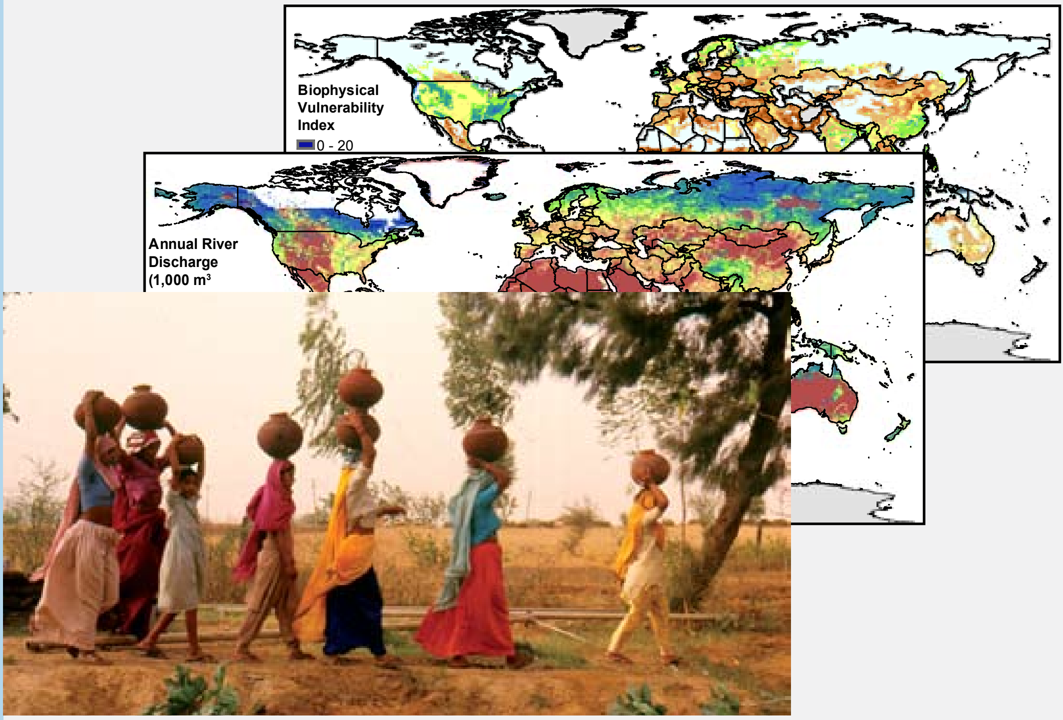
IWMI RESEARCH REPORT

# 133

# Mapping Drought Patterns and Impacts: A Global Perspective

Nishadi Eriyagama, Vladimir Smakhtin and Nilantha Gamage

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*IWMI Research Report 133*

# Mapping Drought Patterns and Impacts: A Global Perspective

*Nishadi Eriyagama, Vladimir Smakhtin and Nilantha Gamage*

**International Water Management Institute**
P O Box 2075, Colombo, Sri Lanka

*The authors:* Nishadi Eriyagama is a Water Resources Engineer (email: n.eriyagama@cgiar.org); Vladimir Smakhtin is Theme Leader – Water Availability and Access (email: v.smakhtin@cgiar.org); and Nilantha Gamage is a Remote Sensing/GIS Specialist (email: n.gamage@cgiar.org), all at the International Water Management Institute (IWMI) in Colombo, Sri Lanka.

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*Cover photograph* shows women walking to collect water in India, 2004 (*Source:* Ms. Mamta Borgoyary, Winrock International, India).

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# Contents

## Acronyms and Abbreviations

| | |
|---|---|
| ATEAM | Advanced Terrestrial Ecosystem Analysis and Modelling |
| FAO | Food and Agriculture Organization of the United Nations |
| GDP | Gross Domestic Product |
| GIS | Geographic Information System |
| IIASA | International Institute for Applied Systems Analysis |
| ILRI | International Livestock Research Institute |
| MCM | Million cubic meters |
| START | global change SysTem for Analysis, Research, and Training |
| UNDP | United Nations Development Programme |
| UNEP | United Nations Environment Programme |
| WB | World Bank |

## Summary


This study examines the global patterns and impacts of droughts through the mapping of several drought-related characteristics – either at a country level or at regular grid scales. Characteristics cover various aspects of droughts – from global distribution of meteorological and hydrological drought risks to social vulnerability and indices related to water infrastructure. The maps are produced by integrating a number of publicly available global datasets. The subsequent discussion of maps allows a number of policy-relevant messages to be extracted. It appears that arid and semi-arid areas also tend to have a higher probability of drought occurrence. The report points out that in drought years, the highest per capita loss of river flow occurs in areas that do not normally experience climate–driven water scarcity. It also illustrates that the African continent is lagging behind the rest of the world on many indicators related to drought preparedness and that agricultural economies, overall, are much more vulnerable to adverse societal impacts of meteorological droughts. Regions with an unreliable and vulnerable nature of river discharge, and having the largest drought deficits and durations are highlighted, pointing to the danger of focusing on drought mitigation measures on river flows alone. The ability of various countries to satisfy their water needs during drought conditions is examined using storage-related indices.

# *Mapping Drought Patterns and Impacts: A Global Perspective*

*Nishadi Eriyagama, Vladimir Smakhtin and Nilantha Gamage*

## Introduction

Drought can be generally defined as a *temporary meteorological* event, which stems from a deficiency of precipitation over an extended period of time compared to some long-term average conditions. Drought always starts with a shortage of precipitation (compared to normal or average amounts), but may (or may not, depending on how long and severe it is) affect streams, soil moisture, groundwater, etc. It is a *recurring* natural event and a *normal part of the climate of all world regions,* regardless of how arid or humid they are. Droughts develop slowly, are difficult to detect and have many facets in any single region. It is, thus, one of the most complex natural phenomena, that is hard to quantify and manage, and has multiple and severe social and economic impacts. The magnitude of these impacts is determined by the level of development, population density and structure, demands on water and other natural resources, government policies and institutional capacity, technology, and the political system. These points of departure set the scene and scope for this study.

Droughts continue to have significant impacts in both developed and developing countries. The latter still suffer from droughts the most. Ever-increasing exploitation of water resources and associated water scarcity coupled with the growing concern that future climate change will exacerbate the frequency, severity, and duration of drought events and associated impacts explains the increasing attention that individual countries are paying to drought-related issues (Wilhite 2005). Since drought is a global phenomenon, it is useful, from a global development perspective, to understand the pattern of various drought-related characteristics and impacts worldwide. Such characteristics should reflect multiple aspects of drought, ranging from quantification of drought hazard and vulnerability of water resources systems - to measures of preparedness to face future droughts. One good way of presenting diverse materials related to droughts is through mapping, whereby various drought-related indicators can be plotted at a country resolution, river basin or a regular grid – depending on the type of indicator and information available.

Despite significant drought research, studies that deal with the global picture of drought patterns and impacts are limited. Even fewer studies deal with global mapping of drought-related indicators. Peel et al. (2004, 2005) conducted an analysis of precipitation and runoff periods (runs) of consecutive years below the median for 3,863 precipitation and 1,236 runoff stations worldwide. Run lengths were found to be similar across all continents and climates except North Africa, which showed a tendency towards longer run lengths. Run lengths for precipitation and runoff at the same location were found to be similar. Run magnitude for both precipitation and runoff was found to be related to inter-annual variability, and run magnitude of runoff was larger than that of precipitation due to a higher coefficient of variability of runoff. Severity of drought events (a total of negative deviations from the median for a run) was found to be independent of run length but strongly related to magnitude. These studies, thus, highlighted the importance of accurately reproducing the inter-annual variability in global climate models if future long-term droughts affected by climate change are to be adequately predicted. Fleig et al. (2006) carried out similar research using daily flow time series data from 16 selected river basins worldwide. The above studies were conducted using observed data, which is useful in examining geographical differences in the statistical nature of droughts but are constrained by limited observation points.

Sheffield and Wood (2007a) used a monthly drought index based on simulated soil moisture data for the period 1950-2000 to identify the locations most prone to short, medium and long-term droughts and to examine severe past drought events on a regional basis. Dai et al. (2004) have developed a global monthly dataset of the well-known Palmer Drought Severity Index (PDSI) for 1870-2002 using historical data on precipitation and temperature on a 2.5$^{o}$ x 2.5$^{o}$ grid and established that, globally, very dry areas had more than doubled since the 1970s. Below et al. (2007) have undertaken a comprehensive review of 807 drought and 76 famine entries from 1900 to 2004 in the EM-DAT database (Emergency Events Database: www.emdat.be/) and revised estimates of global drought-related deaths. Dettinger and Diaz (2000) have used monthly streamflow series from 1,345 sites around the world to characterize and map geographic differences in the seasonality and annual variability of streamflow. The Climate Impact on Agriculture (CLIMPAG) project of the FAO has carried out an analysis of rainfall variability and drought for the period 1961-2002 and presented results through time series maps, which are available at www.fao.org/nr/climpag/nri/nrilist_en.asp. Regionally, Lloyd-Hughes and Saunders (2002) have developed a grid-based (0.5$^{o}$ resolution) climatology for Europe, which provides - for a given location or region in Europe - the time series of drought strength, the number, the mean duration and the maximum duration of droughts of a given intensity and the trend in drought incidence in the twentieth century, based on the well-known Standardized Precipitation Index (SPI). Another regional example is the software, Electronic Atlas for Visualisation of Streamflow Drought (ElectrA), produced by the ARIDE (Assessment of the Regional Impact of Droughts in Europe) project, which is capable of displaying on-screen images of streamflow conditions over Western and Central Europe for several drought events that occurred within the last 30 years (Zaidman et al. 2000).

