Charles J. Vörösmarty, Ellen M. Douglas, Pamela A. Green and Carmen Revenga

Geospatial Indicators of Emerging Water Stress: An Application to Africa

This study demonstrates the use of globally available Earth system science data sets for water assessment in otherwise information-poor regions of the world. Geospatial analysis at 8 km resolution shows that 64% of Africans rely on water resources that are limited and highly variable. Where available, river corridor flow is critical in augmenting local runoff, reducing impacts of climate variability, and improving access to freshwater. A significant fraction of cropland resides in Africa's driest regions, with 39% of the irrigation nonsustainable. Chronic overuse and water stress is high for 25% of the population with an additional 13% experiencing drought-related stress once each generation. Paradoxically, water stress for the vast majority of Africans typically remains low, reflecting poor water infrastructure and service, and low levels of use. Modest increases in water use could reduce constraints on economic development, pollution, and challenges to human health. Developing explicit geospatial indicators that link biogeophysical, socioeconomic, and engineering perspectives constitutes an important next step in global water assessment.

INTRODUCTION

While concerns mount over future climate change and its impact on freshwater resources (witness IPCC), recent studies identify water stress as a major societal challenge that is already upon us. This conclusion can be reached from documentary evidence (1, 2), country- and regional-scale synthesis (3), or relatively fine-grained geographical analysis (4–6). It appears inevitable that during the first half of the 21st century, water shortages will be among the world's most pressing problems, linking issues as diverse as food security, international diplomacy, poverty alleviation, public health, energy production, ecosystem management, and preservation of biodiversity (7).

Given humankind's dependence on freshwater, one would expect the information needed to wisely manage this important resource to be widely and readily available. Surprisingly, water data to support global-scale assessments are in severe decline—be it the basic hydrographic monitoring to estimate sustainable water supplies (8), information on water infrastructure and operations (9), or access to water (6). Water data are ambiguous and sometimes highly politicized, as with the statistics on irrigation (9, 10). Fulfilling ambitious development goals will be impossible without high-quality quantitative information on which to monitor the resource base and to assess progress.

Earth systems science (ESS) data, from modeling experiments, weather prediction, remote sensing, and GIS, constitute an important, alternative source of information. These data are contiguous and political-boundary free, produced operationally using well-documented protocols, available often at high resolutions, and thus ideally suited to assembling time series of geolocated environmental change. For many parts of the world, they provide the only practical means by which to comprehensively monitor the changing state of inland waters and in many cases can better articulate water stress than traditional approaches (10). Country-level tabulations of water scarcity, until recently the mainstay of global assessments (e.g. 3), generate serious underestimates because of spatial averaging of a highly complex interplay between water supply and use expressed over much smaller domains. Global analysis at 50 km resolution, for example, tripled to nearly 2 billion people earlier national-level estimates of world population exposed to high water stress (4). New digital river networks (e.g. 11) permit us to map renewable water supply as a function of locally derived runoff plus remote runoff transported horizontally through river corridors as discharge. An upstream–downstream perspective can thus be articulated, especially important when considering needs of competing stakeholders.

A central goal of this paper is to demonstrate the use of ESS data in information-poor parts of the world. Our focus will be on Africa. The continent, while emblematic of other large and otherwise poorly documented parts of the developing world, is in particular jeopardy with respect to its knowledge base on water. Since 1990, there has been a 90% reduction in routine reporting of African river discharge (an important source of water supply data) to relevant international agencies such as the WMO Global Runoff Data Center (8). Despite some state-of-the-art regional studies (12–14), we have little concrete information on which to systematically and routinely monitor the condition of Africa's water resources as a whole.

This shortage of information is especially tragic given the continent's enormous environmental and social challenges. Extensive, persistent droughts in the 1970s and 1980s focused attention on Africa's water plight (15), and the continent represents a flashpoint for future water scarcity as well (7). It has a large and rapidly growing population, enormous expanses of dry land, extensive poverty, lack of investment in water infrastructure, and chronic health problems. Promoting sustainable development in Africa was a key commitment of the World Summit on Sustainable Development (WSSD) in Johannesburg, and water figures prominently in the WEHAB (Water, Energy, Health, Agriculture, Biodiversity) initiative (16).

We begin this paper with a brief summary of water indicators. We describe and then apply a methodology to estimate the scope of water scarcity over the entire African continent. We will demonstrate how *globally available,* georeferenced data sets can also be used to articulate water stress at much finer spatial scales, those at which policy formulation and management are often executed. We therefore go on to interpret how such quantitative information could be used to assess major water security issues. Throughout, we will emphasize the importance of a topological perspective that unites local water supplies, horizontal transport of runoff through river corridors, and end users.

A BRIEF OVERVIEW OF WATER SCARCITY INDICATORS

Environmental indicators emerged from heightened environmental awareness in the United States and Europe during the 1970s (17). First used to measure the state of the environment or effectiveness of regulations and programs, they more recently have been applied proactively to decision support, establishing policy objectives, and assessing future impacts (2). Water indicators to assess human well-being have been developed as the limits of traditional indicators (i.e. income or gross domestic product) became apparent (2, 18).

