Integrated Global Water Resources Model (H07) with land surface hydrology module | Withdrawal | Actual Runoff minus Environmental flow requirements | 60 arc min | Monthly | Cumulative water withdrawal to demand ratio < 0.5 | 2.4 - 2.5 | Climate change alters the availability of fresh water; but the study considered the water storages in reservoirs which can store water during excess runoff and hence global water |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | stress reduced with the climate change |
| Kummu et al. (2010) | STREAM model | Population Size | Natural Runoff | Sub-basins | Annual | Per capita water use < 1000 $m^3$/ person/ year | 2.3 | Influence of population is 4 times larger than that of the available water resources |
| Wada et al. (2011a);<br>Wada et al. (2011b) | Global hydrological modelling by PCR-GLOBWB with ground water component | Consumption | Actual Runoff | 30 arc minute | Monthly | Water Withdrawal/ Availability > 0.4 | 1.7 - 1.8 | Non-renewable groundwater abstraction was estimated using country wide groundwater abstraction data |
| Hoekstra et al. (2012)<br>Mekonnen and Hoekstra (2016) | Composite Runoff database of Fekete et al., 2002 | Consumption | Natural Runoff minus Environmental Flow Requirements | 30 arc minute | Monthly | Water Consumption/ Availability > 2 | 2.7<br>4 | Environmental flow requirements were assumed as 80% of natural runoff which exaggerated the water scarcity affected population quantile |

The estimation of water availability is similar in most of the studies (Table 1), which is based on using runoff as its measure. However, Wada et al. (2011a) observed that contribution from groundwater in India, USA and China cannot be neglected, as shown in Figure 2. Therefore, there is an increasing need to incorporate groundwater component into the large-scale modelling framework when quantifying water availability.

Spatial and temporal scales are additional important criteria to be considered in the estimation of water availability. The majority of the studies listed in Table 1 use global hydrological models or land surface models for estimation of water supply. However, these models differ in many aspects, which make model selection and their features increasingly important. Based on these findings, the following section discusses the methods by which water availability is estimated in large-scale applications, the scale issues associated with the large-scale modelling framework and how the ground water component can be incorporated.

## 2.1 Estimating water availability

The quantification of sustainable water use and scarcity mainly depends on the accurate estimation of water available to meet the demand, as shown in Figure 1. Recent studies such as Hoekstra et al. (2012) and Mekonnen and Hoekstra (2016) used the global gridded monthly runoff data obtained from selected gauging stations of Global Runoff Data Centre (GRDC) and water balance model (Fekete et al., 2002). While other studies used the total runoff calculated by various global hydrological models (Alcamo et al., 2003; Wada et al., 2011a). Hanasaki et al. (2008) developed an integrated global water resources model that contains modules of land surface hydrology, river routing, crop growth, reservoir operation, environmental flow requirements, and anthropogenic water withdrawal to estimate water availability in each spatial subunit (grid cell). However, most of the large-scale modelling approaches impose limitations on the lateral transport of runoff. To overcome this limitation, Hoekstra et al. (2012) and Mekonnen and Hoekstra (2016) used a flow accumulation function of ArcGIS (Esri, 2008) to route the runoff from upstream to downstream. In a similar way, the Total Runoff Integrating Pathways (TRIP) was used by Oki et al. (2001) to route the runoff from land surface models. Furthermore, Oki et al. (2001) observed that water scarcity can be overestimated when lateral transport is neglected as in the previous approaches. Conversely, other large-scale assessments neglected the lateral transport of runoff due to modelling constraints and scale issues. Further, the complex interactions between atmosphere and vegetation influence the spatial and temporal pattern of local climates, and hence increasingly there is a need to assess these interactions in detail.

Climate variability is important for water availability estimation in large-scale studies. It has been shown that coupled earth systems model can more correctly reproduce climate variability, especially when land cover and land use change with time (Bonan et al., 2002; Zabel et al., 2012). The use of the coupled earth systems model can also improve estimation of large-scale available water, particularly over the regions with sparse ground monitoring networks (Zabel and Mauser, 2013). Moreover, the influence of vegetation on climate is simulated in these models by using biophysical and biogeochemical features such as evapotranspiration, albedo, carbon cycle, trace gas emissions and the roughness of land surface (Sato et al., 2015). The models with the soil-vegetation-atmosphere transfer (SVAT) scheme are superior over the conceptual evapotranspiration models as the former can simulate the actual agricultural water use. Hence, the use of a coupled model can improve the water availability estimation in large-scale sustainable water use framework in changing climate and land use/land cover.