Other relevant mapping projects are carried out primarily by a few international organizations/ projects, although they are not normally focusing on droughts *per se*. UNEP's World Atlas of Desertification shows the global extent and severity of desertification (Middleton 1997; UNEP 1992). It includes several maps derived from the Global Assessment of Human-induced Soil Degradation (GLASOD - described elsewhere in this paper; ISRIC 1990) as well as other maps and information related to global climate and vegetation such as Global Humidity Index, Mean Annual Precipitation, Change in Humidity Index and Mean Annual Temperature (between two 30-year time periods), and Mean Annual Potential Evapotranspiration (PET). Also mapped are the socioeconomics (population estimates, impact on migration and refugees) of the areas at risk of desertification. The study on drylands, people, and ecosystem goods and services by the World Resources Institute (WRI) examines, through the use of maps, the world's drylands from a human livelihoods perspective and how these livelihoods are integrated with dryland ecosystem goods and services (White and Nackoney 2003).

The UNDP's Bureau for Crisis Prevention and Recovery (BCPR) developed an individual Disaster Risk Index (DRI) for four types of natural disasters (earthquakes, tropical cyclones, floods and droughts) as well as a multi-hazard DRI (UNDP 2004). The risk was expressed in terms of the number of people killed and was viewed as a function of physical exposure and vulnerability. The exercise was based on global data from 1980 to 2000. Global maps depicting physical exposure (people exposed per year) and relative vulnerability to each type of disaster (people killed per million exposed per year) were also produced. However, the BCPR acknowledges that the drought DRI that was produced may not necessarily represent actual drought risk given the uncertainties associated with the risk model itself as well as the indirect association of death with drought.

Similarly, The Natural Disaster Hotspots project of the World Bank has assessed the global risks of two disaster-related outcomes - mortality and economic losses - on a 2.5' x 2.5' grid by considering physical exposure and historical loss rates (Dilley et al. 2005). This project also produced global maps of disaster-related mortality risk, risk of total economic losses and risk of economic losses expressed as a proportion of the GDP (per grid cell) for six major natural hazards: earthquakes, volcanoes, landslides, floods, drought, and cyclones as well as for all hazards combined. The Americas program (led by the Institute of Environmental Studies (IDEA) of the National University of Colombia, for the Inter–American Development Bank (IDB)) (Cardona 2007), and the European Environment Agency (2003) have undertaken two regional mapping projects related to various aspects of disaster risk for Latin America and Europe, respectively.

The Global Water System Project (GWSP) examines global water assessment indicators with links to poverty and food security, such as the Water Wealth Index (WWI) (Sullivan et al. 2006). Global Rapid Indicator Mapping System for Water Cycle and Water Resource Assessment (Global–RIMS), a web-based integrated monitoring tool developed by the Water Systems Analysis Group of the University of New Hampshire (with 130 global datasets facilitating indicator calculation and mapping) has been used for mapping WWI and other indicators.

Most of the attention in the recent mapping exercises was paid to various social and environmental impacts of climate change. These studies are relevant to understanding and mapping global drought patterns and impacts because climate change is likely to exacerbate drought severity in many parts of the world. The Atlas of Climate Change by the Stockholm Environment Institute (Dow 2006) examines possible global impacts of climate change including warning signals, vulnerable populations, and health impacts. Cramer et al. (2001) have studied the global response of terrestrial ecosystem processes to climate change using dynamic global vegetation models. The recent '*Africa: Atlas of Our Changing Environment*' (UNEP 2008) and the '*Impacts of Europe's Changing Climate: An indicator-based assessment*' (European Environment Agency 2004) are examples of regional climate change mapping projects. A few other projects by IIASA (Fischer et al. 2002a, 2002b), START (Adejuwon 2006; Snidvongs 2006), ATEAM (Schröter et al. 2004) and ILRI (Thornton et al. 2002) have focused specifically on climate change impacts on agriculture and did not explicitly highlight droughts. Studies to predict future development of drought and changes in the occurrence and intensity of drought have been carried out by Sheffield (2008), Sheffield and Wood (2007b) and Wood et al. (2003) using climate models and future projections of soil moisture. Burke et al. (2006) found that at present climate conditions, on average, 20% of the land surface is in drought at any given time while the proportion of land surface in extreme drought is predicted to increase from 1% at present to 30% by the end of the twenty-first century. A few regional studies spell out the impact of climate change on European droughts with accompanying maps (Kilsby 2001; Lehner et al. 2001; Lehner et al. 2006).

The above review suggests that while the research and mapping of disaster risks, water scarcity, climate change and related subjects has been significant, there has been little, if any, attempt to date to comprehensively describe and map various aspects and impacts of a drought as an individual natural disaster and as a global multi-faceted phenomenon. The aim of this study is, therefore, to start filling this niche. It is important to emphasize the word 'start', because the number of drought-related characteristics, as well as associated maps, is potentially quite large. This study shall not, therefore, be seen as exhaustive, but rather as a starting point for global mapping of drought patterns. A limited set of maps which is designed and analyzed in this study may, with subsequent contributions from other research groups, develop into a comprehensive global drought indicators' 'atlas' in the future.

# Data and Methods

## Datasets

The study used a number of publicly available datasets ranging from demographics and socioeconomics to natural resources and climate. The datasets are briefly described below.

*Gridded Population of the World, version 3 (GPWv3)* - produced by the Center for International Earth Science Information Network (CIESIN) of the Earth Institute at Columbia University, USA (sedac.ciesin.columbia.edu/gpw/). This dataset depicts population (in absolute numbers) and density estimates by 2.5 arc minute geo-referenced quadrilateral grids for 232 countries. Data is available for every fifth year from 1995 to 2015. The product is also available in other resolutions - 0.25, 0.5 and 1 degree. Population estimates for each grid cell are based on national or sub-national population data for a range of reference years. The reference years span the period from 1979 to 2003, depending on data availability for each country. Population density estimates and population (in absolute numbers) for 2000 at 0.5 degree resolution were used in this study.

World Water Development Report II (WWDRII) database (wwdrii.sr.unh.edu/) is part of the compendium of databases developed by the Water Systems Analysis Group of the University of New Hampshire (UNH), USA, describing the current status of global water resources and associated human interactions and pressures. The themes covered include major water balance components (precipitation, evapotranspiration, runoff, etc.), dams, lakes and reservoirs, population, major wetlands and floodplains, irrigated lands and irrigation water withdrawals, water pollution indicators, digitized river networks and climate moisture indices. Four datasets from this database were used in the present study:

*Annual precipitation (mm/year per grid cell)* - a global gridded dataset ($0.5^{o}$ spatial resolution) of long-term average (1950-2000) annual precipitation per grid cell computed from monthly precipitation fields (Mitchell et al. 2004). *The monthly gridded precipitation dataset (CRU TS 2.0)* (Mitchell et al. 2004) is based on a set of observational databases held at the University of East Anglia, UK.

*Annual runoff (mm/year per grid cell)* – a $0.5^{o}$ resolution global gridded dataset of long-term average (1950-2000) annual runoff per grid cell computed by Water Balance Model (WBM) (Vorosmarty et al. 1998) using CRU TS 2.0 (Mitchell et al. 2004) as precipitation input.

*Annual river discharge (blended, $km^3$/year per grid cell)* - computed as long-term average (1950-2000) flow accumulated runoff along a $0.5^{o}$ resolution digital river network (STN-30p) developed at the UNH. Blended river flow represents a composite of observed (from Global Runoff Data Centre (GRDC) data archive) and (WBM) modeled river flow.

*Dams, lakes and reservoirs database* contains both vector as well as raster ($0.5^{o}$) GIS data on dams, lakes and reservoirs of the world. The dams and reservoirs point dataset, which is part of this database, is a global data bank of 668 large impoundments with attributes such as geographic location, dam name and type, reservoir capacity and so forth. This dataset was used in the study along with other dam datasets held by AQUASTAT (FAO's global information system on water and agriculture) and the International Commission on Large Dams (ICOLD) (see the sections on *AQUASTAT* and the *World Register of Dams* below).

*UNH Monthly Runoff and River Discharge Time Series grids* - represent the output (runoff) of the above WBM (spatial resolution - $0.5^{o}$) along with blended river flow – both for a standard period of 1901 to 2000 (100 years).

*World Development Indicators (WDI) (*web.worldbank.org/*)* is the World Bank's premier annual compilation of data about development. It includes some 800 indicators (in 2008) on economic output, welfare, status of the environment and the quality of governance - for some 209 (in

2008) countries in the world. WDI online data on rural access and access to improved water sources, for the most recent available year, were used for construction of infrastructure maps in this study.

*Global Assessment of Human-induced Soil Degradation (GLASOD) (*www.isric.org/UK/About+ISRIC/Projects/Track+Record/GLASOD.htm*)* project of the International Soil Reference and Information Centre (ISRIC), Wageningen, the Netherlands (commissioned by the UNEP), produced a global map of human-induced soil degradation in 1990 at an average scale of 1:10,000,000. The initial GLASOD map had loosely defined physiographic units (polygons), and the degradation status (type, extent, degree, rate and cause) for individual polygons was mapped based on qualitative expert judgment of a large number of soil scientists throughout the world. GLASOD has paved the way for more detailed assessments of soil degradation, such as the Assessment of Soil Degradation in South and Southeast Asia (ASSOD) (1:5,000,000). The results of these assessments have been used to update the GLASOD regional coverage, and additional updates are also in progress. The data are available for download in digital format from the ISRIC website (ISRIC 1990).

*Global Land Use Dataset* (www.sage.wisc.edu/iamdata/) held by the Center for Sustainability and the Global Environment (SAGE), University of Wisconsin-Madison, USA, describe the geographic patterns of the world's croplands, grazing lands, urban areas, and natural vegetation. Data are available in both tabular format (for countries, states, etc., of the world) as well as in map form. The 0.5$^{o}$ resolution grid dataset illustrating global cropland area in 1992 (as fraction of grid cell) (Ramankutty and Foley 1998) was used in mapping the Agricultural Water Crowding Indices.

