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Water depletion: An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments

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Abstract

We present an improved water-scarcity metric we call water depletion, calculated as the fraction of renewable water consumptively used for human activities. We employ new data from the WaterGAP3 integrated global water resources model to illustrate water depletion for 15,091 watersheds worldwide, constituting 90% of total land area. Our analysis illustrates that moderate water depletion at an annual time scale is better characterized as high depletion at a monthly time scale and we are thus able to integrate seasonal and dry-year depletion into the water depletion metric, providing a more accurate depiction of water shortage that could affect irrigated agriculture, urban water supply, and freshwater ecosystems. Applying the metric, we find that the 2% of watersheds that are more than 75% depleted on an average annual basis are home to 15% of global irrigated area and 4% of large cities. An additional 30% of watersheds are depleted by more than 75% seasonally or in dry years. In total, 71% of world irrigated area and 47% of large cities are characterized as experiencing at least periodic water shortage.

Introduction

Human wellbeing depends on adequate supplies of water to meet food, energy, industrial, and household needs, as well as to sustain ecosystem functions that service the global economy. Water scarcity is already a serious global threat: the World Economic Forum (2015) has highlighted water crises in its list of pressing global risks. Meanwhile, there is mounting concern about future water supplies as population growth and changes in food consumption patterns increase water demand while shifts in climate affect water sources (de Fraiture and Wichelns, 2010; Haddeland et al., 2014; Hoekstra, 2014). Quantifying and mapping water scarcity is crucial to understanding vulnerability to water shortages and to scaling solutions across sectors. Corporations, for example, are beginning to examine their operational and supply chain exposure to water related-risks, and the United Nations has sponsored an initiative to codify practices for evaluating water use in life cycle analyses (Boulay et al., 2015). An accurate mapping of water scarcity is increasingly critical to decision-making in many contexts.

Water security is complex, encompassing access as well as availability, and it is a function of culture, governance, and infrastructure development in addition to biophysical supply and demand (Cook and Bakker, 2012; Jaeger et al., 2013; Srinivasan et al., 2013). Yet biophysical indicators are central to risk assessment and strategic decision-making, and a metric that is applied globally enables comparison, shedding light on phenomena such as watersheds at similar levels of biophysical water shortage that experience different degrees of water stress.

Most existing indicators of biophysical water scarcity compare some measure of average yearly or monthly water use with average water availability; they then demarcate water scarcity by a threshold level

of use-to-availability or per-capita availability, occasionally with the incorporation of an environmental flow requirement (see catalogues by Brown and Matlock, 2011; Savenije, 2000). A brief overview of water scarcity metrics is provided in Table S1; Rijsberman (2006) considers the strengths and weaknesses of different types of metrics. At the global scale, these indicators are typically based on data calculated on a distributed grid that may be reported across the landscape or aggregated at the watershed or national scale (Sood and Smakhtin, 2014).

Here we present a straightforward biophysical measure of the fraction of available renewable water consumptively used by human activities within a watershed, which we call water depletion. This metric is an extension of existing water scarcity indicators, detailed in Table S1, and has several advantages. It directly informs the question, "What share of renewable surface and groundwater in a watershed is being consumed seasonally, annually, or in dry years and is thereby not available for other use?" By doing so, it fulfills the demand for an easily interpretable indicator of water scarcity (Rijsberman, 2006) and provides a straightforward way to ascertain the underlying physical status of water resources without a need for complex compounding or adjustments for population or presumed environmental flow (Niemeijer and de Groot, 2008). We present the metric here in conjunction with model outputs from the newest version of the integrated water resources model Water – A Global Assessment and Prognosis, referred to as WaterGAP3. The following sections address indicator development, rational, and an analysis of its implications.

Methods

Our characterization of water depletion uses calculations from WaterGAP3 to assess long-term average annual consumed fraction of renewably available water, then integrates seasonal depletion and dry-year depletion, also based on WaterGAP3 calculations, with average annual depletion into a unified scale.

WaterGAP3 model

Our analysis is based on model outputs from the newest version of the integrated water resources model WaterGAP3. Relevant elements of WaterGAP3 are described here and a more detailed model description is provided in the Supplementary Materials (aus der Beek et al., 2010; Döll et al., 2003, 2012; Flörke et al., 2012). WaterGAP3 minimizes spatial averaging by calculating a daily water balance at the 5 arc-minute scale (~81 km^2 at the equator), routing runoff, and reporting data for 143,653 individual watersheds and sub-watersheds. Our water depletion metric is applied to these sub-watersheds, within which water is frequently managed and redistributed (Molle, 2006), at a finer scale than in previous assessments (Brown and Matlock, 2011).

