A Geospatial Approach to Assessing Water Stress in Africa

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Abstract : In this article we analyze a set of geographically-specific indicators of African water scarcity. These indicators at 6' (longitude x latitude) spatial resolution show that a significant fraction of the African population (40%) and its associated water demands are located in water-scarce regions with <100 mm yr^{-1} runoff. The same fraction of African agricultural land is exposed to a climate where potential evapotranspiration exceeds annual rainfall. These areas show a large degree of intra- and interannual variability in available water supply. Consequently, agricultural demand defines the aggregate water use for the continent. We anticipate that much of this demand is non-sustainable. Paradoxically, the mean annual relative water use stress index for most of the African population is low. To some degree, chronic seasonal shortages of water may be more critical; 200 million people (30%) are exposed to water stress for more than 10 months per year. River corridor discharge is critical in augmenting local runoff in arid regions, reducing the impact of climate variability, and improving access to water supply. This study demonstrates emerging capabilities from the geophysical side of the water scarcity question. A much-needed interaction between the biogeophysical and socioeconomic approaches is still of urgent necessity.

Keywords: *Water scarcity; water stress; climate moisture index; geospatial analysis; indicators.*

1. INTRODUCTION

Human-induced water scarcity and conflicts over water management are now a significant part of the larger global change question, which arguably has focused historically on the climate change question and its relation to water resources (Vörösmarty, 2002a). Despite fundamentally different approaches to the same problem, a number of recent studies (Postel, 2000; Gleick, 2002; Shiklomanov, 1996; Shiklomanov, 1997; Vörösmarty et al., 2000a; Alcamo et al., 2000; Oki et al., 2001) highlight the urgency of global water stress and identify it as a major societal problem that is already upon us. It is inevitable that during the first half of this century water shortages will be among the most important of global problems, linking issues as diverse as food security, international diplomacy, poverty alleviation, public health, energy production, ecosystem management and biodiversity preservation. Given humankind's dependence on water, one would expect the information needed to wisely manage water resources among the competing stakeholders to be widely and readily available. Nonetheless, water data to support global-scale assessments are in severe decline. Water data is also highly politicized, as in the case of irrigated cropland (Vörösmarty, 2002b).

Data collection and monitoring has traditionally been done in the context of national boundaries. However, country-level estimates of water availability and use hide significant within-country differences (Vörösmarty et al., 2000a). By their very nature, large countries cannot be characterized by a single national average and instead, require a spatially-resolved approach. This is especially the case in the world's two most populous countries: China and India (Seckler et al., 1999). Northern China is very dry, while southern China is wet; Eastern India very wet, western and southern India extremely dry. Emerging Earth Systems science data products from models and GIS-based and remote sensing data sets are political-boundary free, developed using standard methodologies, available often at high resolutions, and are ideally suited to detecting elements of geographically-referenced change (Vörösmarty, 2002b). Subject to appropriate validation and interpretation they offer some degree of remedy to these limitations in regions with otherwise poor or unavailable data resources.

2. METHODOLOGY

Outputs from a geographically-referenced Water Balance Model (WBM) were used to determine the spatial distribution of renewable water supply, specifically as the expression of local runoff as discharge in river corridors at a 6-minute (6') spatial resolution (longitude x latitude). The WBM simulates soil moisture variations, evapotranspiration, and runoff on single grid cells using biophysical data sets that include climate drivers, vegetation, and soil properties. The state variables are determined by interactions among time-varying precipitation, potential evaporation, and soil water content (for more details, see Vörösmarty et al., 1998; Federer et al., 2003). While the model version used in this study shows <10 mm yr^{-1} bias in runoff, WBM estimates were constrained where possible by observed hydrographic information (we used 317 sites, representing 86% of the actively discharging land mass of Africa, Fekete et al., 2002). Atmospheric forcings were from New et al. (1998) comprising monthly data from 1960 to 1995 at a 30-minute (30') resolution, bilinearly interpolated to 6'. All water supply estimates were georegistered to a new 6' river network (STN-06). Data sets for population and domestic and industrial water demand (Vörösmarty et al., 2000a; 2003a) were resampled from the original 1-km resolution and co-registered to the 6' grid and river network. Irrigation water use within each sub-basin as defined by FAO was distributed by sub-basin across a data set of irrigation-equipped lands developed by Siebert et al. (2002), resampled from the original 5' resolution to 6'.