Among the first to call attention to global water scarcity were Falkenmark and Lindh (19), who presented the Water Stress Index (people per 10^6 cubic meters water supply per year) as a means of differentiating between climate- and human-induced water scarcity. A value of 1700 m^3 $capita^{-1}$ y^{-1} (20) is widely accepted as a threshold below which varying degrees of water stress are likely to occur. Gleick (2, 21) quantified basic human water requirements (BWR) as 50 L^{-1} $capita^{-1}$ d^{-1} (excluding food production). Gleick (22) and Raskin (23) aggregated water use, resource reliability, and socioeconomic coping capacity into indices of regional water vulnerability. Salemeh (24) redefined the Water Poverty Index (WPI; originally the ratio of available resource to water required for

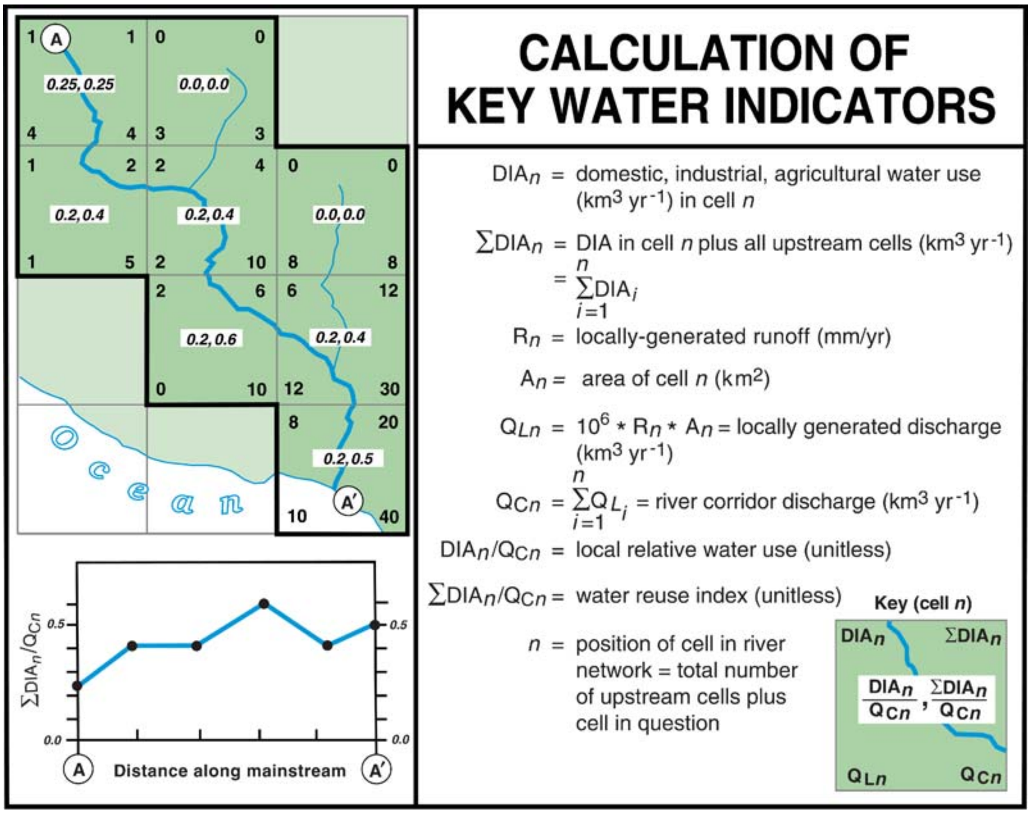

Figure 1. Overall calculation scheme for key water stress indicators with sample application to a hypothetical gridded drainage basin/river corridor system. All computations are made on ≈8-km grid cells (6′ latitude × longitude).

BWR and food production) to account for food productivity differences in arid and semiarid environments and wastewater recycling. As an alternative to the conventional composite index, Sullivan (18) presented a matrix approach to WPI, incorporating ecosystem condition, community well-being, human health, and economic welfare.

While serving as important devices to raise awareness of water issues, the previously noted indicators often reflect country- or regional-scale statistics and thus may greatly understate the full scope of the problem (4, 25). Application of new capabilities to map subnational heterogeneities in climate, population density, and water use, with much higher precision than previously possible, we see as the next logical step in the evolution of water indicators.

METHODOLOGY

Data Sets and Modeling

Outputs from a Water Balance and Transport Model (WBM/WTM) were used to determine the spatial distribution of renewable water supply, expressed as the sum of local runoff and river corridor discharge. The model version used here shows <10 mm y^{-1} mean bias in runoff (26, 27), but estimates were constrained wherever possible by observed hydrographic data (317 sites, 86% of actively discharging African landmass). Monthly atmospheric forcings from 1960 to 1995 were from New, Hulme, and Jones (28). Estimates of domestic and industrial water demands (4, 29) were apportioned by urban/rural population densities. Agricultural withdrawals were based on African water statistics (Jippe Hoogeveen, FAO/AGL, Rome, Italy) at the subbasin level and a mapping of irrigation-equipped lands (30). All supply and demand estimates were resampled as required and georegistered to a (6′ latitude × longitude) grid and river network (STN-06), updated from a previous flow topology (11) using a network rescaling algorithm that processed 1-km digital streamlines (31). STN-06 basin boundaries were compared to a hand-corrected database provided by FAO. When required, monthly discharges were computed from modeled runoff and routed downstream using a uniform channel velocity of 0.5 m s^{-1}.

Water scarcity was evaluated, in part, by computing the Climatic Moisture Index (CMI) (32), the ratio of annual precipitation (P) to annual potential evapotranspiration (PET). Specifically, CMI = $(P/PET) - 1$ when $P < PET$ and CMI = $1 - (PET/P)$ when $P \geq PET$. The CMI ranges from -1 to $+1$, with wet climates showing positive values, dry climates negative. PET was estimated using a physically based function (33). We grouped CMI into major climate categories following Koppen. The coefficient of variation (CV) computed for all variables is the ratio of the standard deviation to the mean over the time series analyzed.