To calculate water depletion for each sub-watershed or time period, we evaluate the fraction of renewable surface water and annually renewable groundwater resources that are consumptively used. Average annual water availability – renewable surface water and annually renewable groundwater – is based on climate data from 1971–2000. Available renewable water includes water generated within the watershed and inflows from upstream that are stored or pass through rivers or move from the land surface into aquifers (renewable groundwater) during the time period of analysis. Storage reservoirs can attenuate seasonal variability by making more water available for consumption during dry months. The WaterGAP3 model used in this analysis incorporates reservoir regulation and evaporation for 1,875 large impoundments (holding 4,038 km^3 of water, about two-thirds of global reservoir capacity; Lehner et al., 2011). Inter-basin transfer of water is not considered.

Consumption is calculated for irrigation, livestock, energy production, manufacturing, and domestic use. Consumptive water use for irrigation is based on irrigated area in 2000 and climate conditions from 1971–2000. Water consumed for livestock, energy production, manufacturing, and domestic use is held constant at 2005 levels. In WaterGAP3, water consumption is not constrained by availability, so consumption may exceed availability due to exploitation of non-renewable groundwater or import of water from outside the watershed.

WaterGAP3 calculates outputs for 143,653 watersheds. However, for data reliability reasons we include only the 11% of these watersheds larger than 1,000 km^2, thereby excluding a large number of small coastal watersheds. The 15,091 watersheds included constitute 90% of total land area. Of these watersheds, 30% are less than 5,000 km^2, 27% are between 5,000 and 10,000 km^2, 39% are between 10,000 and 15,000 km^2, and the remaining 4% exceed 15,000 km^2. We also exclude polar watersheds, including all of Greenland, because they lack regularly flowing water. For any given analysis, the fractional number of watersheds and fractional watershed area are very similar because of the distribution of watershed size.

Development of the water depletion metric

The depletion metric we present here is based on the ratio of consumptive use to renewable available water, building from previous consumption-to-availability indicators including Alcamo et al. (2007), Hanasaki et al. (2008), Hoekstra et al. (2012), and Wada et al. (2011b) (see Table S1). We address consumptive use instead of withdrawals because the latter may overstate shortages by failing to account for return flows and

subsequent reuse of water (Perry, 2007). The volumes involved can be significant: in the Colorado River watershed in the western US, for example, return flows and reuse are so substantial that annual withdrawals exceed renewable annual supply (Richter, 2014). At the global level, water withdrawals are more than three times consumption. The WaterGAP3 model estimates that 62% of water withdrawals for irrigation, 78% of those for manufacturing, 83% of those for domestic use, and 97% of those for thermoelectric power production are returned to water sources after use. While this return flow is often altered in chemistry or temperature, and may be returned to a location different from where it was withdrawn, it nevertheless is available to be used again (Frederiksen and Allen, 2011).

Most water scarcity metrics delineate a continuous variable into categories of risk (e.g., very low to extremely high; Brown and Matlock, 2011; Savenije, 2000). Categories may be of limited relevance. For example, the withdrawal-to-availability threshold of 20% frequently used to demarcate medium-high or economic water stress (United Nations Commission on Sustainable Development, 1997) appears to have been originally developed by Balcerski (1964) and became widely cited after being adopted by Falkenmark and Lindh (1974). Though designed to indicate an increase in the cost of infrastructure development in post-war Europe and based on withdrawals and availability at the national scale, this threshold is now widely used in other contexts, including evaluations of consumption-to-availability and assessments at the grid-scale (Table S1).

We base our water depletion categories on even divisions of consumption-to-availability, with an additional distinction for watersheds less than 5% depleted to account for the large number of watersheds at very low depletion levels. An evenly distributed range of depletion categories gives users flexibility to interpret water scarcity-related risks to food, energy, cities, and ecosystems within their particular context.

In order to evaluate water depletion by category, it was necessary to identify a threshold to define a "depleted" condition on a seasonal basis and in dry years. Using categories allows us to integrate inter- and intra-annual variation with average annual variation into a single scale, the simplicity of which is important for decision-makers. We employ a threshold of 75% based on a natural division we identified in our data and discuss the implications of setting the threshold at this level in the uncertainties and limitations section of the discussion.

We define "seasonal depletion" for watersheds as occurring when annual depletion is below our 75% threshold but at least one month has a consumption-to-availability ratio greater than 75%. Because of the strong relationship between monthly and annual depletion, we integrate this category into our unified depletion scale just below 75% annual depletion. We classify watersheds as having dry-year depletion by evaluating seasonal depletion over each year of the historic range of water availability and evaporative demand (1971–2000). Watersheds are identified as dry-year depleted if they experience one month more than 75% depleted in at least 10% of years during the historic period but on average are not annually or seasonally depleted. We integrate dry-year depletion into our unified depletion scale just below seasonal depletion.

