Water and Economic Development: The Role of Interannual Variability and a Framework for Resilience

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ABSTRACT: We advance the hypothesis that the seasonal and inter-annual variability of rainfall is a significant and measurable factor in the economic development of nations. An analysis of global data sets reveals a statistically significant relationship between greater rainfall variability and lower per capita GDP. Having demonstrated the role played by rainfall variability in reducing GDP, we construct a water resources development index that highlights areas that have the greatest need for storage infrastructure to mitigate the impacts of rainfall variability on water availability for food and basic livelihood. The countries with the most critical infrastructure needs on this metric are among the poorest in the world and a majority is located in Africa.

Keywords: economic development; water scarcity; climate variability; infrastructure; water policy

1. Introduction

Studies of the causes of disparity in the level of economic development between the wealthiest countries and the poorest have all overlooked a fundamental factor that differs between these sets of countries: the availability of water. The amount and temporal variability of rainfall, in particular, presents challenges to food production, trade and infrastructure development. Rainfall variability is most prominent in the least developed parts of the world, yet it has not been considered explicitly in previous studies of economic development. Studies of geographic effects on economic development have used coarse surrogates for the "tropical effect" that do not directly capture the climatic causes of underdevelopment (Rodrik, et al., 2004; Sachs, 2003; Easterly et al., 2003; Masters and McMillan, 2001). Promoters of the primacy of institutions then use these same coarse factors to prove their irrelevance. Within this literature, only Sachs (2001) has argued for more nuanced measures of the tropical effect, but rainfall variability was still overlooked.

Several studies have found institutions, broadly defined, as the most significant variable explaining the discrepancy between the economic development of nations. Easterly and Levine (2003) use the average of six institutional measures from Kaufman, et al., (1999a, b) settler mortality, religion and linguistic diversity, and as geographic variables latitude and binary variables for landlocked countries and the presence or absence of several crops and minerals in a regression model of log per capita income. They find that institutions dominate the other variables and that geography, as they parameterized it, influences through its effect on institutions. Acemeglou et al. (2000) uses settler mortality rates as an exogenous measure of institutions and arrives at similar results. Climate enters in the form of temperature highs and lows, and humidity highs and lows, which are statistically insignificant. Finally, Rodrik et al. (2004), in a very comprehensive study that follows the methodology of previous efforts and incorporates several tests of robustness, finds again that the quality of institutions is the most important explanatory variable and that geography as measured by their preferred instrument, distance from the equator, does have an effect, albeit weaker.

Many other studies argue in favor of the significant impact of geography (Sachs, 2001; Masters and McMillan, 2001; Olsson and Hibbs, 2000; Mellinger et al., 1999; Gallup et al., 1999; Diamond, 1997). Sachs (2001) described the tropical disadvantage in agriculture due to poor soils, the presence of pests and parasites, higher crop respiration rates due to warmer temperatures and difficulty in water availability and control. However, studies investigating the impact of geography have not included any measure of water availability in general or water variability in particular. Sachs (2001, 2003) argues that measures of geography must be more nuanced than simply distance from the equator, a favorite choice of some authors (Rodrik et al., 2004). Accordingly, the use of percent population within Koeppen-Geiger ecozones (see Geiger and Pohl, 1954) categorized as tropical or temperate is probably the best representation of climate as an independent explanatory variable within this literature. No previous cross-country analysis includes the temporal variability of rainfall, a fundamental factor in the tropical effect.

Recent country-level studies suggest the impacts of hydrology and rainfall variability on economic development are significant (World Bank, 2004; 2006). In Ethiopia, a study using an economy-wide model that included hydrologic variability effects found that the occurrence of droughts and floods reduced economic growth by more than one third (World Bank, 2004).