*FAO Digital Media Series* (www.fao.org/landandwater/lwdms.stm) includes global thematic maps such as main soils of the world, soil production index, soil drainage class, effective soil depth, etc. The global map of effective soil depth, which has a spatial resolution of 0.5$^{o}$, was used in this study.

*AQUASTAT* (www.fao.org/nr/water/aquastat/data/query/index.html) is a global database on water and agriculture developed by the Land and Water Division of the FAO which holds data on the global status of land and water resources on a country basis. This study used country datasets on annual renewable water quantities, annual water withdrawals and dam capacities.

*ProdSTAT* (faostat.fao.org/site/526/default.aspx) maintained by the FAO contains detailed agricultural production data, area/stock and yield data on a country basis starting from 1961. Cropped area data for seven types of crops were used in calculating the Socioeconomic Drought Vulnerability index in this study.

*World Register of Dams* compiled by the International Commission on Large Dams (ICOLD) (www.icold-cigb.net/) is a reference to large dams (height - greater than or equal to 15 meters (m)) of the world providing information such as dam type, height, capacity and purpose. The 1998 version of the World Register of Dams, which contains data on 25,410 large dams of the world, was used in mapping storage related indices in this study with supplemental information from AQUASTAT and the Dams and Reservoirs dataset of the WWDRII database.

In addition to the above, other data sources on freshwater resources of the world such as the *Earthtrends Searchable Database* (earthtrends.wri.org/index.php) maintained by the World Resources Institute (WRI), USA, the *World's Water* database (www.worldwater.org/) maintained by the Pacific Institute, USA, the *State of Water* database (www.wepa-db.net/policies/top.htm) maintained by the Water Environment Partnership in Asia (WEPA), Japan, as well as Malik et al. (2000) and White (2005) were also used to inform mapping of storage-related indices.

## Drought Characteristics and Indices

This section briefly describes the indices and characteristics presented and mapped in this study – primarily focusing on the origin of indices and rationale for mapping. Some of them are drought-related indices, which were either used locally rather than globally, or used out of the context with drought studies. Some others are existing indices, which although designed for a different purpose originally, carry useful drought-related information if used either as is or with certain modifications.

*Long-term Mean Annual Precipitation (MAP)* (Figure 1(a)), *its Coefficient of Variation (CV)* (Figure 1(b)), *and Probability (%) of Annual Precipitation in any year being less than 75% of its*

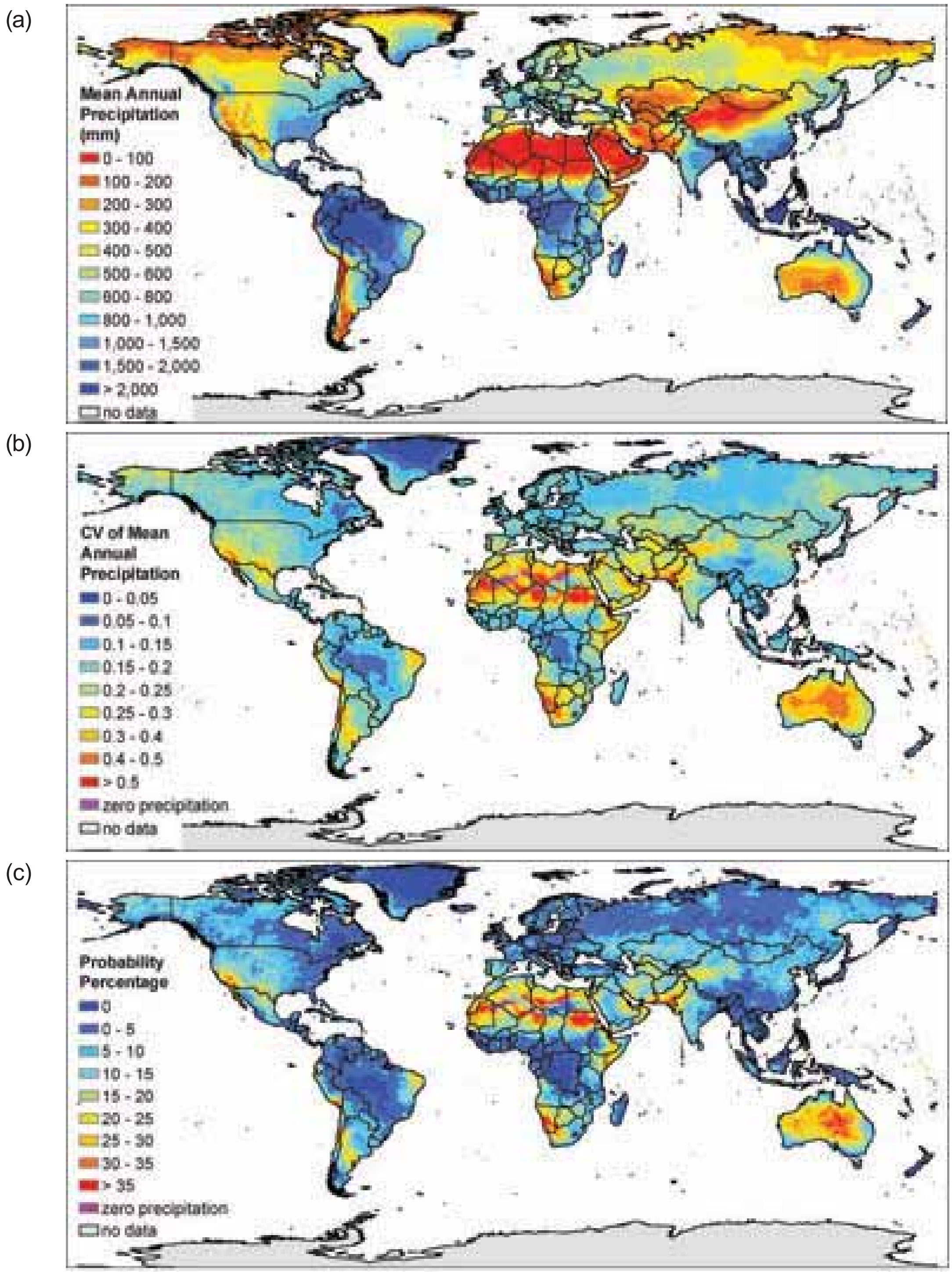


FIGURE 1. (a) Global distribution of long-term Mean Annual Precipitation, (b) its Coefficient of Variation, and (c) Probability (%) of annual precipitation in any year being less than 75% of its long-term mean.

*Long-term Mean* (Figure 1(c)) were calculated and mapped globally on a 0.5° grid. Since drought is generally defined in relation to a long-term average condition, it is worth identifying a global pattern of such conditions - in this case MAP (Figure 1(a)) and its inter-annual variability (Figure 1(b)). The probability of annual precipitation in any year being less than 75% of MAP (Figure 1(c)) can point to regional differences in the frequency of occurrence of annual droughts and links the pattern of these droughts with MAP and CV. A threshold of 75% of MAP, while somewhat arbitrary, is often accepted as an identifier of a meteorological drought. These maps were produced using annual precipitation data from the University of East Anglia (www.cru.uea.ac.uk/cru/data/hrg.htm).

*Per capita Mean Annual River Discharge* (Figure 2) reflects population pressure on river flow within a 0.5° grid cell, which is exacerbated in times of drought. A similar indicator, per capita Mean Annual Surface Runoff, only considers runoff generated internally within a grid cell. Since many rivers in the world are transboundary in nature, the second indicator pictures a hypothetical situation when every country has to rely on its own runoff alone. The pattern of both indicators was, however, found to be broadly similar and, hence, only the first is presented here. The map was produced using population data from CIESIN (sedac.ciesin.columbia.edu/gpw) and annual river discharge data from UNH (wwdrii.sr.unh.edu/download.html).

A more 'agriculture-focused' index is *Agricultural Water Crowding* (Sullivan et al. 2006). It was designed to measure population numbers per one volumetric unit of precipitation falling on croplands, but has not been applied globally. The original index measured crowding with respect to precipitation only. In this study, we made use of two variations of this index (AW1 and AW2) by considering both MAP and mean annual river discharge MAR:

$$AW1 = \frac{P}{MAP \cdot CF} \quad (1)$$

$$AW2 = \frac{P}{MAR \cdot CF} \quad (2)$$

*where: P* = population (number of people) per grid cell; *MAP* = mean annual precipitation per grid cell

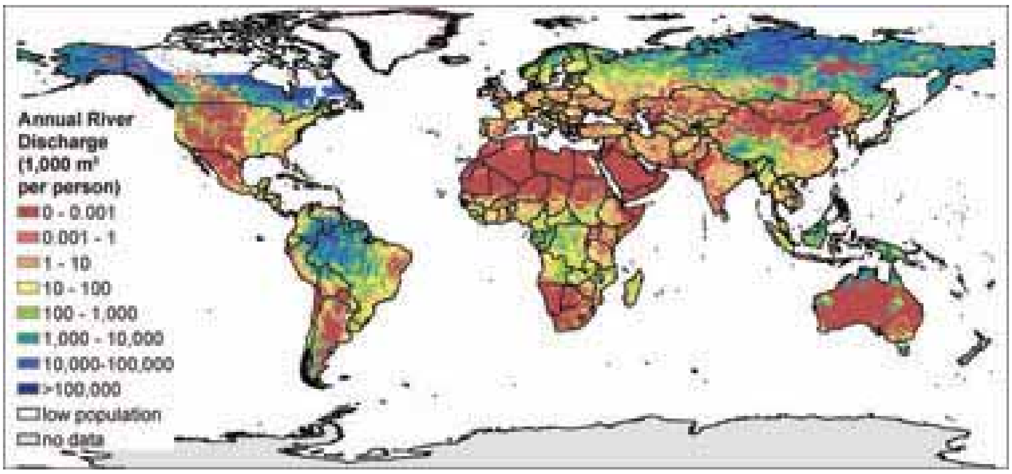


FIGURE 2. Per capita Mean Annual River Discharge by 0.5° grid cell.