Our data constitute the global population of watersheds, not a sample, so statistics evaluating the significance or representativeness of data provide no information. Instead, we analyze our data and consider effect size using linear contrast analysis, which evaluates the ratio of within-group variation to between-group variation, calculated using a one-way analysis of variance (ANOVA) in Matlab 2014b.

Results and discussion

Identifying water scarcity

Previous assessments of water scarcity or stress have revealed patterns of scarcity similar to that illustrated in Fig. 1 (e.g. Alcamo et al., 2007; Hanasaki et al., 2010; Meigh et al., 1999; Wada et al., 2011b). We find that high levels of annual water depletion, as illustrated in Fig. 1A, are not widespread. When seasonal and dry-year variability is made visible, however, water depletion is apparent in a far greater proportion of watersheds, as illustrated in Fig. 1B.

Water scarcity tends to be very heterogeneous at small scales, and fine-scale analysis identifies regions of both much higher and much lower water shortage than the average (Perveen and James, 2011; Vorosmarty et al., 2005). At the global scale as calculated by WaterGAP3, water consumed in agricultural, industrial, and urban settings is just 2.5% of total available renewable water, so differentiation among sub-watersheds to characterize the frequency and intensity of scarcity is crucial for targeting investment and intervention (Wallace and Gregory, 2002). The sub-watershed resolution provided by WaterGAP3 is illustrated in Fig. 2 for the Mississippi River watershed in the central United States. Averaged across the entire watershed, the Mississippi is 25% depleted. However, evaluation of individual sub-watersheds shows that in 7% of the watershed area more than 75% of annually available water is consumed. By contrast, 57% of the total watershed area is less than 5% depleted on an annual basis.

Though their number is limited, identifying watersheds with high annual water depletion is crucial because their extreme biophysical water limitation constrains possibilities for adaptation. Annual water depletion between 75 and 100% occurs in just 0.5% of watersheds, and water depletion over 100% occurs in 1.7% of watersheds. It is possible for consumption to exceed annually renewable water when non-renewable
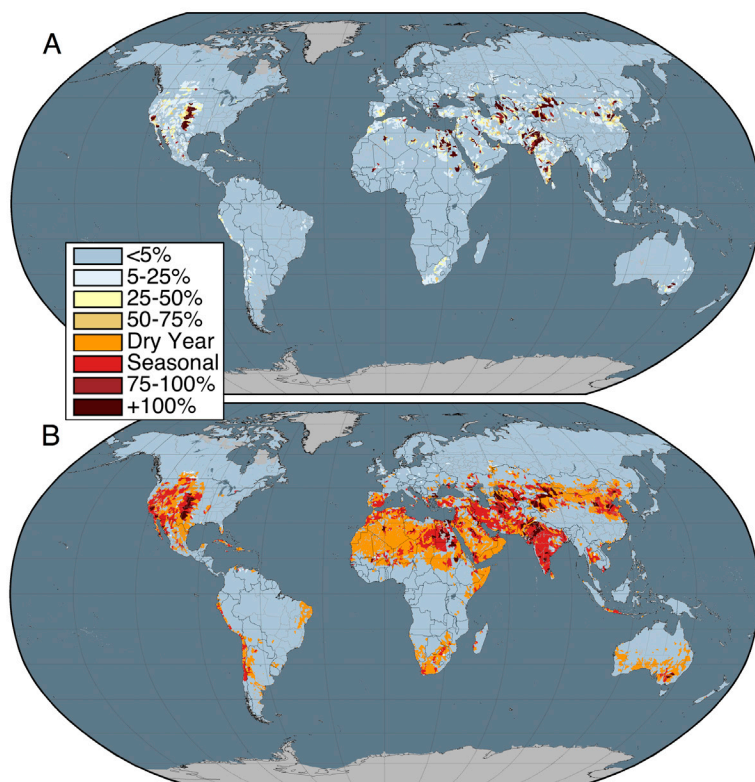
A

B

groundwater is exploited or imported water is accessed. Watersheds where depletion exceeds 100% tend to be arid and have relatively little water available; 80% are semi-arid or drier (Middleton and Thomas, 1997) and mean annual water availability is just 0.2 km³. Water consumption is far greater than 100% of available water in many of these watersheds. In order to consume only 100% of renewably available water in the watershed, 59% of the watersheds in the >100% annual depletion category would have to reduce consumption by more than half of their current level, an average of 0.9 km³.