### 2.1.1 Temporal and spatial scale of assessment

In most regions across the globe, a major share of total water availability is concentrated within a short period, mainly from April to June in North America, March to June in Europe, May to September in Asia and in Africa in January, August and September (Hoekstra et al., 2012). When water availability is quantified at an annual time scale (Oki et al., 2001; Islam et al., 2006; Kummu et al., 2010), it fails to capture the intra-annual variability, which can severely affect water availability even in water abundant regions (Hoekstra et al., 2012). Studies such as Mekonnen and Hoekstra (2016) observed that by moving from annual to monthly assessment of water scarcity, highly populated countries such as India and China that have around 1.0 billion and 0.9 billion people, respectively, experience water scarcity in at least one month of the year. This was not identified by the previous studies, as the assessments carried out at the annual time scale mask the intra-annual water scarcity. As a result, recent studies use a monthly temporal scale of assessment to capture seasonal variations of water scarcity (Hanasaki et al., 2008; Wada et al., 2011a; Wada et al., 2011b; Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016). This approach helps to obtain a better assessment than that based on an annual time scale.

Large-scale assessments are usually carried out at coarser spatial grids greater than $0.5^{o}$ x $0.5^{o}$ rather than country based estimate. Grid based assessments are mostly adopted in large-scale assessments as it is an inevitable choice for computational efficiency and for coupling with the atmospheric module. Further, the major objective of large-scale assessments is to quantify the water stress in regions evolving with the global changes in water use and climate rather than locally focussed assessments (Döll et al., 2003). However, due to lack of such spatially diverse data in most countries, such assessments are difficult. Most of the countries only have country based estimates or observations of water use dataset. Hence these country based estimates are typically distributed onto grid cells based on population density and national boundary information (Hanasaki et al., 2008).

Due to these scale issues and data constraints, many large-scale assessments ignore the groundwater component and its contribution to meet the water demands. However, this assumption can lead to wrong interpretation of water scarcity in many countries where groundwater use is dominant (Wada et al., 2011a). Figure 1 also supports the fact that the groundwater component should be incorporated into the modelling framework of sustainable water use. The significance and methods of incorporating groundwater component are detailed in the following sub–section.

### 2.1.2 Groundwater component

Methods for small scale water resource assessment focus on groundwater recharge contributions to water availability. However, incorporating groundwater component in the global hydrologic modelling framework, especially when it is carried out at grid cells of coarser resolution ($0.5^0$ x $0.5^0$) is rather difficult. For instance as Alcamo et al. (2003) developed a global hydrological model to account for surface runoff and base flow, groundwater storage was not considered. Further, many studies listed in Table 1 neglected the groundwater component in the estimation of water availability. To overcome this limitation, Wada et al. (2011a) assumed that the difference between the total water available from surface runoff and total water demand is met from groundwater. This assumption is only applicable to spatial sub-units (grid cells) where aquifers are present. In applying this assumption, if the deficit between the water availability and demand at the country level is greater than the mean annual groundwater abstraction in the country, the total groundwater abstraction is distributed to each grid cell in proportion to the net water demand.

The significance of incorporating the groundwater component in the large-scale modelling framework shown in Figure 1 is supported by Figure 2 which shows the countries with large non-renewable groundwater abstraction for the periods 1960 and 2000 (Wada et al., 2011a). The non-renewable groundwater abstraction was estimated in Figure 2 as the amount of ground water overdraft in excess to groundwater recharge. It was observed by Wada et al. (2011a) that India is the country experiencing the largest groundwater abstraction. The high rate of increase in groundwater abstraction in India from 1960 to 2000 was mainly driven by the "Green Revolution" (Kumar, 2003). Hence, the sudden growth in groundwater abstraction owing to technological and economic development necessitates accurate quantification.