Figure 1 defines and illustrates the key indicators used in our analysis. Water available within each grid cell has two sources: the locally-generated discharge (Q_{Ln}) and the river corridor discharge (Q_{Cn}) entering from upstream cells. Q_{Ln} is the product of WBM runoff (R_n) and cell area (A_n). Q_{Cn} is computed by accumulating (summing) Q_{Ln} in a downstream direction along the STN-06 digital river system. Water use is represented by local demand, the sum of domestic, industrial and agricultural water use (DIA_n), which represents the total human water demand for each grid cell. Dividing DIA_n by local discharge results in an index of relative water use. A high degree of water stress is indicated with the relative water use index > 0.4 (Falkenmark, 1998). 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 basin-derived runoff is recycled or reused as it accumulates and flows towards the mouth of the river. The water reuse index typically increases in a downstream direction, indicating reuse and recycling of river corridor water. However, the index decreases when mainstream water is diluted by more pristine (less recycled) tributary water. Water scarcity was evaluated by computing the Climatic Moisture Index (CMI) based on the methodology developed by Willmott and Feddema (1992). In this paper, CMI is computed using 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 indicator ranges from –1 to +1, with wet climates showing positive CMI, and dry climates negative CMI. PET was estimated following Shuttleworth and Wallace (1985).

Using biogeophysical data sets and the indicators described above, we developed a series of maps and summary statistics on water availability, water demand, climate variability and their interactions within drainage basins. Some of our results are presented in this paper. A complete description of this work can be found in Vörösmarty et al. (2003b).

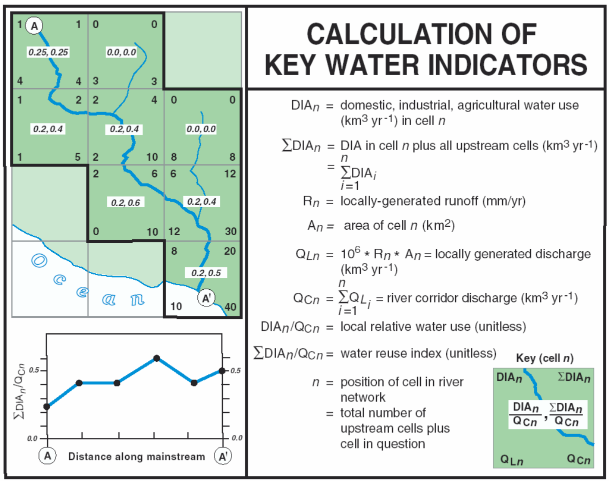

Figure 1. Calculation scheme for key water stress indicators with application to a hypothetical gridded drainage basin/river corridor system.

3. WATER SCARCITY INDICATORS

3.1 Climate Moisture Index and Variability

The Climate Moisture Index (CMI) is an aggregate measure of potential water availability imposed solely by climate. Most of Africa's continental area, 82%, is associated with a negative CMI, indicating that potential evapotranspiration exceeds precipitation over the long term. The corresponding global total is 54%, a fact that highlights the much drier conditions across Africa. The median CMI value globally ranges from –0.10 to –0.25 while for Africa it is less than –0.75. Africa is thus a dry and relatively water-scarce continent. However, it is the distribution of the CMI and its variability together with population that more accurately defines water scarcity.

Figure 2 shows the coefficient of variation (CV) in the CMI. CV is computed as the ratio of the standard deviation to the average of the time series analyzed. In this figure, pink to purple represents the CV associated with wet conditions (positive CMI) and yellow to brown represents CV associated with dry conditions (negative CMI). Note that large areas in the wettest (central Congo Basin) and driest regions (Sahara and southwestern Africa) are characterized by relatively low variability. Much higher variability, and hence potential vulnerability to water stress, is evident in the transition zone between the humid tropics and arid regions. These transition zones show sharp spatial gradients. Good examples of this are the east-west band characterizing the Sahel where the CV increases from low (CV<0.25) to high (CV > 0.75) over a distance of only 100 to 250 km in some areas. Mountain effects invoking sharp gradients in precipitation are evident as well, as for the Katanga and Rift Valley regions in central eastern Africa, the Ethiopian Highlands, and in Madagascar.