The importance of accounting for periodic water shortage in addition to annual water shortage is well recognized, and calculations of distributed monthly shortage date back to Meigh et al. (1999). Since then, a number of researchers have evaluated inter-temporal water shortage in their measures of water stress or security. For example, Wada et al. (2011b) built a compound index based on an assessment of the length
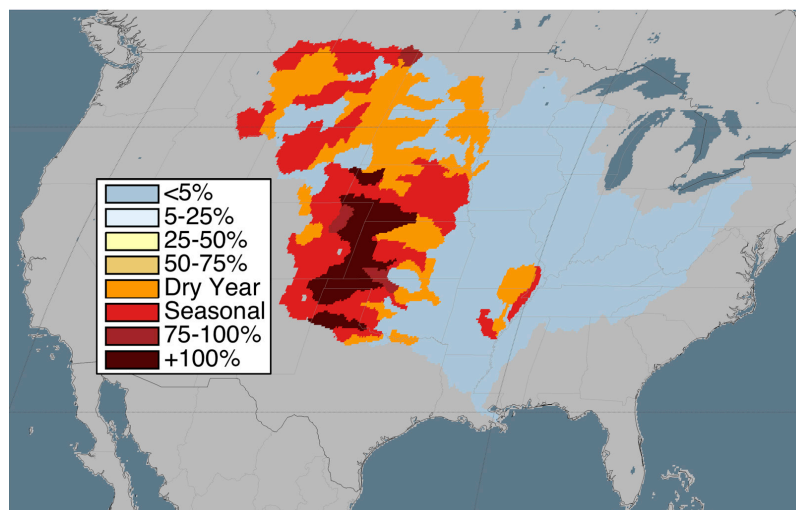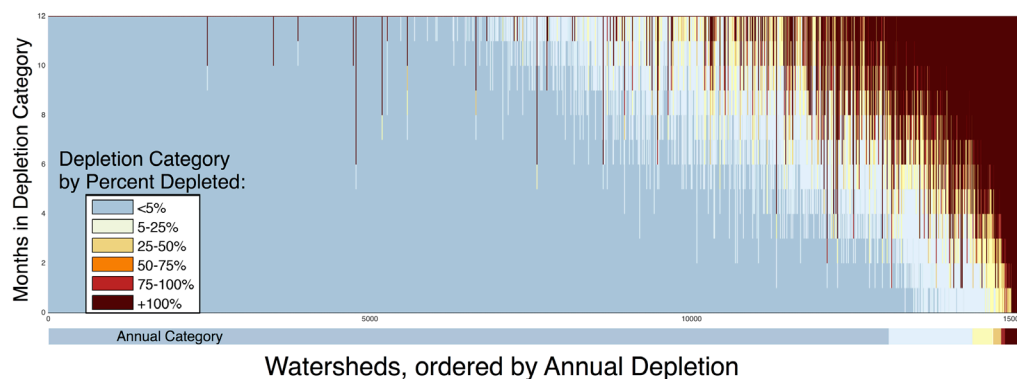
Figure 3

Relationship of monthly and annual water depletion.

Average annual values of water depletion can obscure seasonal depletion. Most watersheds that are moderately depleted on an annual basis experience at least one month of high water depletion. We find that 96% of watersheds that are 25–75% depleted on an average annual basis experience at least one month with >75% depletion. In addition, two-thirds of watersheds that are 5–25% annually depleted experience at least one month with >75% depletion. Each watershed is indicated by a single bar, arranged from left to right in order of increasing annual depletion level. Each bar is composed of 12 vertical segments, each representing one month. Segment color indicates the depletion category for one month. For legibility, segments are arranged vertically from lowest depletion at the bottom to highest depletion at the top. The color bar at the bottom of the figure corresponds to how the watersheds above would be categorized on an annual basis.

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and severity of water shortage, and Pfister et al. (2009) use a withdrawal-to-availability multiplier based on precipitation seasonality.

Using our water depletion indicator, we find 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. Watersheds at the very lowest levels of annual depletion exhibit low monthly depletion throughout the year, and watersheds at the highest annual depletion levels exhibit high levels of depletion year-round, illustrated in Fig. 3. However, for watersheds in the mid-range of annual depletion, we find that high seasonal depletion is ubiquitous. Nearly all (96%) watersheds that are 25%–75% depleted over an average year (418 of 436 watersheds) experience at least one average month that is more than 75% depleted. Seasonal depletion occurs in 9% of all watersheds (1,380). We find that moderate water depletion is uncommon at a monthly time step as well. Only 16% of watersheds have even one month experiencing water depletion between 25% and 75%. Instead, monthly water depletion tends to be very high or very low. In Fig. S1 we include maps of monthly water depletion for each month of the year.

Variation in precipitation among years affects watersheds at all levels of annual and monthly water depletion. Fig. 4 illustrates the re-categorization of watersheds from their average annual depletion level to their depletion level in the driest 10% of years. Dry year depletion occurs in 21% of watersheds (3,104).