Neglecting the groundwater component in large-scale assessment can lead to the wrong interpretation of the water scarcity assessment. Lack of groundwater data in many countries, however, poses a significant problem. Groundwater abstraction data is only available for very few years in many countries. To overcome this limitation, Wada et al. (2011a) used the available groundwater abstraction statistics in the year 2000 to calculate the annual groundwater abstraction for other years, by proportionally distributing the groundwater overdraft based on the net annual water demand. However, this method may lead to an overestimation of the abstraction in areas where surface water is plenty. An additional limitation is that in certain regions, even when surface water is available, groundwater is preferred over the surface water due to ease of accessibility and quality constraints (Wada et al., 2011b).

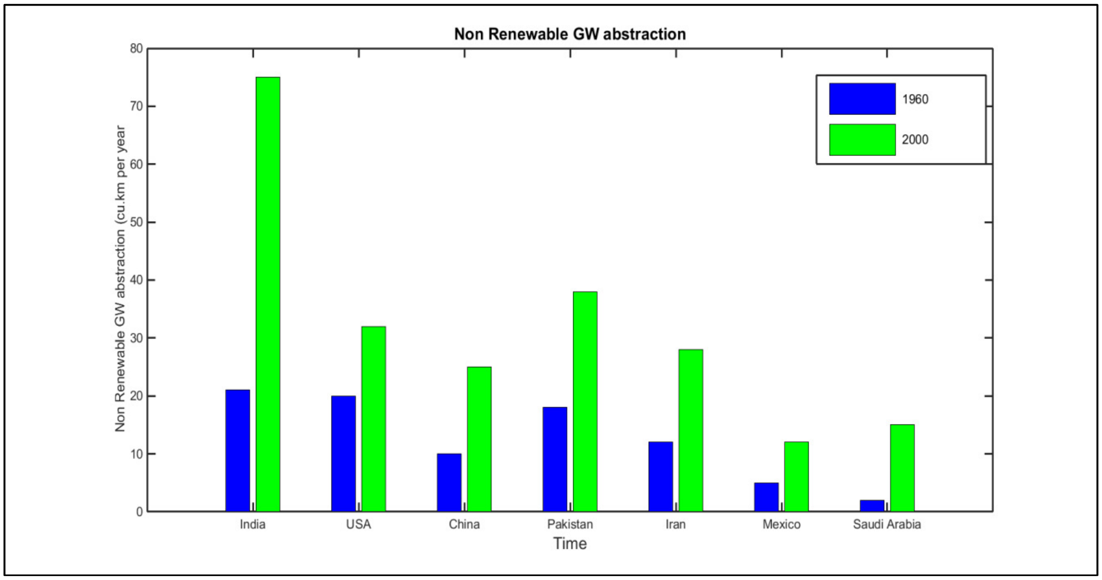


Figure 2. Non-renewable groundwater abstraction estimated for various countries for 1960 and 2000 (Wada et al., 2011a)

Along with the water availability criterion, anthropogenic water demand is another important component in the sustainable water use-modelling framework presented in Figure 1. The following section discusses various methods to quantify various water uses in large-scale assessments. The assumptions and limitations involved in the quantification of water uses are discussed in detail.

## 2.2 Estimating water uses

The increase in water demand across the globe due to population growth and economic development plays a major role in fresh water scarcity. Most of the global level assessments shown in Table 1 focussed on accurate methods to simulate irrigation demand with the available data sets on cropping pattern and irrigation requirements. However, due to data constraints, other water demands were estimated by redistributing the national level census datasets into each spatial sub-unit within each country. Of significant importance in water scarcity assessment as shown in Figure 1 is the quantification of environmental water use. The following section discusses the methods used in large-scale assessments to estimate irrigation, industrial, domestic and environmental water use.