(km$^3$); *MAR* = mean annual river discharge per grid cell (km$^3$); and *CF* = crop area as a fraction of cell area. Water (either precipitation or river discharge) available within a 0.5$^o$ grid cell may be split into agricultural water and non–agricultural water in proportion to the cropped and non-cropped areas in that unit. Agricultural Water Crowding is a measure of the number of people who have to share agricultural water in a grid cell. By mapping it globally (Figures 3(a) and 4), it is possible to identify "agricultural water-stressed" areas, which are becoming even more stressed in times of a drought (Figure 3(b) - produced with an assumption that an average drought (mean precipitation minus mean precipitation deficit) occurs simultaneously over the globe). The variations of the same index relate to different aspects of availability of water from the two distinct sources. Agricultural water crowding maps were produced using population data from CIESIN (sedac.ciesin.columbia.edu/gpw), MAR and MAP data from UNH (wwdrii.sr.unh.edu/download.html), and percentage cropped area from SAGE (www.sage.wisc.edu/iamdata/).

An *Infrastructure Vulnerability Index*, similar to the one developed by the World Travel and Tourism Council (www.wttc.org/eng/Tourism_News/Press_Releases/Press_Releases_2004/New_Statistics_launched/), was used to reflect adaptive capacity of a country to a drought. Similar indices, although much more complex and inclusive of a large number of indicators (10 to 50), are well known (e.g., O'Brien et al. 2004; www.sopac.org/tiki-index.php?page=EVI). The index used in this study only includes two proxy

(a)

(b)

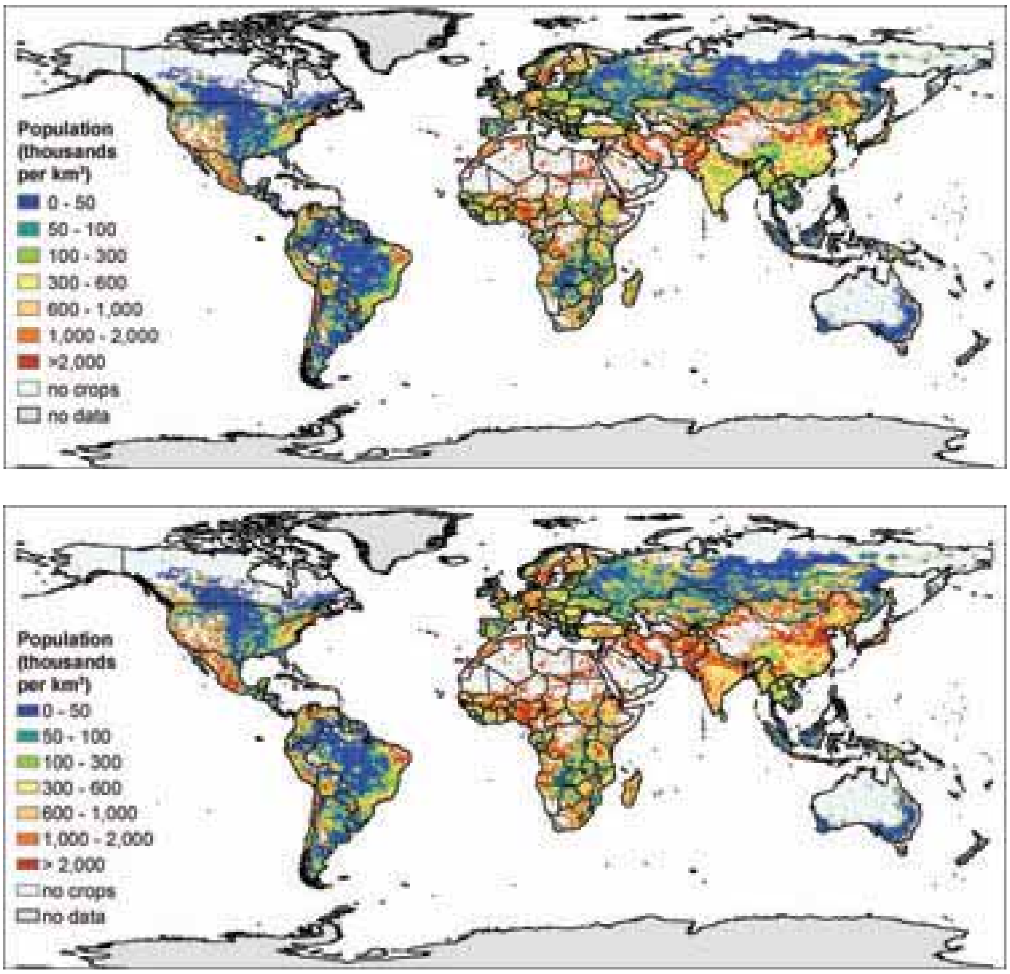


FIGURE 3. Agricultural Water Crowding (population sharing one cubic kilometer of precipitation falling on croplands within 0.5$^0$ grid cell) with respect to (a) mean annual precipitation, and (b) under drought conditions.

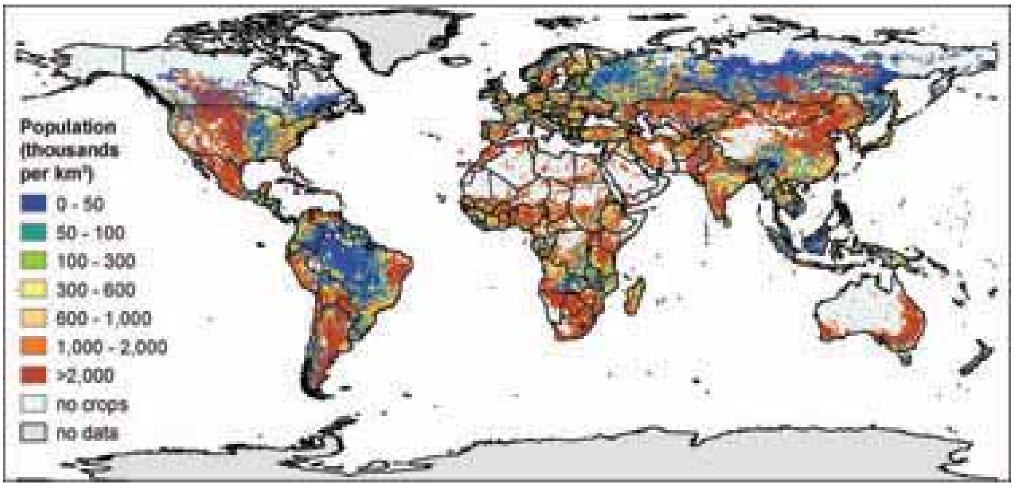


FIGURE 4. Agricultural Water Crowding with respect to mean annual river discharge (population sharing one cubic kilometer of river water available for croplands within 0.5$^0$ grid cell).

indicators - the WB's Rural Access Index (RA) and the percentage of population with access to an improved water source (IDW). The data for both components are available for a large number of countries (web.worldbank.org/). Both components determine the adaptive capacity of agriculture and rural communities to current climate variability and associated droughts. The composite Infrastructure Vulnerability Index (IFI) was constructed in a similar manner to UNDP's Human Development Index (UNDP 2006), in which the values of each component indicator were normalized to the range of values in the dataset:

$$IFI = \frac{RA + IDW}{2} \quad (3)$$

$$RA = 100 - \frac{Ra_{actual} - Ra_{\min}}{Ra_{\max} - Ra_{\min}} \cdot 100 \quad (4)$$

$$IDW = 100 - \frac{Idw_{actual} - Idw_{\min}}{Idw_{\max} - Idw_{\min}} \cdot 100 \quad (5)$$

*where:* $Ra =$ World Bank's Rural Access Index - percentage of rural people who live within 2 kilometers (km) (typically equivalent to a walk of 20 minutes) of an all-season road as a proportion of the total rural population; and $Idw =$ Percentage of people having access to (able to obtain at least 20 liters per person per day from a source within 1 km of a dwelling) an improved water source (household connection, public standpipe, protected well or spring, etc.). The index has a score of 0-100 with 100 implying maximum vulnerability (Figure 5).

The Biophysical Vulnerability Index of O' Brien et al. (2004) applied to India at the resolution of individual states, consists of three sub-indices: Depth of Soil Cover Index (DS), Soil Degradation Severity Index (SD) and Groundwater Scarcity Index (GWS). A similar *Biophysical Vulnerability Index (BVI)* (Figure 6) was constructed in this study by adding a fourth dimension: Surface Water (Runoff) Scarcity Index (SWS).

$$BVI = \frac{DS + SD + GWS + SWS}{4} \quad (6)$$

$$DS = 100 - \frac{Ds_{actual} - Ds_{\min}}{Ds_{\max} - Ds_{\min}} \cdot 100 \quad (7)$$

$$SD = \frac{Sd_{actual} - Sd_{\min}}{Sd_{\max} - Sd_{\min}} \cdot 100 \quad (8)$$

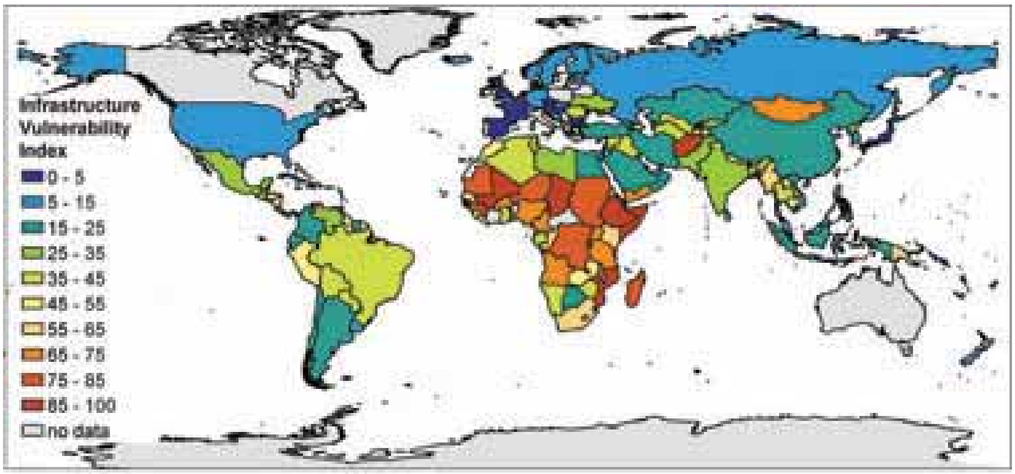


FIGURE 5. Infrastructure Vulnerability Index based on the percentage of people having access to an improved water source and general accessibility of rural areas through the road network.