Globally, all watersheds that appear moderately depleted in an annual analysis experience high depletion at least periodically: 308 (2%) watersheds are classified as 25–50% and 128 (0.9%) as 50–75% depleted when calculated annually. All of these watersheds are reclassified as seasonally or dry-year depleted when inter- and
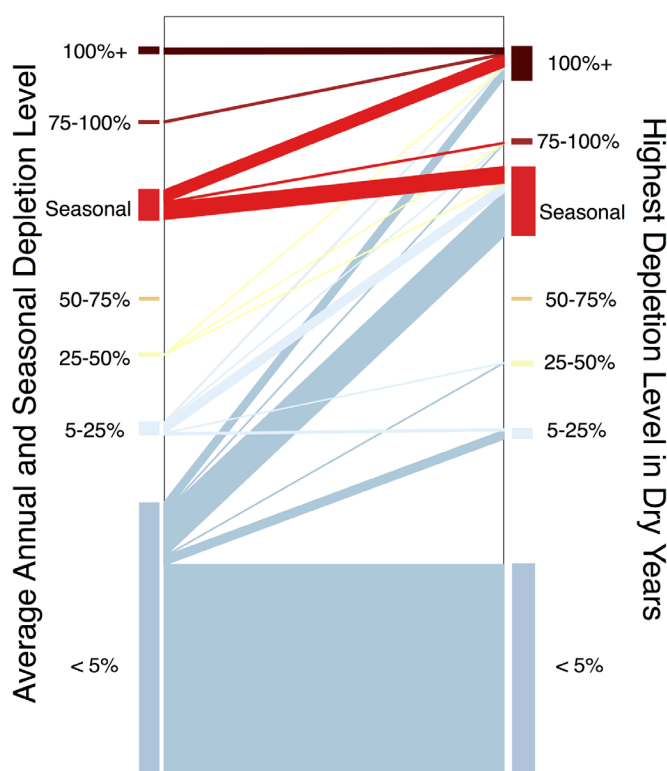

Figure 4

Re-classification of depletion level between average years and dry years.

Most watersheds that are moderately depleted on an annual basis experience more than 75% depletion in at least one month during dry years; most (87%) watersheds 5–25% annually depleted and all watersheds between 25% and 75% annually depleted are re-classified. Colors and groupings in the left column indicate the depletion level in which all 15,091 watersheds are categorized using average annual and monthly depletion values. Colors and groupings to the right indicate the depletion category each watershed falls into during the driest 10% of years. Lines connecting the left and right columns connect a single watershed, illustrating the trajectory of any given watershed re-classification.

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intra-annual depletion is considered. As a result, no watersheds in the integrated analysis fall into the 25–50% and 50–75% annually depleted categories.

Accounting for periodic depletion improves the ability to detect vulnerability to water shortages, just as increased spatial resolution does. In the Mississippi watershed (Fig. 2), in addition to the 7% of watershed area that is annually depleted beyond 75%, 15% of the watershed experiences depletion during dry years and 19% is seasonally depleted.

Characteristics of depleted watersheds

Water depletion is a function of water availability but is not consistently associated with total annual water availability or available water scaled by watershed size. We evaluated how these factors varied within and between depletion categories, finding that watersheds with very little water are no more likely to be depleted than are those with substantial water availability; water depletion categories explain only 0.7% of the variance in mean annual water availability among watersheds. Watershed size also has little impact on water depletion, as depletion categories explain only 1.7% of the variation in size among watersheds.

Climate and year-to-year variation in water availability are more closely related to water depletion. Depletion categories explain 37% of the variation in climate, defined as UNEP climate zones (Middleton and Thomas, 1997), among watersheds, meaning that high levels of water depletion are more common in arid watersheds but that depletion is far from exclusive to these regions. Depletion categories also explain 41% of the variance among watersheds in their coefficient of variation for monthly water availability over the historic period. This illustrates that dry-year depletion is not a one-off occurrence but a phenomenon reflecting consistent inter-annual variation in supply.

WaterGAP3 includes a reservoir storage component; 13% of seasonally depleted watersheds are regulated, as are 25% of watersheds 5–25% annually depleted and ~5% of watersheds in each of the other depletion categories. It is likely that some watersheds experiencing <25% annual depletion would be re-categorized as seasonally depleted were they not regulated.

Water depletion considers only annually renewable surface and groundwater to be available. However, non-renewable groundwater is frequently tapped as a water source. We compared our depletion categories to a measure of unsustainable groundwater and surface water use developed by Wada and Bierkens (2014), finding that unsustainable water use was greater and more common in watersheds more than 75% annually depleted than in seasonal and dry-year depleted watersheds, and that periodically depleted watersheds had a higher mean fraction of unsustainable water use than did watersheds depleted less than 25% annually. Non-renewable water use has a potentially important role to play in relieving water scarcity during dry years. However, the overlap of high annual water depletion with Wada and Bierkens (2014) unsustainable water use indicator suggests that non-renewable groundwater is not always being used strategically; instead, non-renewable sources are frequently accessed in watersheds consistently consuming a substantial fraction of their renewably available water.