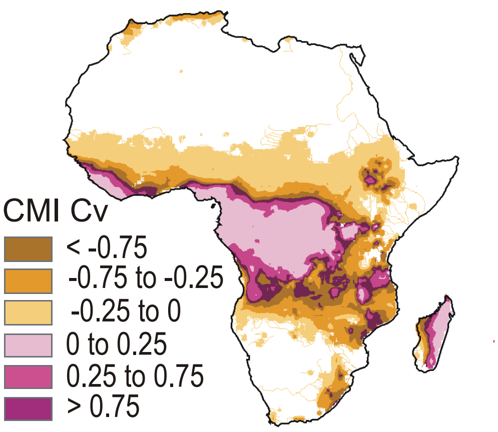

Figure 2. The coefficient of variation (CV) in *CMI*, pink to purple for positive CMI and yellow to brown for negative CMI. Shading denotes increasing degrees of variability and applies to zones of both positive and negative *CMI*. A 35-year time series was analyzed

Approximately 75% of all Africans live in the arid and semi-arid regions of the continent (CMI < 0). Globally the proportion is much smaller, only 52%. Twenty percent of the African population lives within areas that experience high interannual climatic variability as expressed by a CV of CMI >0.75. 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 land mass (75%) and population (60%) are located in areas of low variability (CMI < 0.25) suggesting that the population of Africa is thus distributed in a manner that reduces its overall exposure to climate extremes.

3.2 River Discharge and Variability

Local runoff supplies human settlements and irrigated agriculture with a potentially important source of renewable water. However, a more complete picture must consider how river corridors focus spatially-distributed runoff into discharge (Vörösmarty et al., 2000a). On the one hand, the overall pattern of discharge reflects the fact that most of the runoff-generating areas of the continental land mass reside originally as small streams which later coalesce into larger river corridors (Vörösmarty et al., 2000b). This points to the importance of local runoff and its variation in defining access to and reliability of renewable freshwater resources. On the other hand, river corridors play an essential role in transporting accumulated runoff into areas with little or no access to local renewable freshwater resources, as in the case of the Nile, the Orange and the Niger. River corridors can also act as a buffering agent against natural climatic variability, except where the bulk of the drainage basin resides in arid zones, as for the Orange River. Where major rivers are absent, the highest variability in annual discharge again falls along the transition zones between humid and arid regions as well as across mountainous areas.

With regard to water resources, more than 60% of the population of Africa lives with mean annual runoff of approximately 300 mm yr^{-1} or less and about 40% live with less than 100 mm yr^{-1}. Only about 10% of Africans have access to abundant river corridor discharge (defined here as Q >10 km^3/yr), indicating that the vast majority of the population must rely on local runoff and small streams and rivers, as well as deep groundwater stores, to meet their water needs. Fully one-half of the total population lives in association with limited river corridor flow (defined here as <0.1 km^3/yr), and its relatively high interannual variability in discharge. More than one-third of the African population is exposed to both limited quantities of discharge and high interannual variability (CV > 0.75).

Even in otherwise water abundant areas, seasonality (intra-annual variability) can severely limit water supplies. Relevant measures of seasonal variability are the ratios of maximum-to-minimum runoff (max:min RO) and maximum-to-minimum discharge (max:min Q) over the climatological year. Max:min ratios serve as conservative measures of seasonal variability because they are undefined when the minimum runoff or discharge is zero. Intra-annual variability at the local scale is generally high relative to river corridor discharge due to the integrating effect of river basins and to impoundment. Both of these effects are embedded within the runoff and discharge data sets used in this study. For Africa, the median max:min RO ratio is 113:1 and the median max:min Q is 80:1, while for the globe**,** these ratios are 132:1 and 99:1, respectively.