### 2.2.1 Irrigation water use

Irrigation is the largest water use and many large-scale assessments have followed different methods to estimate its magnitude. Country wise irrigated areas, cropping maps, cropping calendar, census data on irrigation water withdrawal are some of the most common methods used to estimate irrigation water demand in large-scale assessments (Figure 1). The global map of irrigated area was used by Alcamo et al. (2000) to estimate the water requirements for irrigated crops assuming only two crop types, rice and other crops. Later, studies such as Döll and Siebert (2002) used the CROPWAT model (Smith, 1992) to calculate net irrigation water requirements. Afterwards, a global crop calendar with irrigated and rain-fed crops was developed by Portmann et al. (2010) for around 26 major crops. The global crop calendar is then enhanced with crop factors and crop rooting depth for each crop stages by Siebert and Döll (2010). Subsequently, Wada et al. (2011a) combined together the irrigated areas with crop factors, crop growth period and reference evapotranspiration to estimate monthly crop-specific potential evapotranspiration, assuming no water stress condition. In a similar way, the irrigation demand for each grid cell was estimated by Mekonnen and Hoekstra (2016) based on crop-maps, period of crop growth and country level census data on irrigated areas and irrigation water withdrawals.

Most of the available irrigation datasets present water withdrawal rather than water consumption because transmission losses, return flow and groundwater recharge are not segregated (Hanasaki et al., 2008). Hence, in studies such as Hanasaki et al. (2008), consumptive water use was converted to withdrawal using the irrigation efficiency estimate of Döll and Siebert (2002). The irrigation efficiency was defined by Döll and Siebert

(2002) as the ratio of consumptive water use to water withdrawal and the study has consolidated the irrigation efficiency across the world taking into account the irrigation facilities and practices.

Figure 3a shows a comparison of global irrigation water demand between various studies (Shiklomanov, 2000; Shen et al., 2008; FAO, 2009; Wada et al., 2011b). Water withdrawal for irrigation is reported by Shiklomanov (2000) and FAO (2009) while gross irrigation demand is estimated by Shen et al. (2008) and Wada et al. (2011a). It can be observed that the demand simulated by these methods closely match for the period 1990-2000. Other studies such as Hoekstra et al. (2012) and Mekonnen and Hoekstra (2016) also used these estimates as reliable measures of irrigation demand for validation purposes while modelling global irrigation water use.

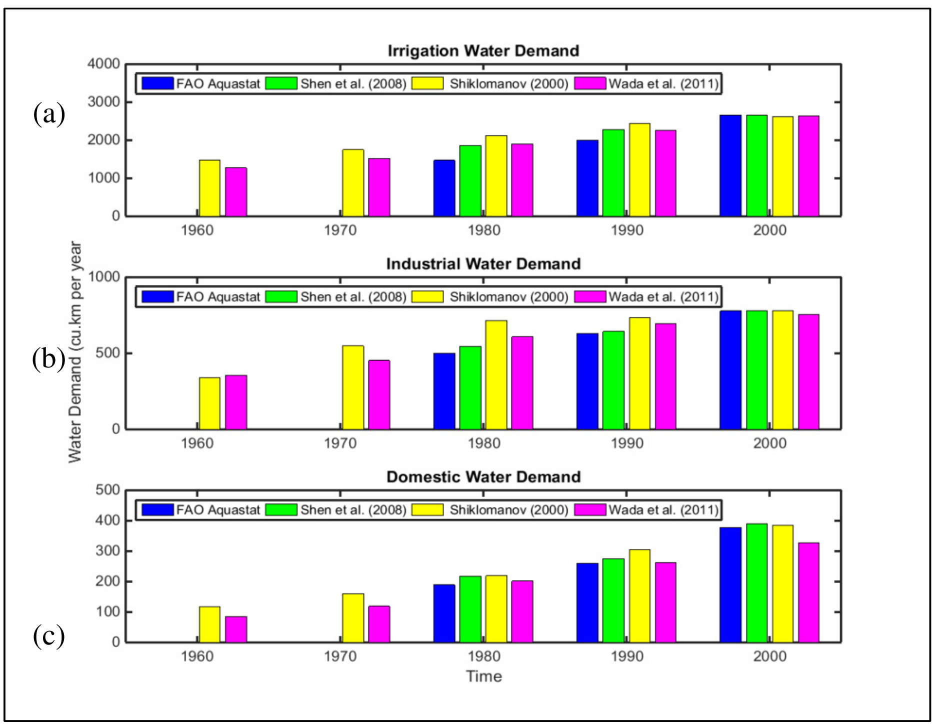


Figure 3(a) Irrigation water demand estimates , (b) Industrial water demand estimates, (c) Domestic water demand estimates from FAO (2009), Shen et al. (2008), Shiklomanov (2000) and Wada et al. (2011a) for 1960 – 2000