Potential impacts of water depletion on human well-being

The global fraction of food and people potentially affected by water shortage is far greater than the fractional areal extent of water depletion. For example, only 2.2% of watershed land area is more than 75% depleted on an annual average basis, but this area includes 15% of global irrigated land. When seasonal and periodic water depletion are incorporated, this figure rises substantially: 71% of irrigated area occurs in watershed areas that are depleted annually, seasonally, or in dry years. This suggests that the vast majority of irrigated agriculture is at least periodically vulnerable to water shortages (Fig. 5).
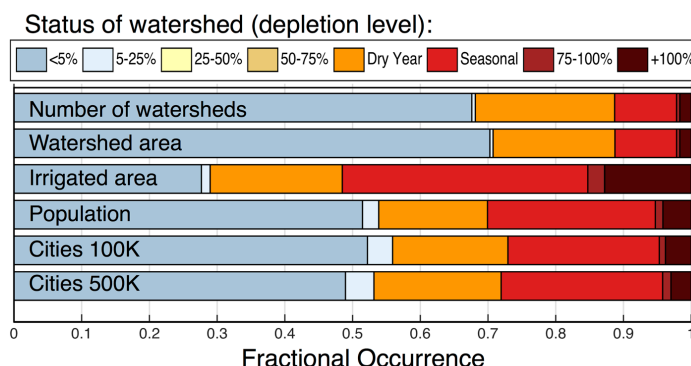
Figure 5

Distribution of cropland, irrigation, and population in watersheds.

Food and water security are at risk from water depletion, at both annual and periodic time scales. Though only 29% of the watershed area and 32% of the number of watersheds evaluated experience depletion of 75% or more on an annual or periodic basis, 71% of world irrigated area and 46% of the global population are in these depleted watersheds. Watersheds < 1,000 km² are excluded from our analysis (primarily small coastal watersheds).

Status of watershed (depletion level): <5% | 5-25% | 25-50% | 50-75% | Dry Year | Seasonal | 75-100% | +100%

Number of watersheds
Watershed area
Irrigated area
Population
Cities 100K
Cities 500K

Fractional Occurrence

Globally, irrigation is by far the largest human use of water. Based on calculations from WaterGAP3, irrigation constitutes 84% (773 km³) of annual consumptive water use and 66% (2,050 km³) of annual withdrawals. However, high rates of water consumption are not consistently associated with high levels of water depletion, as illustrated in Fig. 6 and Fig. S2. Depletion categories explain 17% of the variance in consumption among watersheds (linear contrast analysis in Matlab 2014b). This is in part because total water consumption is concentrated in just a few watersheds: 75% of global consumptive water use occurs on just 8% of global area in 6% (897) of watersheds worldwide.

Urban populations face risks associated with water shortage as well. Our analysis evaluated 3,525 cities with more than 100,000 inhabitants as well as the subset of 570 cities with more than 500,000 inhabitants (CIESIN, 2005). Of cities with more than 100,000 inhabitants, 5% are situated in watersheds experiencing more than 75% annual depletion, 22% experience seasonal depletion, and 17% experience dry year depletion (Fig. 5). Larger cities (>500,000) show a nearly identical pattern. These estimates align with calculations by other researchers that 25-48% of the global population lives in water stressed watersheds (studies summarized in Wada et al., 2011a, 2011b). Water scarcity in urban areas implies risks to electricity generation and industrial and household use, as most cities import food from beyond the watershed and even beyond national boarders (MacDonald et al., 2015). Because food is frequently imported, however, food-security risks to cities may occur as a result of water depletion in distant agricultural regions.

Uncertainty and limitations

Our analysis is based on a depletion threshold of 75% for monthly and dry-year depletion. However, we find that the number of watersheds classified as depleted under those conditions changes by no more than 3% when the threshold decreases to 50% or increases to 100%. We report comparative statistics in Table S2. The choice of threshold to define periodic depletion has limited impact because moderate water depletion is uncommon at a monthly time step – only 3% of watersheds experience a maximum monthly water depletion between 50% and 100%. We selected a 75% depletion threshold for two main reasons. First, it is unlikely that the 1970–2000 period used in our analysis captures the full range of climatic variability experienced in most watersheds, so most watersheds exhibiting >75% depletion during any period have likely experienced 100% depletion historically (Griffin and Anchukaitis, 2014). Second, it is likely that ecological health and ecosystem services will be significantly impaired long before 100% depletion is reached (Richter et al., 2012).