Topology-Based Indicators of Water Availability, Use, and Scarcity

Calculations of key indicators are shown in Figure 1. Water supply in each grid cell (n) has two sources, locally generated discharge (Q_{Ln}) and river corridor discharge (Q_{Cn}), which enters from upstream cells. Q_{Ln} is the product of runoff (R_n) and cell area (A_n). Q_{Cn} accumulates Q_{Ln} in a downstream direction along the STN-06 digital network. Cells with mean upstream runoff <3 mm y^{-1} were considered inactive or nonperennially discharging (11).

Water use is represented by local demand (DIA_n), the sum of domestic, industrial and agricultural water withdrawals. Dividing DIA_n by Q_{Cn} yields an *index of local relative water use*. A high degree of stress is indicated when the relative water use index is >0.4 or 40% (34). DIA_n summed in a downstream direction (in a similar manner as Q_{Cn}) and divided by Q_{Cn} is called the *water reuse index* and represents the extent to which runoff is recycled or reused as it accumulates and flows toward the basin mouth. The water reuse index typically increases in a downstream direction, indicating reuse and recycling of river corridor water. This index can, however, decrease when mainstream flow is diluted by more pristine (less recycled) tributary waters.

THE CHARACTER OF AFRICAN WATER SCARCITY

Climatic Moisture: Spatial Characteristics and Variability

The CMI is an aggregate measure of potential water availability imposed solely by climate (Fig. 2a). Most of Africa's continental area, 82%, is arid and semiarid (Fig. 2a, *inset*), with evaporative demands exceeding rainfall over the bulk of the landmass. The corresponding global total is 54%. Table 1 compares the distribution of land area by CMI class for Africa and for the entire globe. The median CMI value globally ranges from -0.10 to -0.25, while for Africa it is below -0.75. Not surprisingly, Africa is a relatively dry and water-scarce continent.