### 2.2.2 Industrial and domestic water use

Quantification of industrial and domestic water uses in large-scale assessments is challenging due to data constraints in many countries. Hence, surrogates for these water demands, such as gross domestic product, electricity consumption and population density, were used by many large-scale assessments. Changes in gross domestic product per capita and the amount of electricity generation to estimate water withdrawals in the industrial sector was followed by Alcamo et al. (2000), while country based estimates of industrial water use, using a global geographical information system, with global distribution of population was used by Oki et al. (2001). In a similar way, Wada et al. (2011a) calculated the spatially distributed industrial water use for each country based on the population density, industrial output and gross domestic product (GDP).

Industrial water use is less affected by seasonal within-year variations, and thus many large-scale assessments distributed the annual industrial water demand evenly between months (Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016). Industrial water withdrawals typically involve large returns to the environment (return flow), as shown in Figure 1. Calculating the return flow component is difficult as the necessary datasets are typically not available. Due to the lack of reliable return flow estimates, Wada et al. (2011a) assumed three representative return flow rates (or recycling rates) of 80%, 65% and 40% for developed (high income), emerging (middle income) and developing (low income) countries.

For a better quantification of industrial water use, it is necessary to have more census datasets on water withdrawal by different types of industries and time series across the world. However, these datasets are unavailable in many developing countries. Therefore, alternative methods to estimate industrial water use are required. Studies such as Shen et al.

(2008) identified that electricity consumption and industrial gross domestic product are some of the indicators that can be used to estimate growth in industrial water demand.

Another important water use to be considered in large-scale assessment is domestic water use, which requires census population datasets and per capita water use to estimate it (Figure 1). Domestic water demand is usually quantified on the basis of country specific per capita domestic water consumption and population (Wada et al., 2011a). Under this approach, the per capita water use within the country is assumed uniform due to the lack of within country data. However, owing to economic and technological development, per capita water use has changed across the world, which necessitates an accurate quantification of variation in per capita water use spatially and temporally.

Census datasets that describe variation of population density within the country is available for the majority of countries. Hence large-scale assessments such as Wada et al. (2011a) distributed the national level domestic water demand based on population in each spatial sub-unit (grid cells). A similar approach was followed in Hoekstra et al. (2012) and Mekonnen and Hoekstra (2016) which spatially distributed national data on domestic water withdrawals from FAO (Food and Agriculture Organisation) based on grid-cell population density. Further, domestic water use is also affected by seasonal variations within the year. To account for this variation, some large-scale assessments (Mitchell and Jones, 2005; Wada et al., 2011a; Wada et al., 2011b) used air temperature as a proxy to convert annual domestic water use to monthly values.

A comparison of industrial and domestic water estimates from FAO (2009), Shen et al. (2008), Shiklomanov (2000) and Wada et al. (2011a) for 1960 – 2000 is shown in Figures 3b and 3c. It can be observed that domestic and industrial demand increased more rapidly than irrigation demand. Hence, when considering future scenarios of sustainable water use, these water uses needs to be quantified more accurately. However, data constraints on water withdrawal in many countries indicate that future work needs to quantify these demands with the support of datasets such as population, electricity consumption and gross domestic product.

### 2.2.3 Environmental water use

Environmental water use is defined as "*the quantity, timing and quality of water flows required to sustain fresh water and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems*" (Declaration, 2007). The quantification of environmental flows in large-scale assessments is difficult due to data constraints and lack of proper methods to estimate it. For quantifying environmental flows, Tharme (2003) listed various approaches as Hydrology-based, Hydraulic-Rating, Habitat-Simulation and Holistic methodologies. The Hydrology based approach allocates environmental flows by mimicking the natural flow regime while Hydraulic-rating approach focusses on hydraulic parameters such as wetted perimeter and depth. The Habitat-simulation method focusses on conservation of aquatic habitat by allocating sufficient amount of flows and the Holistic approach combines data and information from hydrology, hydraulics, fluvial geomorphology and sedimentology together to calculate the environmental flow allocation (Tharme, 2003). The selection of the appropriate method to quantify environmental flows is site-specific and expert based assessments are essential to address ecological effects (Stewardson and Webb, 2010). This view was supported by Horne et al. (2010) who propose that environmental risk in the site is the major decisive factor for choosing the evaluation method. Environmental risk is defined as a function of the deviation from the natural flow regime. A similar approach was followed by Latu et al. (2014) who observed that an increase in the magnitude of the unmet environmental demand increases the environmental risk resulting in negative impacts to environmental habitat.