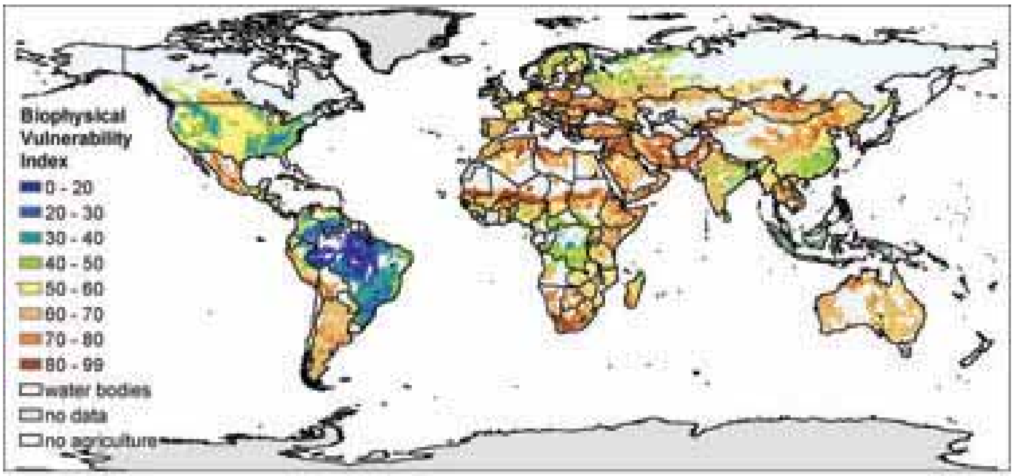


FIGURE 6. Biophysical Vulnerability Index based on mean annual surface runoff, mean annual groundwater recharge, soil depth and soil degradation severity within 0.5$^0$ grid cell.

$$GWS = 100 - \frac{Gr_{actual} - Gr_{min}}{Gr_{max} - Gr_{min}} \cdot 100 \quad (9)$$

$$SWS = 100 - \frac{MAS_{actual} - MAS_{min}}{MAS_{max} - MAS_{min}} \cdot 100 \quad (10)$$

*where:* $DS$ = Depth of Soil Cover Index; $SD$ = Soil Degradation Severity Index; $GWS$ = Groundwater Scarcity Index; $SWS$ = Surface Runoff Scarcity Index; $Ds$ = Depth of Soil Cover; $Sd$ = Soil Degradation Severity; $Gr$ = Annual Groundwater Recharge; and $MAS$ = Mean Annual Surface Runoff. The final composite index was mapped at 0.5$^o$ resolution. Data for proxy variables Ds, Sd and MAS are available at that resolution (e.g., Ds – from FAO Digital Media Series (www.fao.org/landandwater/lwdms.stm); Sd – from ISRIC (www.isric.org); and MAS from UNH (wwdrii.sr.unh.edu/download.html)). Since high resolution global groundwater data are not available in the public domain, country-scale groundwater recharge data from WRI (earthtrends.wri.org/index.php) were converted into 0.5° resolution grid data - for mapping purposes. The index may be seen as a measure of sensitivity of agriculture to droughts. It has a score of 0-100 with 100 implying maximum vulnerability. Areas with higher biophysical vulnerability are those which are most vulnerable to agricultural drought whenever meteorological drought occurs.

The *Socioeconomic Drought Vulnerability Index (SDI)* (Figure 7) measures the vulnerability of individual countries to socioeconomic drought. It is formulated on the consideration that higher GDP contributions from non-agricultural sectors, lower percentage employment in the agricultural sector and higher crops diversity will collectively lower a country's chances of developing socioeconomic drought when meteorological drought occurs. Three sub-indices, namely, the Income Diversity Index (IDI), Employment Diversity Index (EDI) and the Crop Range Index (CDI), make up the composite Socioeconomic Drought Vulnerability Index. IDI and EDI use World Bank Indicators (web.worldbank.org/): percentage contribution from agriculture to national GDP (Av), and percentage employed in agriculture (% of total employment) (Ea), respectively, as proxy variables. The proxy variable in CDI is the Crops Diversity Index (Ci) suggested by Jülich (2006). A weight of 0.4 is assigned to each of IDI and EDI, while a weight of 0.2 is assigned to CDI in the composite index. The latter is done to emphasize that the importance of crops diversity in a country depends on how large a contribution is made by the agricultural sector to the country's economy. SDI has a score of 0-100 with 100 implying maximum vulnerability.

$$SDI = 0.4IDI + 0.4EDI + 0.2CDI \quad (11)$$

$$IDI = \frac{Av_{actual} - Av_{min}}{Av_{max} - Av_{min}} \cdot 100 \quad (12)$$

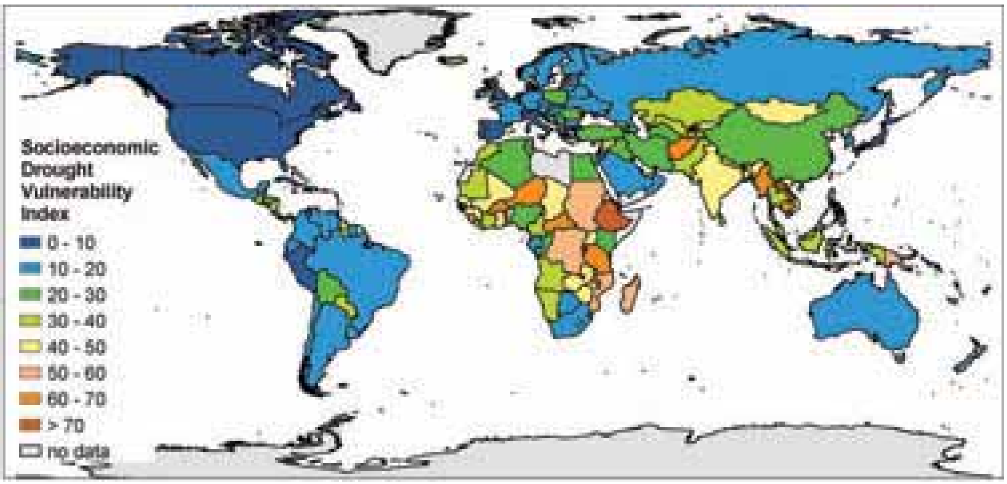


FIGURE 7. Socioeconomic Drought Vulnerability Index based on the crop diversity of individual countries and their dependence on agriculture for income and employment generation.

$$EDI = \frac{Ea_{actual} - Ea_{min}}{Ea_{max} - Ea_{min}} \cdot 100 \qquad (13)$$

$$CDI = \frac{Ci_{actual} - Ci_{min}}{Ci_{max} - Ci_{min}} \cdot 100 \qquad (14)$$

$$Ci = \sum P^2 \qquad (15)$$

*where:* $IDI =$ Income Diversity Index; $EDI =$ Employment Diversity Index; $CDI =$ Crop Range Index; $Av =$ percentage contribution from agriculture to national GDP; $Ea =$ percentage employed in agriculture (% of total employment); $Ci =$ Crops diversity Index suggested by Jülich (2006); and $P =$ Fractional cropped area out of total cropped area for each type of crop. Cropped area data for seven types of crops (cereals, vegetables, fruits and nuts, oil crops, roots and tubers, pulses, and fibers) in FAO's ProdSTAT database (faostat.fao.org/site/526/default.aspx) were used in calculating $Ci$. Smaller $Ci$ values indicate higher crops diversity.

A number of indices are proposed in literature, which measure the performance of water resources systems in terms of reliability, resilience and vulnerability of water resources (e.g., Hashimoto et al. 1982). Reliability in essence is a probability that monthly precipitation (or discharge) is larger than its long-term monthly mean value. Vulnerability, in this context, refers to the likely magnitude of a failure (maximum drought intensity) if one occurs. Relative vulnerability is the vulnerability divided by the expected threshold value (Hashimoto et al. 1982; McMahon et al. 2006): in this study - long-term monthly mean precipitation or discharge. Resilience may be interpreted as a measure of how quickly a system is likely to recover from failure once failure has occurred. Vulnerability and Resilience are, hence, effectively complementary. Some of these measures were mapped before for certain geographical regions (e.g., parts of Europe - Bernardino and Corte Real 2004), but not globally. Some authors attempted to combine these measures to derive composite Drought Risk Indices (Zongxue et al. 1998; Loucks 1997; McMahon et al. 2006). This study attempted to map several such indices. Two maps of drought risks are presented here to avoid showing too many maps (which are often similar). *Drought Risk Index (DRI)* is calculated as:

$$DRI = \frac{1 - REL}{3} + \frac{2RV}{3} \qquad (16)$$

*where:* $REL = \frac{Ns}{N}$; $RV = \frac{V}{MMP}$;

$V = \frac{\sum_{i=1}^{N} \mathrm{Im}ax}{ND}$; $V =$ Vulnerability; $\mathrm{Im}ax =$ Maximum drought intensity (maximum individual deficit per time step) in each drought run; $ND =$ Number of drought runs; $RV =$ Relative Vulnerability; $MMP =$ Mean Monthly Precipitation or Mean Monthly River Discharge; $Ns =$ number of intervals (months) that the target demand (Mean Monthly Precipitation or Mean Monthly River Discharge) was fully met; and $N =$ total number of intervals (months). The DRI was mapped at 0.5° resolution for both monthly precipitation (Figure 8) and monthly river discharge (Figure 9). Regardless of its seemingly complex formulation, the DRI in essence is an integrated index which shows the combined drought risk at any given location in terms of precipitation/river discharge reliability and vulnerability. It ranges from 0-1. Higher DRI values imply that the area has less reliable precipitation/discharge. The datasets used for calculating drought risk indices are monthly precipitation and monthly river discharge from the University of East Anglia (www.cru.uea.ac.uk/cru/data/hrg.htm) and UNH (www.grdc.sr.unh.edu/html/Data/index.html), respectively.