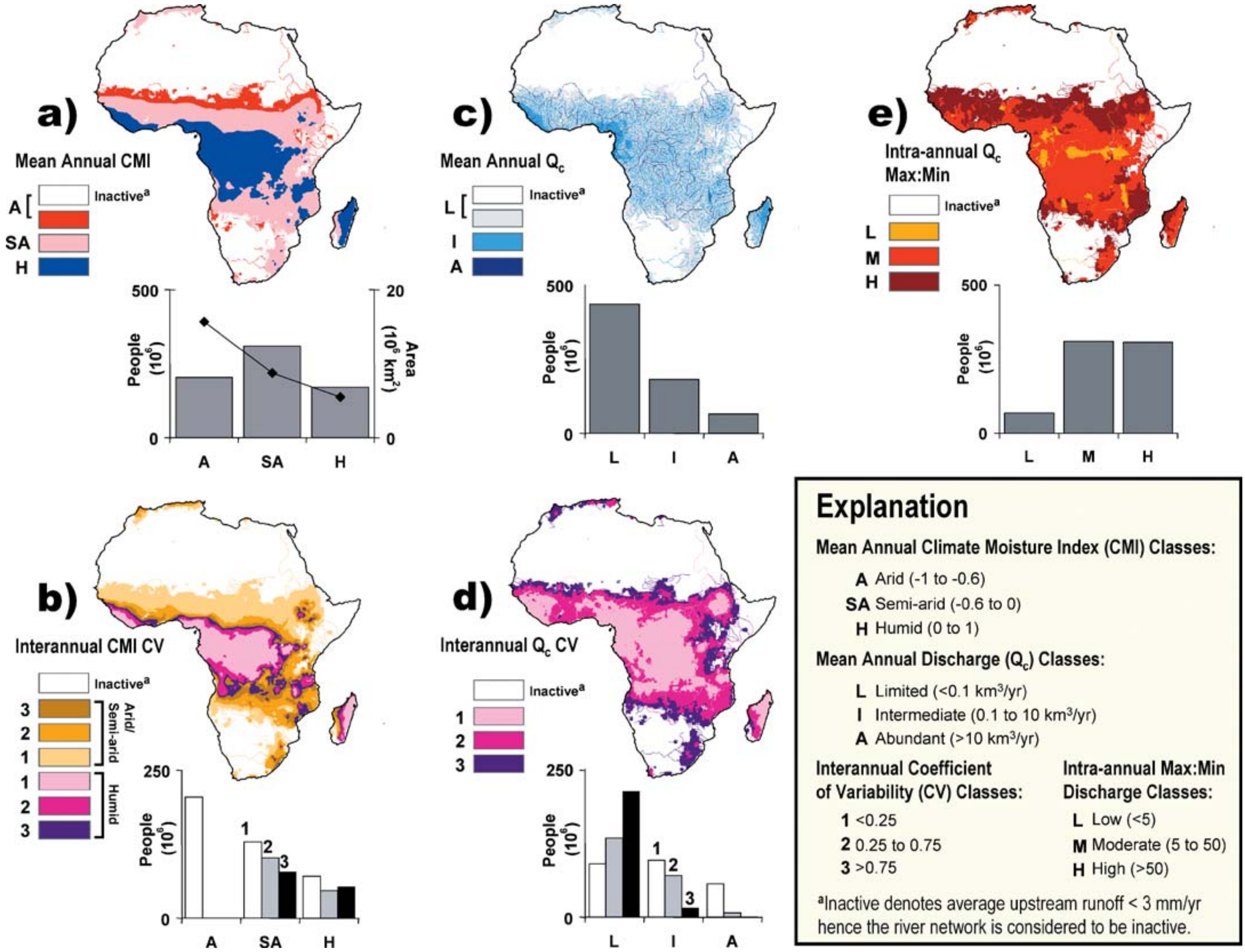

Figure 2a. Distribution of climate and relative dryness, expressed as classes of the Climate Moisture Index (CMI) (32). Widespread, negative CMI values across Africa show potential evapotranspiration in excess of precipitation and thus the potential for climate-based water scarcity for resident populations. Inset shows a large fraction of area (*line*) and total population (*bars*) in arid and semiarid climate zones.
Figure 2b. The coefficient of variation (CV) in the Climate Moisture Index (CMI). The shading denotes degrees of variability and applies to zones of both positive and negative CMI. High variability and sharp spatial gradients are noted in the transition zones between the humid and arid regions over a 35-y time series. The bar chart indicates distribution of population with respect to CMI classes and levels of interannual variability. Arid zone populations show uniformly low CV, while populations in semiarid to humid regions show a distribution of variability.
Figure 2c. Discharge fields representing accumulated runoff at ≈8 km resolution. Spatial aggregation of runoff reveals the importance of river corridor flow (Q_c). For much of the continent, however, local runoff serves as a primary source of renewable water supply. The inset shows that the vast majority of the African population is highly dependent on intermediate to limited levels of supply, with 17% showing no discernible quantity of renewable resource.
Figure 2d. The coefficient of variation (CV) of discharge, Q_c. The pattern bears similarity to the variation in the Climate Moisture Index (CMI) but is dampened because of the integrating effect of runoff coalesced as discharge in river corridors. Nonetheless, the transition zones between the humid and arid zones once again show generally high variability. The bar chart shows the high degree of variability in the major water sources across Africa (i.e. limited and intermediate classes of Q_c). A 35-y time series was analyzed.
Figure 2e. Ratios of the monthly maximum-to-minimum discharge. Geographic patterns are defined by the distribution of climate and its seasonality, the size distribution of river corridors, and river regulation. Local runoff shows typically large extremes, while major rivers generally show dampened ranges. The inset shows the high degree of seasonal variation experienced by the bulk of the African population.

Africa displays a complex pattern of interannual variability in CMI, accentuated near the boundaries of the major climate zones (Fig. 2b). While large areas in the wettest (central Congo basin) and driest (Sahara and southwest Africa) regions display relatively low variability, much sharper gradients are apparent in the transition zones between the humid tropics and arid regions. The southern flank of the Sahel is a good example, with high variability moving across the boundary between humid to dry conditions, in some cases spanning a distance of only 100–250 km. Mountain effects also invoke sharp gradients in precipitation and CMI, as for the Katanga and Rift Valley regions in central eastern Africa, the Ethiopian Highlands, and Madagascar.

River Corridor Discharge and Its Variability

While climate and its variation are arguably critical for determining the reliability of rain-fed agriculture and local water supplies, a more complete picture must consider how river corridors focus spatially distributed runoff into discharge Q_c (Fig. 2c). Dry areas with little or no local water can thus have access to a potentially abundant renewable resource generated far upstream and delivered through large rivers, floodplains, and deltas. This "reconditioning" of local runoff (Table 2) shows the great benefit such corridor flow conveys to the driest parts of the continent. In regions with CMI < –0.6, we see nearly a doubling of locally derived runoff (90 $km^3\ y^{-1}$) and hence available water resource conveyed as river corridor flow. The importance of river corridors by this calculation is actually understated, as the associated flows include consumptive losses in heavily used rivers.

Much of the actively discharging landmass is composed of low-order streams subject to the character of local climate (Fig. 2c). Paradoxically, many of the dry regions of Africa that show low variability in climate (Fig. 2b) are those with high variations in local Q_c because of episodic runoff (Fig. 2d). Nevertheless, these lands ultimately generate water resources bearing low variability when their local runoff is routed through river corridors. This buffering capacity is especially apparent where rivers are present within the

Table 1. The total area (in millions km^2) in Africa and globally at different levels of the Climatic Moisture Index (32), which here represents annual conditions, derived from a time series spanning 1960-1995.

Climate Moisture Index	Africa cumulative area	Global cumulative area	Africa cumulative area (%)	Global cumulative area (%)
−1.00 to −0.75	11.8	30.3	39	23
−0.75 to −0.50	17.4	46.6	58	35
−0.50 to −0.25	21.0	59.8	70	45
−0.25 to −0.10	23.0	67.7	77	51
−0.10 to +0.10	25.7	79.2	86	60
+0.10 to +0.25	27.4	89.7	92	67
+0.25 to +0.50	29.6	109	99	82
+0.50 to +0.75	30.0	126	100	95
+0.75 to +1.00	30.0	133	100	100

highly variable transition zones. For example, the Niger and the upper reaches of the Nile have low CV, while the surrounding areas show moderate to high variations. A notable exception is the Orange River, which rises in a zone of high interannual variability and then flows through an arid zone.

Even in otherwise water abundant areas, seasonality (intraannual variability) can severely limit water supply. Similar to results describing interannual variability, we find the seasonality of local runoff to be generally high relative to river corridor flows (Fig. 2e). For Africa, the median max:min local runoff ratio is 113:1, while median max:min Q_c is 80:1. After incorporating the effects of reservoirs (i.e. constraining Q_c by discharge records), the median max:min Q_c ratio for Africa drops to 71:1. Even with impoundments, intraannual variability of discharge in Africa is generally high, and the transition zones between wet and dry climates show the greatest intraannual fluctuation, with typical max:min Q_c ratios >100:1. Only in humid tropical areas and along large, highly regulated rivers (i.e. the Nile and Orange) is the seasonal variability low (max:min $Q_c < 5$).