Quantifying the environmental risk in large-scale assessments remains a difficult task due to lack of available data and associated uncertainty of environmental responses. In a catchment based environmental flow assessment, George et al. (2011) reports several environmental flow rules based on the aquatic habitat, magnitude, frequency and duration of flows. Such assessments are data intensive and are specific to each particular catchment. As a result, in large-scale assessments, environmental flows are usually defined using hydrological methods owing to lack of global level eco-hydrological data in large-scale assessments (Hoekstra et al., 2012). A similar observation was made by Gippel et al. (2012) who posit that, if the flow magnitudes and frequencies are made to match the natural flows that existed before extensive anthropogenic interventions, ecosystem will be restored to a greater extent.

Most of the studies listed in Table 1 analyse water scarcity at grid cell resolution greater than 50 km x 50 km, that makes the application of other environmental flow estimation methods, difficult. On this account, adopting a Hydrology Based approach that allocates environmental flows as a threshold percentage of total water available is acceptable for the purpose of water scarcity assessment studies (Hanasaki et al., 2008; Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016).

A global level environmental flow assessment by Smakhtin (2006) proposed to use various environmental flow thresholds to use for hydrology based approach. The study suggested that a threshold of 10% of the mean annual runoff is at least required to avoid severe degradation of ecosystems, 30-40% for ensuring fair habitat conditions, and 60-100% for environmental optimum. More important, the environmental water requirements within a year vary depending on different seasons. Pastor et al. (2014) observed that environmental water demand is higher during low flow periods (46-71% of average low flows) while it is lower during high flow periods (17-45% of average high flows). This view was supported by several studies in which environmental flow allocations are made after classifying the months into low flow and high flow months (Tennant, 1976; Tessmann, 1980; Smakhtin et al., 2004; Pastor et al., 2014). Table 2 provides the environmental water demand thresholds for different seasons adopted by these studies. Mean monthly flow (MMF), mean annual flow (MAF), flow exceeding 50% of period of record (Q50) and flow exceeding 90% of period of record (Q90) are the variables used to classify the hydrological seasons.

Table 2. Comparison of environmental flow calculation methods (Pastor et al., 2014)

| Hydrological seasons | Low flow months | Low flow requirements | High flow months | High flow requirements |
|---|---|---|---|---|
| Tennant (1976) | MMF <= MAF | 0.2*MAF | MMF>MAF | 0.4* MAF |
| Tessmann (1980) | MMF <= 0.4*MAF | MMF | MMF>0.4*MAF and 0.4*MMF>0.4*MAF | 0.4*MMF |
| Smakhtin et al. (2004) | MMF<=MAF | Q90 | MMF > MAF | (0-0.2)*MAF |
| Pastor et al. (2014) | MMF<=MAF | Q90 | MMF > MAF | Q50 |

As shown in Figure 1, environmental flow allocation is an integral part of large-scale assessments. For a more accurate quantification of environmental flows in large-scale assessment, the Hydrology Based approach, defined for each seasonal time scale can be adopted. Due to the lack of global eco-hydrological data, the use of other methods such as Hydraulic Rating, Habitat Simulation and Holistic methodologies is precluded for global level assessments.