There are substantial uncertainties in our calculations of water depletion stemming from uncertainties in estimates of both water availability and water consumption (Döll et al., 2015). Previous work comparing estimates of water availability generated by a suite of global hydrologic models found as much as 45% variation around mean calculated runoff (Haddeland et al., 2011). WaterGAP3 is calibrated against average annual observed discharge for ~1,600 gauging stations globally, which should reduce error in our metric (Müller Schmied et al., 2014).

Water consumption is difficult to measure in almost all settings, so it must be modeled; as a result, estimates of water consumption and thus water depletion are model dependent. Water consumption estimates differ among models by roughly 25% globally (Haddeland et al., 2014), largely due to variations in the way irrigation demand is calculated (Siebert and Döll, 2010). Water withdrawals are straightforward to measure, and withdrawals for domestic, manufacturing, and electricity generation are frequently reported for countries. However, withdrawal data are seldom collected for irrigation and estimates of irrigation withdrawals are generally built from models of irrigation consumption (Döll et al., 2015).

To explore the implications of uncertainties inherent in modeling global water resources for our water depletion metric, we recalculated water depletion assuming uniform decreases in water availability and increases in water consumption of ±25%. Table S3 in the supplement summarizes the re-classification of watersheds based on this adjusted input data.
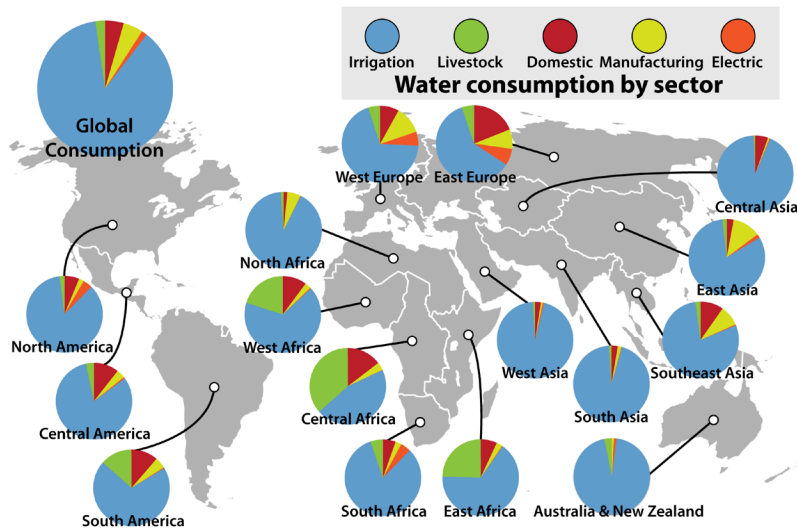
We found that reducing water availability or increasing water consumption changes the depletion level of only a small number of watersheds, with watersheds that experience higher levels of annual depletion more likely to be affected. This suggests that watersheds experiencing 5–25% annual depletion may be well served by active management of water resources that are not yet heavily depleted. More broadly, however, lack of sensitivity of our water depletion metric to artificial alterations in water availability and consumption reflects our finding that moderate water shortage in any given time period is almost always the result of severe shortage at shorter time scales.

For data reliability reasons, we excluded watersheds less than 1,000 km^2, primarily small coastal watersheds. Though the number of excluded watersheds is large (128,562), the land area included is small (12.9 million ha, 9.5% of global watershed area). Coastal areas that are part of larger watersheds are included in the analysis. As a result of excluding small watersheds, 12% of global population, 19% of global cities greater than 100,000 people, and 5.6% of global irrigated area are excluded. Fig. 5 is recreated with this excluded area included in Fig. S3.

Conclusions

Water security depends on reducing society's vulnerability to water shortages. An important first step is to identify watersheds where a large fraction of renewable freshwater is consumed seasonally and in dry years as well as on an annual basis. The metric of water depletion presented here provides a more comprehensive picture of areas vulnerable to risks associated with water shortage. This simple, cohesive metric effectively characterizes water shortage and thus vulnerability to associated risks, setting the stage for targeted interventions, strategic investments, and evaluation of water-related economic and environmental shocks (Richter, 2014).

As the biggest consumer of water globally and in all regions of the world (Fig. 7), irrigated agriculture must be a major focus for reducing water depletion. Conjunctive use of surface and groundwater resources is a promising strategy for managing seasonal water depletion (Döll et al., 2012). In addition, reducing non-beneficial water consumption and improving the water productivity of agriculture, perhaps through economic incentives, will be essential to reducing water scarcity for downstream cities and freshwater ecosystems while providing food for a hungry planet (Brauman et al., 2013; Perry et al., 2009; Tsur et al., 2004). This is particularly important looking to the future, as expansion and intensification of agriculture to meet rising food demands will likely increase pressure for expansion of irrigation (Pfister et al., 2011).