Losses in Kenya due to flooding associated with El Nino in 1997-98 and La Nina drought in 1998-2000 caused annual damages ranging from 10 – 16% of GDP during this period. Interestingly, the majority of damages were not incurred by agriculture. Transport losses represented 88% of flood losses and foregone hydropower and industrial production totaled 84% of the drought losses (World Bank, 2006).

Many parts of the world experience a large degree of intra-annual rainfall variability. This is typical of the tropics, marked by the cycle of wet and dry seasons; too much water in one season followed by too little in another. The impacts on economic activity are widespread. A concentrated season of heavy rainfall can inundate the means of transportation, limiting trade potential and communication as well as flooding homes and offices. The rainfall in a typical wet season exceeds the infiltration and storage capacity of soils and a large portion is lost as runoff. Flooding rivers, inundated roads and landslides in mountainous regions hinder movement, transport and trade. In the dry season agriculture is constrained by lack of water and high temperatures. An extended dry season may prohibit crop production and reduce the flow of surface waters that could otherwise provide irrigation, navigation and hydroelectricity production. Rivers flow only seasonally. Aquifers can be tapped throughout the year, but the required well boring technology is a recent development.

Living in these areas, one can expect to receive all the year's rainfall in a spell of about 4 months. Agriculture is tuned to this rhythm, planting crops to coincide with the arrival of the rainy season. Farmers in monsoon climates that are marked by a distinct transition from dry to wet seasons face difficult decisions regarding when to plant their crops. Plant too early and the seeds may not germinate without adequate rain; plant too late and the wet season may end prior to the end of the crops' growth. Farmers in areas with less variability in the annual cycle of rainfall do not face this decision. This sensitivity to the timing of the arrival and departure of the rainfall season is unlike methods used in regions where rainfall is more equitably distributed throughout the year and where the more gradual progression of temperature is the key variable. As Sachs (2001) described, difficulty in food production may have been a key factor in the slower economic development of the tropics.

Interannual variability, i.e., large differences in the annual total of rainfall, may be caused by quasi-periodic phenomena such as the El Nino/Southern Oscillation (ENSO), or longer-term climate shifts such as those that caused the Dust Bowl in the American Midwest during the 1930s and drought in the African Sahel since the 1970s. The economic impacts of such events are well documented. In the United States, until recently drought was the most costly form of natural disaster, averaging $6-8 billion annually (FEMA, 1995). Globally, drought is the largest single cause of deaths due to natural disasters, accounting for approximately 50% of the total (World Bank, 2005). The tropics experience the strongest effects of ENSO. Since many tropical areas receive rainfall in a single season, a "failure" of this wet season can leave a country dry for over a year – a significant setback in any agricultural country. The World Bank study of the Ethiopian economy found that a single drought in a 12 year period reduced economic growth over those 12 years by 10% (World Bank, 2004). Therefore, countries with high intra-annual variability (rainfall concentrated in a single season) and interannual variability (typically symptomatic of ENSO or longer term climate shifts) can be expected to lag in economic development. Furthermore, these countries typically lack the most common industrialized country response to hydrologic variability, water storage infrastructure.

In the last century the most prominent response to drought and dry season water scarcity was the construction of dams. Dams also provide flood control and can assist navigation. Toward the end of the century a reevaluation of the benefits and costs of dam construction and a lack of suitable locations led to a consensus shift away from this approach (World Commission on Dams, 2000). Management alternatives and efficiency improvements, including the adjudication of water rights, privatization of water supply companies, development of water markets, and investment in water saving technology, were heralded as the preferred methods for solving water scarcity issues. In nations' that lack water infrastructure such recommendations have been received with skepticism. The debate between the need for investment in infrastructure and investment in stronger water institutions continues. One may consider it an extension of the debate described above, where the demand for infrastructure mirrors a "geography" argument for the cause of water scarcity and improved water management represents "institutions."