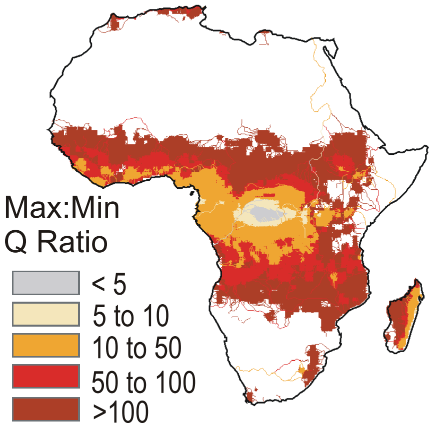

Figure 3. Ratios of the within-year maximum-to-minimum river discharge (Q). Geographic patterns are defined by the distribution of climate and its seasonality, the size distribution of river corridors, and river regulation.

These max:min ratios were computed from long-term mean monthly WBM runoff, from which discharge was derived by accumulating runoff along the simulated topological network (STN) and assuming a uniform channel velocity of 0.5 meters per second. After incorporating the effects of reservoirs, the median max:min Q ratio for Africa is reduced to 71:1. Even with impoundments, intra-annual variability of discharge in Africa is generally high. Figure 3 shows the spatial distribution of mean annual max:min Q ratios (including impoundments). Just as with the interannual variability (reflected in the CV), transitions zones between wet and dry climates show the most dramatic intra-annual fluctuations. Throughout much of these transition zones, max:min Q ratios are on the order of more than 100:1. Nearly 90% of the African population lives with a max:min Q ratio (representing intra-annual discharge variability) greater than 5:1. Only within humid tropical areas and along large, highly regulated rivers (i.e., the Nile and Orange Rivers) is the intra-annual variability low (max:min Q < 5). Coordinating these high seasonal contrasts with water supplies, in particular to the phenology of crop production, remains a major impetus for the construction of reservoirs over much of the world.

3.3 Human Water Demand and Water Stress

The accumulated sum of domestic, industrial and agricultural water demand can be expressed as a function of the CMI to begin exploring how contemporary water usage corresponds to the capacity of African climate to provide adequate supplies of renewable water. In general, agricultural water demand (over irrigated croplands) in Africa is an order of magnitude higher than domestic and industrial demand combined. In aggregate agricultural withdrawals essentially define total water use for the continent as a whole. As with the population distribution, much of African agriculture is embedded within a relatively dry continent, with about 65% of all cropland in areas where the CMI < 0. Water demand (predominantly for irrigated agriculture) is highest in the driest parts of the continent. As a consequence, irrigation water demands increase more or less exponentially with a decreasing CMI. For instance, in the combined areas with CMI < –0.8, irrigated croplands comprise 97% of total agricultural land and total water use (56 km^3/yr) exceeds local discharge (5 km^3/yr) by more than an order of magnitude. This is precisely the same area where local water availability is low or non-existent. Undoubtedly, much of this water use is unsustainable. The implications are clear: irrigation is being pursued aggressively in precisely the regions that can least sustain it.

More than 25% of the contemporary African population experiences high relative water stress (*DIA/Q* >0.4). Despite the overwhelmingly dry conditions for Africa documented above, surprisingly, most of the African population (66%) lives under conditions of relative water abundance, at least as measured by mean annual *DIA/Q*. In fact, the distribution for Africa is not much different than for the rest of the world. Total water use is less than would be expected given the "natural" water demands placed on Africa arising from its position as one of the driest continents. However, such modest use does not necessarily indicate the absence of water problems. A broad spectrum of socioeconomic problems reflects this low level of water usage. Lack of water infrastructure and poor delivery systems translates into public health problems as well as limits to private sector growth.

Water availability, demand and potential stress also vary by season. We evaluated seasonal water stress (*DIA/Q* > 0.4) on a monthly basis. Domestic and industrial demands were assumed to remain constant throughout the year, however agricultural demands (irrigation) can vary greatly by season. We computed the monthly water stress index (DIA_i/Q_i where *i* represents the month) and summed the number of months in which this index exceeded the water scarcity threshold of 0.4. Figure 4 shows an apparent bifurcated pattern of persistent water stress, with nearly 200 million (M) people exceeding the threshold for more than 10 months per year. In contrast, nearly 400M show no monthly water stress.