Distribution of Population with Respect to Climate and Water Supply

Associated with each map in Figure 2 are insets illustrating the population exposed to different levels of CMI and discharge. There are important distinctions between means and variability. Compared to a global proportion of 52%, approximately 75% of all Africans live in the arid and semiarid regions of the continent (mean CMI < 0) (Fig. 2a). Twenty percent of all Africans live in areas that experience high interannual climatic variability as expressed by a CV of CMI > 0.75 (Fig. 2b). They are generally located in the transition zones between humid and arid regions that cover a relatively small proportion (10%) of the continental area. Populations in the humid zone can also be exposed to high CMI variability. Nonetheless, the majority of both landmass (75%) and population (59%) are located in areas of low variability (CMI < 0.25) (Fig. 2b). The population of Africa is thus distributed in a manner that generally reduces overall exposure to climate extremes. As we will see, this does not necessarily translate into low variability in water supply, nor does it make a statement about seasonal shortages.

With regard to water resources, more than 60% of Africans live with mean locally generated runoff of approximately 300 mm y^{-1} or less, and about 40% live with less than 100 mm y^{-1}. We assumed that people living within a grid cell had access only to the water within that grid cell (a maximum distance of 8 km). In this context, only about 10% of Africans have access to abundant river corridor discharge (defined here as $Q > 10$ km^3 y^{-1}), indicating that the vast majority of the population must rely on local runoff in small streams and shallow groundwater, as well as deep groundwater stores, to meet their water needs (Fig. 2c). About 25% of the population is exposed to intermediate conditions (0.1–10 km^3 y^{-1}) and 65% lives in association with limited river corridor flow (<0.1 km^3 y^{-1}), the latter with moderate to high interannual variability in discharge (Fig. 2d). Thirty percent of Africans are exposed to both limited quantities of discharge and very high interannual variability (CV > 0.75). The inset associated with Figure 2e demonstrates that normal patterns of seasonality add to this stress. Nearly 90% of the African population lives with a max:min Q_c flows ratio in excess of 5:1 and slightly under half with ratios >50:1.

Distribution of Water Demands with Respect to Climate and Water Supply

We explore briefly the capacity of African climate and water systems to provide adequate renewable supplies in the face of contemporary domestic, industrial, and agricultural demands. In general, irrigation water use in Africa is an order of magnitude higher than domestic and industrial demands combined and thus defines aggregate use for the continent. Much of Africa's agricultural capacity is distributed across dry regions, with 75% of its cropland located in areas with CMI < 0 (Table 2). Irrigation water demands increase more or less exponentially with a decreasing CMI, reflecting the absolute requirement for irrigation in arid and semiarid zones and higher water use in these drylands relative to more humid environments. In the driest cropped areas (CMI ≤ –0.8), 97% of agricultural area is irrigated. Across these areas, irrigation withdrawals (43 km^3 y^{-1}) exceed locally generated runoff (5 km^3 y^{-1}) by almost an order of magnitude, necessitating use of river corridor flows or aquifer mining. We compute that 39% of irrigation withdrawals in areas with CMI ≤ –0.8 are from nonsustainable sources. The remaining 61% is from corridor flows that have been progressively depleted, as in the lower Nile, which loses much of its available water resource from natural and human consumption (35). This result further highlights the importance of river corridor flow in supporting dryland agriculture. At the same time, irrigation in such regions may seriously compromise the integrity of an important renewable resource on which both human society and aquatic ecosystems depend (36, 37).

Table 2. Distribution of total agricultural land area, % irrigated area, and total irrigation withdrawals distributed by Climate Moisture Index (CMI) class. River corridor discharge is at mouth of river (27), classified by CMI, to demonstrate the reconditioning of local runoff as horizontally transported discharge.

Climate Moisture Index	Local runoff (km^3 y^{-1})	River corridor discharge[1] (km^3 y^{-1})	Agricultural area (1000 km^2)	Fraction irrigated area (%)	Irrigation withdrawals (km^3 y^{-1})
−1.0 to −0.8	6	101	74	97	43
−0.8 to −0.6	84	99	310	16	20
−0.6 to −0.4	287	145	278	10	8
−0.4 to −0.2	591	192	313	5	3
−0.2 to 0.0	932	1646	282	2	1
0.0 to +0.2	864	139	205	3	0.8
+0.2 to +0.4	996	297	119	6	0.6
+0.4 to +0.6	908	601	91	5	0.4
+0.6 to +0.8	99	563	9	1	0
+0.8 to +1.0	0	0	0	0	0

[1] Entry represents the accumulation of runoff through river corridors plus the additional impact of irrigation consumptive losses and natural flow depletion (through open water evaporation, floodplain evapotranspiration, recharge into streambeds).

A Climatology of African Water Stress

Water stress is determined here using the index of water use relative to renewable supply (DIA/Q) (Fig. 1). By this measure, 25% of the contemporary African population experiences high water stress with $DIA/Q > 0.4$ (Table 3). Despite the overwhelmingly dry conditions documented previously, surprisingly, most of the African population (69%) lives, on average, under conditions of relative water abundance and another 6% under intermediate levels of water stress. In fact, the relative distribution of population across different levels of stress for Africa is not substantially different than for the rest of the world. Aggregate water stress is much less than expected given the "natural" water demands placed on Africa arising from its position as one of the driest continents.