These arguments have not previously accounted for the role of climate variability and its impact on the performance of infrastructure or management initiatives. Similarly, several studies have addressed the question of present and future water scarcity without considering variability. Postel et al. (1996) estimated present water usage to be 54% of accessible runoff and could rise to over 70% by 2025 due to population growth. Vorosmarty et al. (2000) assessed the relative impacts of climate change and population growth on global water resources using output from general circulation models and annual figures for water demand and availability. The results indicate population growth and economic development assumptions trump the potential impact due to climate change on water resources. Falkenmark (1997) found the water needed for agriculture to support future populations to be lacking in parts of Africa and Asia.

Annual averages of rainfall, as used in the above studies, mask the actual availability of water, and especially the seasonality of rainfall. If the water were to fall equally throughout the year, as is the case in Europe and North America, these would characterize the level of water scarcity actually faced. However, in many parts of Africa, Asia and South America, water arrives in excess amounts during a rainy season and then departs leaving regions dry for months. Therefore, evaluating the proper response to water scarcity requires a country-by country approach that incorporates the variability of rainfall and distinguishes between water scarcity due to shortages in mean climate conditions and that due to variability. Here we suggest water scarcity that is due to mean climate shortages should be solved through water management and institutional measures, while scarcity due to variability often requires additional storage. Possible water management responses to climate variability include the use of economic instruments to mitigate the risk of vulnerable groups and early warning systems based on the use of interannual and seasonal climate forecasts (Lenton, 2002).

In this study we do not evaluate institutions versus geography or climate, but rather attempt to demonstrate that climate variability in the form of rainfall variability is a significant factor in economic growth, and importantly, one whose impacts could in many cases be mitigated. The analysis explored the hypothesis that the amount and the variability of rainfall were significant factors in the development of early agricultural economies and contributed to the differences in the wealth of nations in the early 19th century that has grown to the wide spread in national wealth now measured. Using selected statistics of rainfall and a binary variable that accounts for war, approximately 60% of the variance in per capita GDP across countries is explained. We also suggest approaches for achieving resilience to this variability through an investigation of whether water storage is needed to meet food needs, or whether improved efficiency or trade in water is needed, at a country level.

The hypothesis of this paper is that climate variability is important and translates directly into the need for water infrastructure as a key factor in global development. We use global datasets of rainfall, temperature and per capita GDP to reveal the role of rainfall variability in the economic well-being of nations and to prescribe appropriate responses at the national level to achieve resilience. We propose that (1) rainfall variability is a key factor explaining the geographic influence on national wealth and (2) appropriate methods for achieving resilience to water scarcity must incorporate the stochastic properties of rainfall in addition to the usual measures of average supply and demand. We test the first hypothesis using multivariate regression to model the variation in cross-country GDP growth data and develop the second by assessing the reliability of water availability on a national basis relative to demand, accounting for seasonal and interannual variability in rainfall. This analysis produces two indices, the "hard water" need, representing water demand that can be met through construction of reservoirs, and the "soft water," need, representing the volume that could be gained through management methods or trade. This terminology echoes that of Gleick (2002) and others and was introduced to promote policy and conservation as alternatives to traditional infrastructure investments. The data used for this analysis consist of a gridded (2.5° x 2.5° cells) global dataset of monthly temperature and rainfall, the NOAA Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP)

(Xie and Arkin, 1996), GDP data for 1979 – 2004 from the UN online statistical database and food crop data from the FAO online database Aquastat.

2. Analysis

2.1. Climate and GDP – A Regression Analysis

A regression model was developed to explore how per capita GDP (average value of 1979 – 2004) of nations may relate to a suite of climate attributes. Factors considered included mean annual temperature, mean annual precipitation, intra-annual rainfall variability, interannual rainfall variability and the spatial variability of rainfall within the country. In addition, a binary index was used to identify whether a nation had experienced a major war or revolution over the 25 year period of analysis.