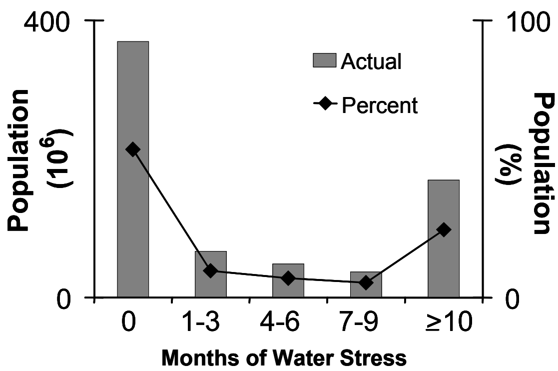

Figure 4. Persistence of seasonal water stress (*DIA/Q* > 0.4). Populations dependent on local runoff and living in transitional zones in the arid/semi-arid zone are most at risk. River corridor flow dampens the seasonal variability and reduces the duration of water stress.

The mapping of seasonal variability supports the geographic patterns of stress developed in previous sections. People living in transition zones (i.e. the Sahel) and on the fringes of desertic regions suffer the most seasonal water stress, despite improved access to river discharge for those living on floodplains and deltas. This access is particularly important in accurately describing water stress along arid river corridors, as in the example of the Nile River (Figure 5). Ignoring river corridor access, the majority of people living on the Nile delta and along the floodplains would appear to be suffering from water stress throughout the entire year. However, by incorporating simulated floodplains and deltas into our analysis, the picture is closer to what we know to be the real situation. This algorithm was applied to all rivers, but the most dramatic corrections were along the Nile River.

Our analysis shows that, using a traditional measure of relative water demand, the majority of Africans are not under severe water stress. However, our results are based solely on water use as related to it natural availability. We do not account for other equally important factors, such as the lack of access to clean drinking water and sanitation facilities, factors that reduce the amount of water actually available for human use. In fact, even though considerable improvement in access occurred during the 1990's, only 62% of the African population had access to improved water supply in 2000, giving it the lowest total water supply coverage of any region in the world. This lack of access is much worse in rural areas, where coverage is only 47%, compared to 85% in urban areas (WHO/UNICEF, 2000).

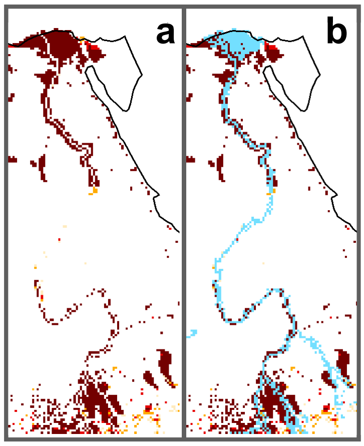

Figure 5. Water stress of populations living along the Nile River appears more extensive if access to river discharge within floodplains and deltas is ignored (a). Dark brown indicates water stress (DIA/Q>0.4) for 10 months or more. Simulating such access shows that water stress is greatly reduced within floodplains and deltas (b). Blue indicates simulated floodplains and delta areas.

4. CONCLUSIONS

The study reported here has applied a series of spatially-resolved data sets depicting the biogeophysical and socioeconomic properties of the African continent. We, as others, have found that Africa is a relatively dry continent. Associated with this dryness is a highly dynamic water cycle, providing a large degree of variability in terms of climate, runoff and discharge. A significant fraction of agricultural land and human population is located in regions of low runoff and high variability. Hence, agricultural water demand defines the aggregate water use for the continent. These characteristics of human-water interactions, in turn, provide challenges to the water infrastructure of the continent, and we have seen evidence that the continent may be experiencing curtailed use of water, relative to its high demands.

Biogeophysical data sets, emerging rapidly from the earth systems science community, can make important contributions to emerging water resource assessments. Our analysis indicates that both biogeophysical as well as socioeconomic indicators will be necessary to map the patterns and intensities of water scarcity. Interdisciplinary study is thus an important component of future research.

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