# 3. Impacts of demand vs. water availability

Climatic variations affect the total water availability, which contributes to the changes in sustainable water use, as shown in Figure 1. Owing to the increase in population and economic development, the continuous increase in water demand in the past 50 years across the world also poses a serious challenge to the sustainable water use. However, various assessments have observed that the past extreme water stress experienced in the emerging developing countries is mainly due to the increased population and economic growth than being climate induced (Postel, 2000; Kummu et al., 2010; Wada et al., 2011a). Postel (2000) have estimated that almost half of the annual runoff is lost to rapid flow off the land in floods and another one fifth of the annual runoff is geographically too remote to be economically accessed to meet the water requirements. Further, Hanasaki et al. (2008) identified that even though climate change varies the availability of fresh water, the total volume of annual water availability is not changing significantly. The study further added that the water storages in reservoirs, which help to transfer water from high flow season to low flow season, reduces the rate of increase in water scarcity. This observation was supported by Arnell (2004) who identified that the climate change reduces the global water stress indirectly. To this end, a linear regression analysis was carried out by Kummu et al. (2010), to distinguish the impacts of climate change and increase in water demand on water scarcity. The study inferred that the impact of population increase on sustainable water use is four times more than that of the water resources availability. The study also observed that, from 1960 onwards, a rapid increase in the population affected by chronic water shortage was experienced with 9% (280 million people) in 1960 to 35% (2300 million people) in 2005. Further, Wada et al. (2011a) has identified that extreme water stress was experienced in many countries including India, Turkey, Romania and Cuba in the past 50 years. This was mainly driven by increase in water demand than being induced by climate. However, a clear distinction of the impacts of water demand and climate change on sustainable water use is yet to be made at a global level. Hence, to quantify the impacts of climate change and increase in water demand on to the heightened water stress, a more detailed study focussing on such countries is required.

Along with estimating water demand and water availability in the quantification of sustainable water use, the virtual water trade or the transport of water between different river basins or countries is another important criterion in large-scale assessment. The next section reviews the large-scale assessments that have accounted for virtual water trade. Following that, the methods by which future prospects of sustainable water use can be projected and the major limitations of the large-scale modelling approaches are discussed in the subsequent sections.

# 4. Virtual water trade

The majority of the large-scale water resource assessments do not incorporate virtual water trade into the modelling framework. This is principally due to the lack of sufficient data regarding the transport of water. Such assessments assumed that each country or region has sufficient resources to meet the internal water demand. However, studies such as Islam et al. (2006) have observed that a large share of population in Middle East, North Africa and Sub-Sahara region are highly dependent on the virtual water import from other countries. This observation is supported by Hoekstra and Mekonnen (2016) who found that around 55% of United Kingdom’s blue water footprint is located in six countries, Spain (14%), USA (11%), Pakistan (10%), India (7%), Iran (6%) and South Africa (6%). Although global estimates of virtual water trade has been made by several studies it is not combined with water availability in a spatially distributed manner (Turton, 1999; Wichelns, 2001; Hakimian, 2003). Further, these studies use crop trading statistics from FAO (Food and Agriculture Organisation) which are only applicable at country level (Oki et al., 2003; Hoekstra and Hung, 2005). To overcome these limitations, Islam et al. (2006) quantified the virtual water export within the country by distributing the country level values into each grid cell based on population density and agricultural areas. However, a large share of the studies listed in Table 1 has not accounted for virtual water trade in their modelling approach owing to data constraints. Although the major implication of considering virtual water is that it can account for the water export and water scarcity in a country, accurate methods to disaggregate the total amount of virtual water are not yet available. What's more, some studies listed in Table 1 use water consumption as the measure of water use, and if virtual water is accounted separately, it may result in double counting of water use within the country. Lack of sufficient datasets in most developing countries is another reason for not accounting virtual water trade in these assessments.

# 5. Future projections of sustainable water use

Brundtland et al. (1987) define sustainable development as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Increasing demand and climate change are a threat to the sustainable water use creating an emerging need to estimate future sustainable water use. The advantage of large-scale assessments is that most of them use continental to global-scale earth system models, as listed in Table 1, facilitating the link to future climate projections to enable prediction of future sustainable water use.

Several studies have assumed different scenarios of development and climate change for future water demand projection (Alcamo et al., 2000; Rosegrant et al., 2002; Santikayasa et al., 2014). Santikayasa et al. (2014) considered various scenarios such as an increase in irrigated area, increase in cropping intensity and variations in cropping patterns while Alcamo et al. (2000) identified the impact of demographics, economic and technological changes as important criteria that need to be considered in future assessments. Three future water withdrawal scenarios were considered by Rosegrant et al. (2002) namely the (1) Business As Usual Scenario (BAU), (2) Water Crisis Scenario (CRI), (3) Sustainable Water Use Scenario (SUS). In business as usual scenario, the water demand growth is projected according to the past trend, but with current conditions of water withdrawal capacity and physical constraints on pumping. While in water crisis scenario, the deterioration of current trends and policies in the water sector are considered and in sustainable water use scenario, the improvement in policies and trends in the water sector are considered. Business as usual scenarios were also followed by Alcamo et al. (2000) and observed severe water stress and water shortages in many developing countries in future. It is important to note that these projections assumed that the influence of economic and technological changes in the per capita water use is negligible.