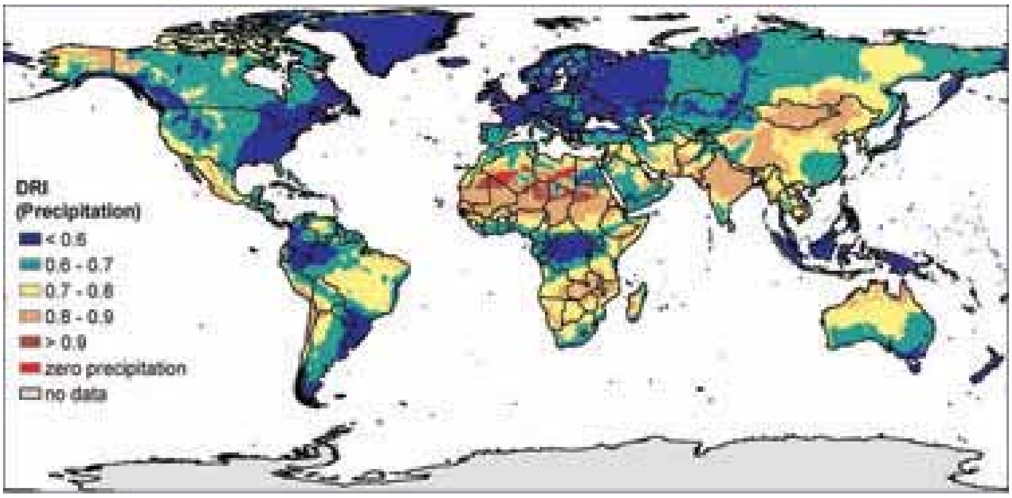


FIGURE 8. Drought Risk Index with respect to Monthly Precipitation based on the frequency of meteorological (precipitation) drought occurrence and drought intensity (deficit below long-term mean).

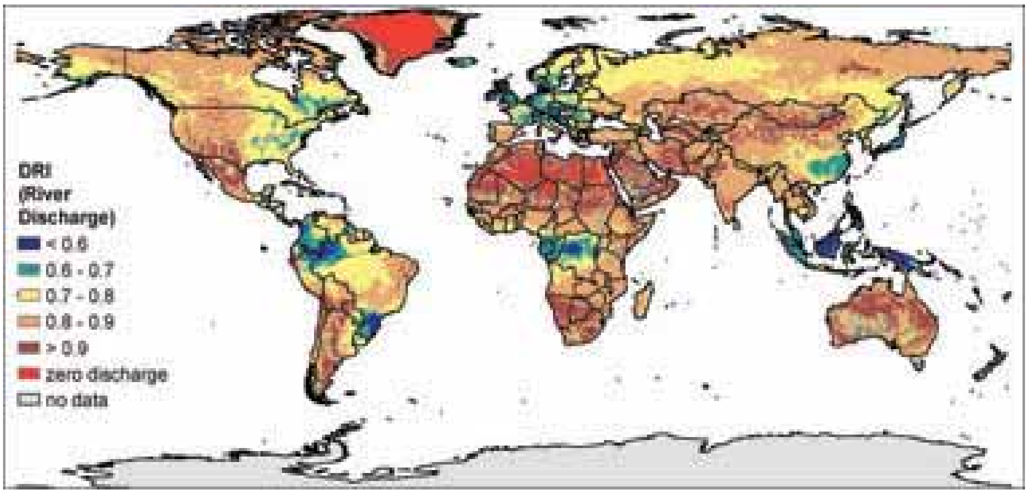


FIGURE 9. Drought Risk Index with respect to Monthly River Discharge based on the frequency of hydrological (river discharge) drought occurrence and drought intensity (deficit below long-term mean).

*Drought Duration* is another important characteristic which varies globally very significantly. It is possible to distinguish between the actual duration of a drought (which can last more than a year – a drought 'run') and the duration of an annual drought (i.e., how long can a drought last in a single year). The latter case refers to a number of dry months within a year and cannot be more than 12 months, while the actual duration can. Figure 10 shows the distribution of the mean drought run duration based on monthly river discharge (sum of durations of all indentified drought runs divided by number of runs). This map was produced using 0.5° resolution monthly river discharge grids from UNH (www.grdc.sr.unh.edu/html/Data/index.html). The distribution of annual drought duration is broadly similar.

A few indices were mapped, which aim to capture the adequacy of water storage capacity in a country or other spatial unit to meet its annual water withdrawals in the event of a drought. *Storage Capacity (SC) as a proportion of Total Annual Renewable Freshwater Resources (ARW) within a country* (Figure 11) is an indicator of the extent of exploitation of national water resources in a country. Total annual renewable freshwater resources include both surface water as well as groundwater. White (2005) has calculated this ratio for a few countries with reservoir storage in excess of half the total annual freshwater resources.

$$SCI = \frac{SC}{ARW} \tag{17}$$

where: $SCI =$ Storage Capacity Index; $SC =$ Storage Capacity; and $ARW =$ Total Annual Renewable Freshwater Resources within a country.

The *Storage–Drought Duration (length) Index* (*SLI)* is the ratio between the duration (in months) that the storage capacity in a country (SC) is able to satisfy national water needs (based on monthly surface water withdrawals (SW)), and annual hydrological drought duration (DDM) (in months),

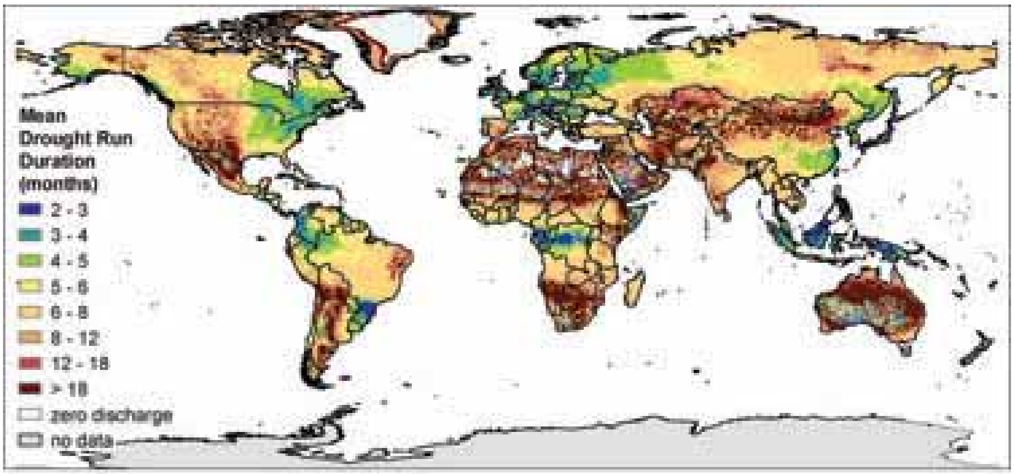


FIGURE 10. Mean Drought Run Duration based on monthly river discharge (sum of durations of all identified drought runs divided by the number of runs).

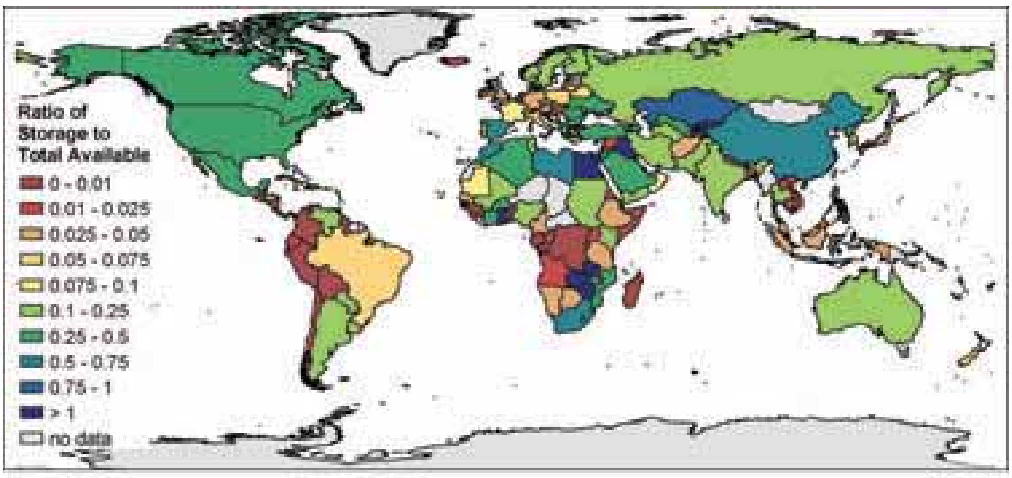


FIGURE 11. Storage as a Proportion of a Country's Total Annual Renewable Freshwater Resources.

calculated relative to an arbitrary drought threshold (long-term mean monthly river discharge). *The Storage–Drought Deficit Index* (*SDI*) is an indicator of how much of the annual (hydrological) drought deficit (MAD) (relative to long-term mean) is satisfied by the existing storage capacity (SC) in a county.

$$SLI = \frac{SC/SW}{DDM} \qquad (18)$$

$$SDI = \frac{SC}{MAD} \qquad (19)$$

*where*: $SLI =$ Storage–Drought Duration Index; $SDI =$ Storage–Drought Deficit Index; $SC =$ Storage Capacity; $SW =$ monthly surface water withdrawals; $DDM =$ annual hydrological drought duration (months); and $MAD =$ annual (hydrological) drought deficit relative to long-term mean.