The modest, overall level of stress does not necessarily reflect an absence of water problems for Africa. Our results are conservative

Table 3. Populations in Africa living under progressive levels or water stress under different return intervals for low flow, a measure of hydrologic drought. The 30-y interval is the most extreme and high levels of stress ($DIA/Q > 0.4$) are evident. The totals for the 30-y recurrence interval correspond to the ~8-km pixels shown in Figure 3.				
	Population (millions)			
	Recurrence interval			
DIA/Q class (mm y^{-1})	2-y (mean)	10-y	20-y	30-y
Low (<0.1)	477	420	405	385
Moderate (0.1 to 0.2)	23	21	22	26
Medium-high (0.2 to 0.4)	16	17	18	19
High (>0.4)	174	232	247	262

insofar as they do not account for other equally important factors, like poor access to clean drinking water and sanitation, which reduces the effective quantity of freshwater available for human use. In fact, even though considerable improvement in access occurred during the 1990s, only 62% of African population had access to improved water supply in 2000, giving it the lowest water supply coverage of any region in the world (38). The inaccessibility is much worse in rural areas, where coverage is only 47% compared to 85% in urban areas. Poor water infrastructure and delivery systems translate into water pollution and public health problems that entrench existing limitations to economic and social development (18).

Water availability, demand, and potential stress also vary by season. As shown in Figure 2e, the majority of Africans are exposed to moderate to seasonal hydrologic variability. We evaluated the degree of seasonal water stress ($DIA/Q > 0.4$) computed on a monthly basis. Domestic and industrial demands were assumed to remain constant throughout the year, while agricultural use (irrigation) varied temporally and proportionally based on the ratio of monthly average PET to average annual PET. The number of months in which the monthly version of the relative stress index exceeded the threshold of 0.4 was recorded. A bifurcated pattern of persistent water stress became apparent, with 370 million people (53% of the population) showing no apparent monthly water stress and 170 million (25%) exceeding the threshold for 10 or more months per year. A mapping of seasonal variability (not shown) corroborates the geographic patterns of stress described in previous sections. People living in transition zones (i.e. the Sahel) and on the fringes of African deserts suffer the most seasonal water stress. In contrast, large river corridors, even in the driest regions, demonstrate a stabilizing effect on seasonal flows. River regulation further increases the reliability of freshwater sources throughout the year and reduces apparent levels of both annual and seasonal stress.

Climate Variability and Water Stress

Annual and seasonal means give us one important view of water stress. But a more complete geography of water stress must necessarily consider the inherent variability of the water cycle and its possible changes over time. Of primary concern is a potential acceleration of the hydrologic cycle associated with greenhouse warming, leading to greater frequency and intensity of extreme events like floods and drought (39). While the future remains highly uncertain, initial analysis indicates minor climate-borne consequences on regional water resources (4, 25) relative to much larger impacts from population growth and economic development.

As a contribution to one component of this dialogue and to provide a benchmark against which future change can be assessed, we present an analysis of historical patterns of drought across Africa and its impact on water stress. Figure 3 shows population densities (in thousands per grid cell) that fall either above or below the 0.4 DIA/Q threshold of severe water stress. The map expresses the 30-y low-flow condition (which, for this analysis, we equate with the 30-y drought). It is easy to see large populations experiencing high levels of water scarcity in northern Africa, the Sahel, the horn of Africa, and southern Africa. However, it is noteworthy that even in the wet tropics (e.g. northern shore of Lake Victoria), there is evidence of population and development pressure on water supplies, with many of the grid cells reflecting rapidly urbanizing populations.

The difference between the mean (2-y recurrence) and 30-y low-flow conditions is substantial (Fig. 3 and Table 3). Total population living above the water stress threshold under mean annual conditions is 174 million, whereas under 30-y drought, it rises to 262 million, a 50% increase. The corresponding estimates for the 10- and 20-y droughts are 232 million and 247 million, respectively. Especially hard hit are the Sahel, southern Africa, and eastern Africa, where the population under water stress triples for the 30-y drought (Fig. 3, *inset*). Hence, in these regions, substantial water stress is experienced and becomes a significant environmental challenge at least once every generation.

Water Stress along River Corridors

Our discussion so far has focused on indicators relating local water withdrawals to renewable supply (i.e. local runoff plus river corridor flow). In reality, water use within a drainage basin often constitutes a recursive phenomenon through which freshwater is used and reused many times during its passage to river mouth. Data from earlier analysis (4) demonstrated for many of the world's river systems that this water reuse can exceed, sometimes greatly, natural discharge. A similar set of calculations has been made for the major river corridors in Africa, with two examples shown in Figure 4. A "signature" for water resource exploitation emerges as a plot of the water reuse index *versus* distance (Fig. 1), arising from basin-specific combinations of river discharge and water use progressing downstream. Each mainstem shows a unique trajectory, starting from zero at the headwaters. Rises indicate that the river encounters either a significant water use (i.e. municipal or irrigation withdrawals) or a tributary with relatively large withdrawals. In contrast, reductions in the index reflect the impact of runoff and tributary inputs with less water use. With increases in water reuse, we expect to see increasing competition for water, pollution, and potential public health problems.