Intra-annual or seasonal variability is defined through a "normalized" spread of average monthly rainfall over the year. Formally, this is defined as the coefficient of variation (CV) of 12 average monthly rainfall values for the country, defined as $CVM_k = \frac{\sigma(\overline{P}_{j,k})}{\mu(\overline{P}_{j,k})}$; i.e. as the ratio of the standard deviation of calendar month average rainfall to its grand mean across all calendar months. Figure 1 shows the global distribution of intra-annual rainfall variability as measured by the coefficient of variation of monthly rainfall calculated on a grid cell basis. India and Pakistan, sub-Saharan, eastern and southern Africa, Mexico and parts of Australia are prominent.

The second measure of temporal variability we discuss is interannual variability. This corresponds to the degree to which the total annual rainfall for a country differs from year to year. This measure is defined as $CVI_k = \frac{\sigma(P_{t,k})}{\mu(P_{t,k})}$ where $P_{t,k}$ is the total annual rainfall in year t for country k. Figure 2 shows the global distribution of interannual rainfall variability as measured by the coefficient of variation of annual rainfall totals. Higher values indicate areas that experience large variations in the total amount of rainfall received relative to the average amount received. When the total annual rainfall is much less than is expected, regardless of the absolute magnitude of rainfall, an area will likely suffer from a possible water shortage, i.e., drought. Where the CVI is high droughts are more frequent. Familiar cases stand out, such as the Greater Horn of Africa, where drought has spawned famine in Ethiopia and perhaps ethnic strife in Sudan, and the Sahel region of western Africa, where the decline in rainfall has been well documented. The Nordeste of Brazil, one of the poorest regions of the country, also bears the mark of strong interannual rainfall variability. Mexico, Australia, Argentina, Pakistan and southern Africa also exhibit high *CVI* values.

Spatial variability of rainfall within a country was computed as $CVS_k = \frac{\bar{\sigma}(P_{n,k})}{\mu(\bar{P}_{n,k})}$ where $\bar{\sigma}$ is the average of all months of the spatial standard deviation over n grid cells for each country. This variable indicates the degree to which the two previous statistics are representative of the country as a whole or whether there are large differences within the country. The full regression model is presented in Table 1.

The statistical significance and fraction of variance explained with this model are comparable to those of previous efforts, which relied on endogenous variables such as the strength of institutions and the rule of law (Rodrik et al., 2004). The most important variable was CVM , supporting the notion that intra-annual rainfall variability presented a significant challenge to early agriculture. Next in significance was the interaction term between interannual variability (CVI) and spatial variability (CVS). This is likely due to the effects of extended droughts on economic activity and rural livelihoods. Interannual variability is not statistically significant on its own, likely due to the varying sizes of nations and the smoothing induced by taking spatial averages of rainfall for entire nations. Graphical analysis presents an enhanced view of the complex relationship between these variables. Figure 3a shows that well off countries tend to have lower CVM and moderate annual rainfall averages, while the less well off have higher CVM. Figure 3b indicates that the most well off countries have low values of CVI while less well off countries may have high or low CVI. The figures indicate a climate of low CVI, low CVM and moderate rainfall favors prosperity. These results are consistent with the hypothesis that rainfall variability is a determining factor in economic development.

2.2. Water Storage Development vs. Efficiency Need Screening

Addressing water scarcity is a major challenge of this century (Postel et al., 1996; Falkenmark, 1997; Vorosmarty et al., 2000). There has been much debate on the appropriate approach to solving water scarcity, notably between the viewpoints supporting improved water management efforts and those arguing for greater infrastructure development, including dams. The preceding analysis demonstrates that mean annual precipitation and intra-annual variability are the dominant hydrologic factors for per capita GDP growth. Water policy responses intended to engender economic growth at the lowest fiscal and environmental cost will benefit from discerning between the causes of water shortages and the appropriate response. Where the cause is intra-annual variability, storage is needed to transfer water from wet seasons to dry seasons. Alternatively, where water shortage is due to lower than needed mean annual precipitation, efficiency gains or alternative water sources, including the importation of virtual water, are the preferred option.