Monthly river discharge grids (0.5° resolution) from UNH (www.grdc.sr.unh.edu/html/Data/index.html) were used in calculating both indices. Only grid cells with MAR > 0.01 MCM were considered. The annual drought duration, and the annual drought deficit were initially calculated at a 0.5° resolution and averaged across each country, while storage capacity, MAR and water withdrawal data were available on a country scale. Finally, SLI and SDI were mapped at a country scale (Figures 12 and 13). For mapping the three storage related indices, Storage Capacity data were obtained from the World Register of Dams, ICOLD (www.icold-cigb.net/), AQUASTAT (www.fao.org/nr/water/aquastat/data/query/index.html) and the dams, lakes and reservoirs database of UNH (wwdrii.sr.unh.edu/download.html). Total Annual Renewable Freshwater Resources data were obtained mainly from AQUASTAT, Earthtrends Searchable Database of WRI (earthtrends.wri.org/index.php) and World's Water database of the Pacific Institute (www.worldwater.org/).

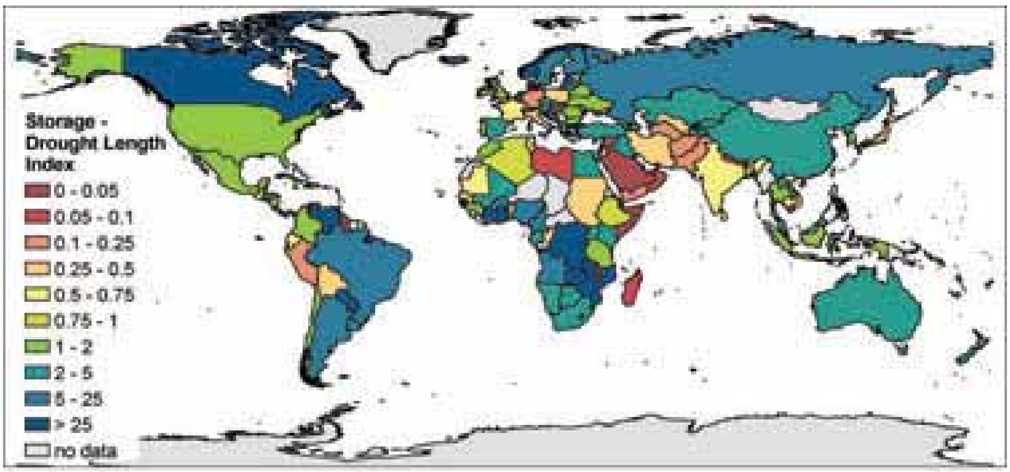


FIGURE 12. Storage–Drought Duration (Length) Index - ratio between i) the duration (in months) that the storage capacity in a country is able to satisfy national water needs, and ii) annual hydrological drought duration, calculated relative to the long-term mean monthly river discharge.

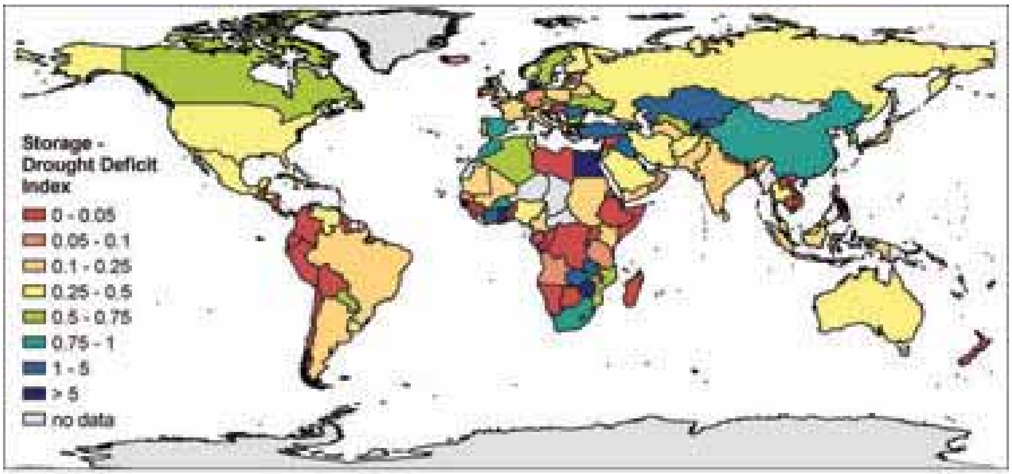


FIGURE 13. Storage–Drought Deficit Index (how much of the long-term annual hydrological drought deficit is satisfied by the existing storage capacity in a country).

## Discussion

The maps presented in Figure 1 effectively describe the natural availability of water resources in any specific region. This availability certainly determines whether droughts are seen as a severe problem or not. In arid areas, there may even be a lack of distinction between drought and aridity (Smakhtin and Schipper 2008). Aridity is a measure of how dry/wet a region is on average over the long term; it is a permanent climatic characteristic of an area. Drought is a deviation from this long-term mean (which is different in different physiographic areas). Thus, droughts come and go, but aridity in an area remains. In arid areas, however, the intra-annual variability of precipitation is generally higher than in humid areas. Figure 1 illustrates this point. Figures 1(a) and 1(b) show the distribution of mean annual precipitation on a global scale and the distribution of the coefficient of variation (CV) of mean annual precipitation, respectively. Figure 1(c) shows the probability that annual rainfall in an area will fall below the threshold of 75% of the long-term mean annual precipitation. The latter threshold is used here as an arbitrary limit, below which a year can be considered a 'drought year'. It appears, that areas which are naturally arid or semi-arid (e.g., receiving less rainfall over the long term) also tend to have higher CV of mean annual precipitation and, consequently, higher probability of drought occurrence - at least in the case of an 'annual' drought. This partially explains the occasional confusion between drought and aridity and also suggests, that management measures taken in arid areas to alleviate unreliable water supplies, whether in a drought or not, are similar.

More insights may be inferred if population is added to the picture. Per capita availability of mean annual river discharge (Figure 2) allows areas of both 'climate-driven' and 'population- driven' water scarcity to be identified (Falkenmark et al. 2007). For example, Afghanistan, Iran and Pakistan, which together occupy a comparable land area (3,193,340 square kilometres ($km^2$)) with India (3,287,260 $km^2$), collectively generate only some 20% of India's MAR of 1,858 cubic kilometres ($km^3$). However, India on one hand and the other three countries (on average) on another, have close per capita MAR (1,613 cubic meters ($m^3$) and 1,300 $m^3$, respectively). Due to India's higher population density, this observation may be interpreted as 'population-driven' water scarcity in India as opposed to 'climate-driven' water scarcity in the other three countries. Southeastern China, Thailand and East Africa are other areas more likely to be experiencing population–driven water scarcity, although they are some of the wettest parts of the world (Figure 1). Australia, Southwest and Central Asia, North Africa, northern China, Mongolia, southern Africa, western United States, Latin America and southern American countries such as Argentina and Paraguay are, on the other hand, more likely to experience "climate–driven" water scarcity being in arid or semi-arid environments. At the same time, almost all of them are also categorized as having or approaching "demand-driven" scarcity (Comprehensive Assessment of Water Management in Agriculture 2007). In drought years, per capita water availability drops. The overall distribution pattern remains the same, but regions with limited per capita flow availability increases. In the earlier example, if a global drought year is defined as a year when annual river discharge is 75% of long-term MAR, then India's per capita river discharge drops by 402 $m^3$ while that of the other three countries (Afghanistan, Iran and Pakistan) drops by only 325 $m^3$. In a 'global' drought year, the highest per capita water losses occur not so much in the driest regions, but rather in regions which are not normally water scarce due to climate.

The two maps of agricultural water crowding (Figures 3(a) and 4) illustrate much higher values of crowding with respect to river discharge than with respect to precipitation. The obvious reason for this is that annual precipitation is higher than annual runoff in any part of the world due to various losses on the ground. According to the Comprehensive Assessment of Water Management in Agriculture (2007), globally, about 39% of rain contributes to river discharge and groundwater collectively. Only in a few countries of the Middle East; South, East, and Central Asia; and Northern and Western Africa in Figure 3(a), the cropped areas appear to be under Chronic Agricultural Water Scarcity (Falkenmark 1989; FAO 2000), i.e., where water crowding is greater than 1,000,000 people per 1 $km^3$ of water. Figure 4 presents a completely different picture with more than half of the cropped areas of the world under the same condition (the only exception being major river corridors). A closer look at South and Southeast Asia, or the Murray–Darling Basin in Australia, suggests that if mean precipitation is considered a measure to calculate water crowding, then most of the cropped areas are not under agricultural water stress (Agricultural Water Crowding is less than or equal to 600,000 people per 1 $km^3$ of water) (Figure 3(a)). Figure 4, on the contrary, points to escalated water crowding if river flow is used as a measure. In a drought year (Figure 3(b)), agricultural water crowding increases, depending on the severity of a drought. In Figure 3(b), a drought year in a grid cell is defined as a year when precipitation is less than its long-term mean value by the long-term mean annual precipitation deficit. However, agricultural water crowding levels in Figure 3(b) are still much lower than those in Figure 4, suggesting that even in a drought year precipitation water availability is higher than that of river discharge under long-term (normal) conditions, which is also true in areas which rely heavily on river water for agriculture. Therefore, there may be a potential for rainwater use in agriculture that can be tapped by enhanced rainwater harvesting. This is yet another argument in support of frequent calls to view rainfall as the ultimate source of water (Comprehensive Assessment of Water Management in Agriculture 2007; Falkenmark et al. 2007), instead of focusing only on river flow/groundwater. According to the earlier definition of a drought year (which is equally applicable to river discharge), the number of people living under Falkenmark's chronic (agricultural) river water scarcity (1,000,000 people per $km^3$) may reach 3.3 billion, of which over 2 billion would be in areas with an extreme crowding of 2,000,000 people per $km^3$. While a similar dry year could not happen simultaneously over the entire planet, the estimates above point to the danger of droughts in various parts of the world.