In the case of the Nile, we see a progressive increase moving downstream, with initial rise associated at El Gezira irrigation works and Khartoum, followed by intensified use downstream of Aswan. At

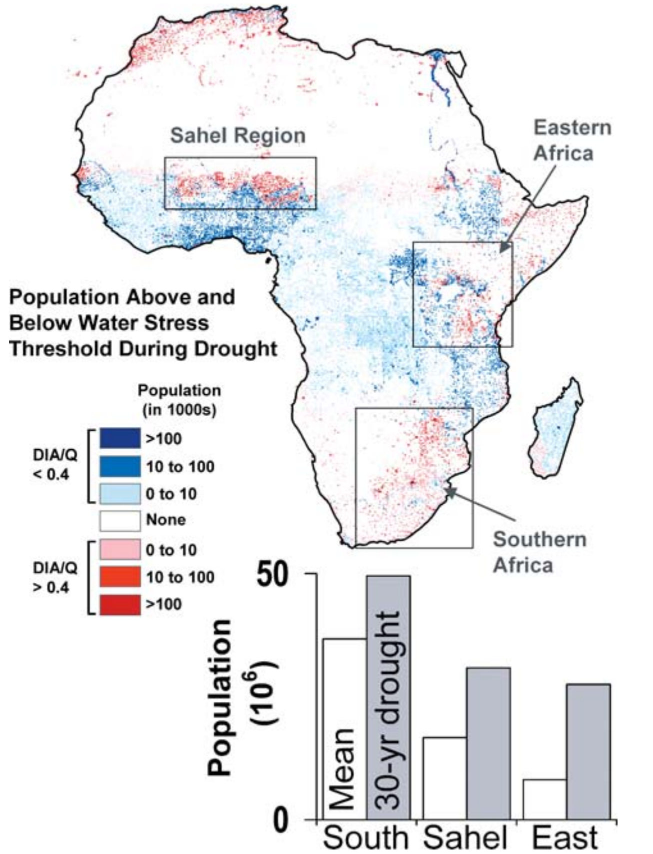

Figure 3. The density of human population living above (*red*) or below (*blue*) the relative water use threshold of 40%, presumed to indicate severe stress (34), under the 30-y recurrence drought. Three examples of the sensitivity in regions located in hydrologically complex transitional zones between arid/semiarid and humid climates are shown.

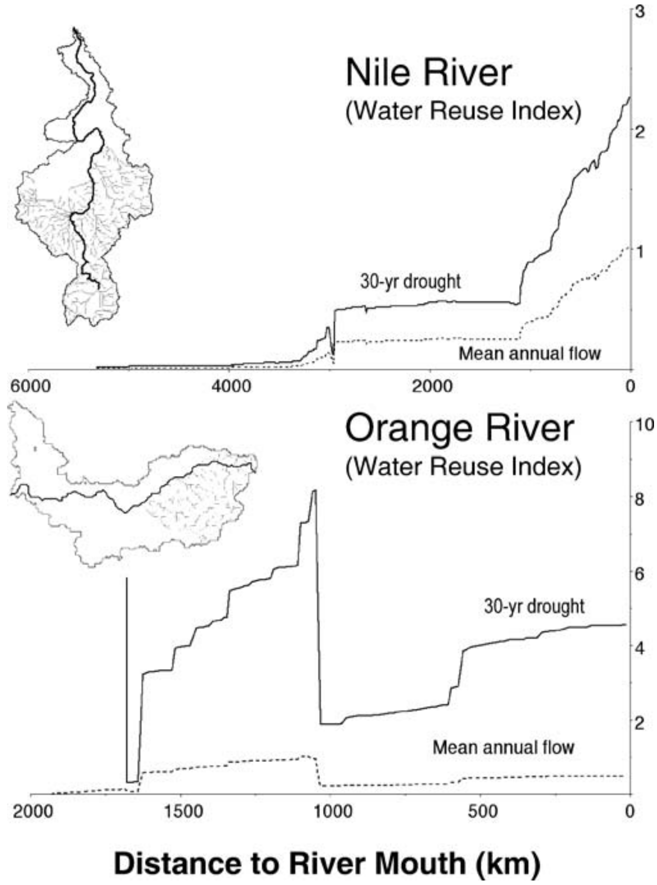

Figure 4. Signature of aggregate water use relative to available discharge along two major river corridors under normal and 30-y drought conditions. A value of 1.0 indicates complete reuse of river water equivalent to discharge over an entire year. Increases and decreases arise from contrasting rates of water usage relative to inflow and dilution from less exploited tributaries.

the mouth of the river, withdrawals equal to 1 y of mean annual flow are tabulated. Relative water reuse more than doubles under 30-y low-flow conditions. The Orange River reacts far more dramatically to climate variability. While the relative water reuse progresses downstream to a level <50% under mean annual flow, it rises an order of magnitude under 30-y low-flow conditions. Without the beneficiary effect of headwater flow from the wet tropics (as for the Nile), the nearly complete exposure of the Orange River to the arid/semiarid climate zone makes it particularly sensitive to climate variability.

POLICY IMPLICATIONS

While biogeophysical variables have been emphasized in this work on Africa, a far broader suite of measures is required to support ongoing global water assessment activities. The sequence of triennial World Water Development Reports (WWDR) (7), essentially a "report card" on the state of the world's freshwater, provides a practical example of the need for such indicators. In the 2002 WWDR we find no fewer than 150 current or proposed metrics. Harmonizing their spatial and temporal characteristics, ensuring consistency, and distilling these into meaningful aggregates that can be conveyed to the policy and management communities is critical to the success of this reporting process. Examples of potential policy applications using the topological approach developed here follow.