Cities must also rebalance their water budgets. In their own hinterlands and farther afield, urban diets shape agricultural water demand, and it has been estimated that nearly a quarter of water used in food production ends up as food waste (Kummu et al., 2012). Within urban borders, challenges and strategies for water management will differ from those in agriculture because urban water use is dominated by electricity generation and industrial and household use. In these sectors, withdrawals greatly exceed consumptive use, so cities will likely turn to water reuse and efficiency improvements to reduce water demand (Flörke et al., 2013). Cities that face water shortage because much of their upstream supply is being consumed may also work directly with their agricultural neighbors, engaging with upstream irrigators to reduce their consumption of shared resources (Brauman et al., 2007; Richter et al., 2013).

Many of the watersheds that experience high levels of depletion annually, seasonally, or during dry years are critical to human wellbeing. The specific impacts of different levels of water depletion will vary for each watershed and user community. However, to buffer against climate fluctuations, and to protect the ecological health of rivers and watersheds, we echo calls for a "cap" or "sustainability boundary" (sensu Postel and Richter, 2003) to limit total consumptive water use. Evidence of the undesirable economic and social impacts of water shortages at or near "basin closure" (sensu Molle et al., 2010), at which point all of the available water is being consumed, provide motivation to limit consumption (Postel and Richter, 2003; Richter, 2014; Richter et al., 2013). Our findings suggest that any watershed currently experiencing seasonal depletion, dry-year depletion, or annual depletion greater than 75% may be in urgent need of regulatory limits to avert the social, economic, and ecological consequences associated with water shortages.

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Water depletion: Improved metric for seasonal and dry-year water scarcity

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- Contributed to conception and design: KAB, BR, SP
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Competing interests
The authors declare no competing interests.

Supplemental material
- **Text S1. WaterGAP model and methods to compute water availability and consumption in sub-watersheds**
  Detailed methodology for the WaterGAP3 model and for calculating net water. doi: 10.12952/journal.elementa.000083.s001
- **Figure S1. Water depletion in global watersheds for each month of the year**
  Depletion categories based on the ratio of long-term average monthly water consumption to long-term average monthly water availability for each month. doi: 10.12952/journal.elementa.000083.s002
- **Figure S2. Median water consumption by sector for watersheds at each depletion level**
  Water consumption for irrigation is an order of magnitude greater for irrigation than for any other use. Median irrigation consumption increases at higher levels of depletion, but variation among watersheds, indicated by black error bars showing the 25th and 75th percentile of consumption, is large. At the median, irrigation in watersheds experiencing dry-year depletion is low, similar to median use in watersheds at less than 5% depletion. doi: 10.12952/journal.elementa.000083.s003
- **Figure S3. Role of excluded watersheds on distribution of irrigation and population**
  Figure 5 is recreated to include the distribution of watershed area, irrigation, and population in small coastal watersheds excluded from our analysis. Food and water security are at risk from water depletion, at both annual and periodic time scales. A large number of watersheds are excluded, but this constitutes a much smaller population of area, irrigation, and population. doi: 10.12952/journal.elementa.000083.s004
- **Figure S4. Water availability and consumption in sub-watersheds**
  When water availability is aggregated in downstream watersheds (**A**), more water is available than when net availability (**B**) - aggregate upstream water availability less aggregate upstream consumption - is considered. Similarly, more water is consumed when values for sub-watersheds are aggregated (**C**) than when consumption only within a sub-watershed is considered (**D**). Units for water availability are km^3 while water consumption is show in m^3. This figure is referenced in Text S1. doi: 10.12952/journal.elementa.000083.s005
- **Figure S5. Re-classification of watershed depletion in sub-watersheds**
  The fraction of available water consumed when upstream water availability and upstream consumption are aggregated (**A**) compared to depletion calculated for net water availability and in-watershed consumption only (**B**). More watersheds are more highly depleted based on the aggregate calculation. This figure is referenced in Text S1. doi: 10.12952/journal.elementa.000083.s006
- **Table S1. Overview of water scarcity metrics and water stress thresholds**
  doi: 10.12952/journal.elementa.000083.s007
- **Table S2. Sensitivity of seasonal and dry-year category definitions to cutoff threshold**
  doi: 10.12952/journal.elementa.000083.s008
- **Table S3. Reclassification of watersheds assuming decrease in water availability and increase in water consumption**
  doi: 10.12952/journal.elementa.000083.s09
- **Table S4. Impact of spatial disaggregation of water consumption and availability**
  This table is referenced in Text S1. doi: 10.12952/journal.elementa.000083.s010

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Data accessibility statement

Water depletion data for all 15,091 watersheds are freely available at http://www.earthstat.org.

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