Infrastructure development of any country determines, amongst others, the level of its preparedness to drought. The availability of improved drinking water and general accessibility of rural areas (where most of the world's poor reside) through the road network are two important factors determining a country's anti-drought coping capacity. The countries most vulnerable to adverse societal impacts due to drought are those which already have low MAP and high CV (thus having higher probability of occurrence of drought – see Figure 1). They often score similarly low in infrastructure development terms and have lower institutional capacity to respond effectively or mitigate the effects of drought. It is evident that the African continent is lagging behind the rest of the world (Figure 5) in this context. European countries such as UK, Spain, France and the Netherlands score the lowest on the Infrastructure Vulnerability Index (higher infrastructure development) while Ethiopia, Somalia, Chad, Mali and Mozambique, as well as Afghanistan in Asia score the highest.

According to Figure 6, the arid and semi-arid areas of the world, especially the Sahel, Southern Africa, Southwest Asia, parts of China and Latin America show higher biophysical vulnerability. Comparison of Figures 1(a), 6 and 10 illustrates that the above areas are also subject to prolonged droughts and low MAP, which often results in low crop yields.

Socioeconomic Drought Vulnerability (Figure 7) is generally higher throughout Africa and Asia since many African and Asian countries are largely agricultural economies. In contrast, North and South America, Australia and Europe display much lower socioeconomic drought vulnerability. This is not surprising considering the fact that percentage employment in agricultural endeavors is as high as 93% in Bhutan and 92% in Burkina Faso while it is as low as 1% in the United Kingdom and 2% in the United States. African Countries such as Guinea-Bissau, Ethiopia and Niger, and Asian countries Lao PDR, Afghanistan and Cambodia score the highest on this index (i.e., most vulnerable), while Hong Kong, Macau and Singapore score the lowest. Agricultural economies are much more vulnerable to adverse societal impacts due to meteorological drought. The more complex economies of developed countries insolate the population to fluctuations in agricultural productivity due to drought.

Figures 8 and 9 illustrate that the river discharge Drought Risk Index is higher than the precipitation Drought Risk Index throughout the world, except for a few pockets in South America, Africa and Southeast Asia. This comparison highlights the unreliable and vulnerable nature of river discharge, and further confirms the widely voiced dangers of relying on river water alone. In general, the arid and semi-arid areas have a higher drought risk index than the rest of the world implying frequent drought occurrence and higher drought intensity (deficit below long-term mean) when drought does occur. Europe is 'better-off' in terms of this index and Africa is the worst case.

Figure 10 shows how average hydrological drought duration (run length) varies across the globe. A large part of Africa, South, Southwest and Central Asia and northern Australia (all arid and semi-arid regions) are more prone to multi-year hydrological droughts. An analysis of annual drought durations (not mapped here), suggested that these areas also experience longer annual droughts (how long a drought can last in a single year). Long-term droughts coupled with high infrastructural (Figure 5) and socioeconomic (Figure 7) vulnerability contribute to poor soil quality, food shortage, malnutrition, disease, conflict and famine in Africa. However, large parts of South and North America and most of Europe appear to be less prone to multi-year hydrological droughts, while they also have shorter annual drought durations.

The Storage–Drought Duration (Length) Index (Figure 12) indicates the fraction of the annual drought duration in any country that its present storage capacity is able to satisfy based on its monthly surface water demand. An index value of 1 implies that the country's present storage capacity is satisfactory in comparison to its surface water demand and mean annual drought duration. Out of all the areas having comparatively longer drought run durations (Figure 10), southern Africa, Australia, most of South and Central America and the United States seem to be able to satisfy most of their needs with the current storage facilities, unlike some countries in Central and South Asia, where this index is lower than 0.5. Overall, Africa appears to be more ‘drought-ready’ than South Asia with respect to reservoir storage. The worst cases include Saudi Arabia, Oman, Madagascar, Somalia, Kuwait, Syria, Slovakia, Hungary and Nepal. A look at Figure 11, which maps the present storage capacity as a percentage of total available annual freshwater resources, reveals that many of the countries which score low on this index (especially those in Asia) have no apparent hydrological barriers for increasing storage in the future except perhaps Libya which is already storing 05-0.75% of its annual freshwater resources.

Only a few countries score high on Storage–Drought Deficit Index (Figure 13). They are Egypt, Morocco, Ghana, Cote-d’Ivoire, Burkina Faso, Zambia, Malawi, Zimbabwe, Burundi, South Africa, China, Uzbekistan, Kyrghystan, Tajikistan, Iraq, Turkey, Azerbaijan, Romania and Spain. They are also the countries “performing satisfactorily” on both storage indices (Figures 12 and 13) while having the highest ratios of storage to total available freshwater resources (Figure 11). A low value of Storage–Drought Deficit Index does not necessarily mean that a particular country is unable to meet its freshwater demands during drought. Australia, for example, has enough storage to last twice as long as the annual drought duration when compared with its monthly water withdrawal or monthly demand (Figure 12). However, according to Figure 13, its storage volume is 0.25-0.5 of the annual drought deficit (with respect to long-term mean), which implies that its annual demand is much less than the annual deficit. Therefore, those countries which score high on the Storage–Drought Duration (length) Index can be reasonably assumed to possess satisfactory storage to meet their freshwater demands during drought. On the other hand, those countries which score high on Storage-Drought Deficit Index are also often the ones which are more susceptible to river fragmentation and over–exploitation of freshwater resources (e.g., China, Egypt, South Africa) (Revenga et al. 2000).

## Conclusions

This study reviewed all previous known attempts to approach the issue of drought analysis at the global scale as well as attempts to map disaster risks, water scarcity, climate change and related subjects. The review showed that there has been little, if any, attempt to date to comprehensively describe and map various aspects and impacts of a drought as an individual natural disaster and as a global multi-faceted phenomenon. Hence, the study aimed to start filling this niche by producing a set of global maps of various drought-related characteristics. These characteristics reflect various aspects of drought patterns and impacts ranging from global distribution of meteorological and hydrological drought risks to social vulnerability and indices related to water infrastructure. The maps - either at a country level or regular grid scale - have been produced by integrating a number of publicly available global datasets.

This study should not be seen as exhaustive, but rather as a starting point for global analysis of drought patterns, impacts and preparedness. The limited set of maps designed and analyzed in this study may, with subsequent contributions from other research groups, develop with time into a comprehensive global drought indicators’ ‘atlas’. There are many possibilities on this avenue. At the same time, it is critically important to note that the occurrence of a drought and a specific location’s vulnerability to drought is the result of a combination of many *local* factors. This study gives a rather general, ‘global’ illustration of various drought-related factors, and should not be used to make sweeping generalizations at the local scale.

The present study used monthly rainfall and flow data as they are the only globally available hydrological data so far. Impacts and response options for short-term droughts (weeks to months) and long-term droughts (years to decades) may be different. Future research should examine the differences between short-term (e.g., dry spells) and long-term droughts more closely. However, for the former, daily precipitation and flow time series are needed at the global scale – these are currently not available or are not reliable.

Quantifying and indexing vulnerability to droughts represents another challenge and research niche. A number of attempts are made to quantify vulnerability to climate change and natural disasters (e.g., Downing et al. 2001; www.vulnerabilitynet.org; www.eci.ox.ac.uk; unfccc.int/files/adaptation/methodologies_for/vulnerability_and_adaptation/application/pdf/vulnerability_indices.pdf; www.fao.org/sd/EIdirect/EIre0049.htm). Vulnerability indices can help identify and target vulnerable regions or populations, raise awareness, and form part of a monitoring and adaptation strategy. However, vulnerability definitions vary a lot between various sectors and disciplines. Vulnerability to agricultural drought (low, moderate, high) can be quantified by combining GIS coverages of individual meteorological and basin parameters (e.g., soil root zone available holding capacity, land-use type, etc). Such vulnerability coverage can provide information on which crops are better in which parts of the state/country. Vulnerability indices could be based on damage incurred, population affected, number of droughts relative to land area, etc. It should be possible to map drought vulnerability at smaller administrative subdivisions within countries. But similarly important is to evaluate it at the local level and at the level of households, where different indicators are needed.

Drought indicator mapping eventually feeds into development of a scientific knowledge base for operational drought tools such as drought monitoring, drought early warning systems, which, in turn, should form part of national drought preparedness plans. It is also necessary to note, that since droughts are projected to become more severe, longer or frequent in many parts of the world in the future (e.g., Bates et al. 2008), understanding and quantifying drought patterns and anticipated impacts is becoming a matter of ever-increasing importance.

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**Postal Address**
P O Box 2075
Colombo
Sri Lanka

**Location**
127, Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

**Telephone**
+94-11-2880000

**Fax**
+94-11-2786854

**E-mail**
iwmi@cgiar.org

**Website**
www.iwmi.org

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International Water Management Institute

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