Human Health

The well-publicized realization (40) that over 1000 million people worldwide lack access to improved water supply and that nearly 2500 million are still unserved by improved sanitation embodies the nexus of human health, poverty alleviation, and water resources. Ambitious Millennium Development Goal initial targets, namely, to halve by 2015 the proportion of people lacking adequate drinking water and sanitation, requires information on physical access to water and to services that provide adequate delivery and protection from water pollution (41). Reconciling differences in the spatial distribution of biogeophysical, socioeconomic, and health survey data is a required next step. Water also determines habitat for disease vectors and serves as the conveyance medium for pathogens. Articulating continental-scale patterns of these highly localized issues, potentially in near real time, will provide a capacity to pinpoint emerging problem areas and to implement suitable interventions.

Water Conflict and Cooperation

At the heart of the debate on water as a source of conflict or cooperation (42) lies the control and use of temporally variable river flows. Georeferenced data on climate variability, discharge, upstream–downstream water demands, flow diversion, and reservoir control can be combined with information on water governance and allocation agreements among riparian stakeholders to better articulate the nature of potential conflict and to design political instruments for cooperation. Defining the geospatial character of international water disputes requires a formal recognition of the topology of borders, specifically rivers running across or themselves forming political boundaries (43). Civil conflicts are also correlated with water cycle variability (44) and the links are imminently mappable.

Food Provision

A large and growing population will place increasing demands on both rain-fed and irrigated agriculture in the coming decades. Globally, three-quarters of contemporary water use is for irrigation, with regions such as North Africa/Near East and South Asia utilizing, respectively, from 35% to over 50% of their renewable water supplies for growing crops (7). A systematic picture of irrigation's role in current and future basin dynamics needs to account for the great diversity in how freshwater is secured (from aquifers, trapped precipitation, mainstem rivers), nomenclature problems, and difficulties in monitoring use (10). Efficiencies expressed as the ratio of withdrawal from source-to-crop consumption are <40% throughout the developing world (7), suggesting opportunities for substantial improvement. Yet our notions of field efficiency may seriously underestimate reuse when viewed at the basin scale (45). The topology of local precipitation, runoff, groundwater sources, river discharge, and downstream impacts on supply arising from flow reduction and elevated concentrations of agrochemicals can provide a more systematic framework for such analysis.

Water Engineering and Ecosystems

Emphasis in alleviating water scarcity has traditionally focused on expanding supply through dams, reservoirs, and interbasin transfers. Although this approach is being recognized as costly in both financial and environmental terms (9, 46), our analysis indicates that there will be mounting pressure to stabilize flows in Africa and other water-stressed parts of the world because of an unreliable resource base, defined by limited and highly variable runoff and corridor flows. Policies aimed at stabilizing upstream water resources have produced global signatures of river fragmentation, habitat destruction, nutrient and sediment retention, and biodiversity changes that extend in many cases fully to the coastal zone (36, 37). While the benefits for development are clear, the decision to regulate river systems is not without its impacts and requires a topological perspective to address tightly linked, upstream–downstream phenomena.

Natural Hazards

Water-related risks are among the most costly, with annual damages from catastrophic drought and floods totaling tens of thousands of millions of US dollars (47). The human and economic costs of such events fall disproportionately on a developing world population with poor emergency preparedness and response capacity (7, 47). While droughts and floods are fundamentally weather phenomena, they express themselves through a topological hydrologic perspective. Though many parts of Africa show what is essentially a drought expressed as a seasonal or even perennial lack of rainfall, river corridor flows are critical in sustaining dry-season water supplies over large portions of the continent. Floods, either through local flash floods or major regional episodes, are determined by excess rainfall and the capacity of river networks to transport this additional water. The ability to globally map population and downstream infrastructure (48) over entire basins affords us the opportunity to identify areas of greatest vulnerability and to support better disaster prevention, warning, and response. Analyzing the degree to which upstream deforestation and other land cover changes elevate hydrological risk downstream also requires a topological perspective (49).

CONCLUSIONS

We, as others, see Africa as a dry continent with pressing water problems but arrived at this conclusion by analyzing high-resolution, geospatial data sets and a topology of digital river networks. From this perspective, we demonstrated that Africa is much more than simply dry. We showed, for example, that 75% of all Africans live in arid/semiarid regions with relatively low climate variability, with exposure to restricted freshwater supplies but bearing great temporal variability. A significant fraction of cropland in Africa is dry, with much of the required irrigation nonsustainable. We demonstrated how large river discharges augment local runoff, reducing the impact of climate variability and improving access to water, but also identified these as the very locations of high reuse and potential abuse. Chronic water stress (mean use:supply) is high for 25% of the population, and 40% experiences drought stress once each generation. Water stress for the vast majority of Africans, however, is typically low, reflecting its poor water delivery infrastructure. A well-engineered increase in use might thus be advantageous in mitigating water-related constraints on development, pollution, and chronic public health problems.

The work presented here demonstrated the importance of a geographical perspective using widely available biogeophysical data sets. But water challenges facing Africa and other parts of the developing world also engender an array of social science and engineering issues. A more complete understanding of human–water interactions and the design of appropriate policy interventions to alleviate water stress thus require a broader interdisciplinary approach. Uniting these perspectives in a geographical framework is an important next challenge for the water sciences.

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Charles J. Vörösmarty is at Water Systems Analysis Group, Institute for the Study of Earth, Oceans and Space, and Earth Sciences Department, University of New Hampshire, Durham, NH 03824, USA.
charles.vorosmarty@unh.edu

Ellen M. Douglas is at Water Systems Analysis Group, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824, USA.

Pamela A. Green is at Applied Geosolutions, Durham, NH 03824, USA.

Carmen Revenga is at The Nature Conservancy, Arlington, VA 22203, USA.