Climate change is another important factor, and large-scale assessments can utilize the future climate projections to predict the water scarcity estimate for future. Nevertheless, the future trajectory of sustainable water use depends mainly on population and economic development changes than the changes in climate (Vörösmarty et al., 2000). However, an integrated modelling framework is required to address sustainability of water use for various future scenarios. The various scenarios should include the future projections of water use and climate change.

# 6. Limitations of modelling approaches

One of the major limitations in many large-scale assessments is the absence of an environmental flow component. However, several large-scale assessments have adopted a higher threshold value for water scarcity measure to indirectly account for environmental flow requirements (Wada et al., 2011a; Wada et al., 2011b; Mason and Calow, 2012). In these studies, water scarcity is defined as the ratio of water consumption to water availability and hence adopting a higher threshold value indirectly includes environmental flow requirements. Some of the recent studies considered environmental flows, but the sub-annual variations are neglected in the studies (Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016). This approach precludes the assessment of seasonal variations in environmental water demand.

Another important limitation in the large-scale assessment is the absence of *groundwater component*. This is mainly due to lack of data on groundwater abstractions from different countries. As highlighted by Wada et al. (2011a), in countries like India, the usage of groundwater has substantially increased during the past 50 years (Figure 1). Thus, it is imperative to develop accurate methods to quantify groundwater use while quantifying water scarcity.

Most of the large-scale assessments do not account for the *virtual water trade* between countries in their assessments. This is important in countries such as the United Kingdom (UK), in which more than half of the blue water footprint is contributed by other countries. However, accurate methodologies for estimating virtual water trade in the context of large-scale assessments have not yet developed primarily due to the pervasive lack of adequate data.

# 7. Conclusions

This review showed that the sustainable water use is a major concern globally and various large-scale assessments indicate increasing fresh water scarcity. The projected rises in demand and climate change are together contributing to the deterioration of sustainable water use, with the rise in demand having greater impact than climate change. Irrigation is typically the largest water demand while the major water supply is natural runoff. The majority of the studies have focussed on these two variables and have attempted to quantify how much of the water available can be used to meet demands, which in turn form the basis for the quantification of water use scarcity indices. Recent studies highlighted the significance of considering environmental flow requirements and groundwater contributions for meeting demand and estimating sustainability of water use. While due to inadequate datasets, industrial and domestic demands are often estimated using simplified assumptions that distribute demand over a country based on population density, per capita water use, gross domestic product and electricity generation.

Some of the salient points from the review include the following:

- Selection of modelling approach: the study critically reviewed the framework (Figure 1) to quantify sustainable water use. It also discusses the significance and methods of each component that contribute to the water scarcity framework. The review observes that the use of coupled earth system based model to quantify the water availability and the use of census statistical database to quantify water uses will improve the water scarcity assessment at large-scale.
- Scale of assessment: assessment of monthly temporal scale of water scarcity is preferred over annual temporal scale to capture the seasonal within-year variations.

- Estimation of water availability: rather than the conventional method of using surface runoff alone as the water availability measure, it highlights the advantages of methods that incorporate the groundwater component in large-scale assessments.
- Estimation of water uses: the review identifies the increasing significance and need to account for industrial, domestic and environmental water use in large-scale modelling frameworks and compares the various methods to quantify these water uses. Seasonal variations in domestic (air temperature as a proxy) and environmental water use (Table 2) in the large-scale assessments require appropriate methods of accounting.
- Impacts of future demand and water availability: although climate change can impact the sustainability of water use, it is observed that the impact of anthropogenic demand is almost four times greater than that of the climate change (Kummu et al., 2010).

Acknowledgements

The research is financially supported by the M.K.N. Johansen scholarship through the Department of Infrastructure Engineering, University of Melbourne.

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