In this section, we calculate the water storage requirement and water efficiency needs on a country-by-country basis and identify those that are most in need of action. The calculations are performed using rainfall and agricultural data and some simple assumptions to develop a framework for identifying which approach is favored in each country analyzed. The model is described fully in the Appendix. We proceed by (i) estimating water demand on a national basis, (ii) calculating the intra-annual water balance, (iii) calculating the annual water balance, and (iv) using these numbers to calculate the water storage requirement ("hard water") and water efficiency needs ("soft water") for each nation. In general, if the estimated annual demand exceeds the average water availability in a year, the shortfall should be met through soft water. Alternatively, if there is sufficient water on average, but the seasonality or interannual variability cause shortfalls during certain months or years, then storage can transfer excess to the needed time periods and thus hard water is needed.

National water requirements were calculated as the amount needed to feed a country's population on an annual basis. This allows a calculation of water demand that is independent of water use efficiency and socioeconomic status. Annual per capita water demand for each nation based on food requirements was calculated using standard assumptions for caloric need, crop water requirements and yield data for each nation. Since the vast majority of water resources are used for the evapotranspirative needs of crops, both rainfed and irrigated, the food requirement represents the bulk of a nation's water needs.

The intra-annual (i.e., seasonal) water balance for each nation was calculated based on the average annual cycle (average monthly precipitation for each month) of precipitation. The storage requirement is then calculated as the volume needed to transfer water from wet months to dry months. This volume is termed the seasonal storage index (SSI). Nations with positive values of SSI are listed in Table 2 and shown in Figure 4.

Each nation listed here needs water during dry seasons and has water available to be captured during wet seasons. Storage additions could come from surface water reservoir development or groundwater development, both of which have economic and ecological consequences. Of the 23 nations on the list, 14 (61%) are located in Africa.

Almost half the countries in Figure 4 can achieve their water needs solely through constructing seasonal storage. We designate this volume as "hard water" and water gained from efficiency and trade as "soft water." The average GDP of countries with hard water requirements is US$ 601. In contrast, the GDP of countries with soft water needs is US$ 8,477. Soft water represents the water need that exceeds the volume that can be captured from internal renewable water resources. Soft water may be created through improving the productivity of water, or importing water via virtual water (Allan, 1993). Nations that lack water supply can relieve water scarcity through the import of water-intensive products. Barriers to virtual water include trade restrictions, subsidies and an inability to afford imports. Security incentives for self-sufficiency in food supply and other political incentives may also preclude water importation. In fact, in some cases water scarce countries export water. The value of exports may justify it. At the minimum, a comparison of the value of water in exports versus the opportunity cost of water in competing demands should be computed. Table 4 lists the soft water needs of each country. Soft water requirements include a current estimate of net virtual water exchange (Ramirez-Vallejo and Rogers, 2004).

The correlation between the percent of estimated storage requirement achieved and GDP is 0.55 for countries requiring hard water. The difference in strategies appropriate for building resilience to water variability in wealthier countries has implications for the less wealthy countries. The construction of infrastructure creating hard water is often funded through development aid from wealthy nations. The soft water strategies that are needed in these countries may influence funding toward soft water strategies in countries receiving aid. In many of these nations, such as listed depicted in Table 2, hard water strategies may be more appropriate.

Water availability is subject to interannual variability in addition to the intra-annual variety that is considered above. Accordingly, we calculate the required storage to satisfy drought year deficits by capturing surpluses in other years using 1979 – 2004 rainfall data. The water deficit or surplus for each year of the record was then used to calculate the storage required to provide water during droughts using the mass curve method (McMahon, 1993). The required storage for mitigating droughts depends on whether droughts tend to be single or multi-year. Both the maximum one year deficit as well as the maximum cumulative (consecutive year) deficit were calculated. We designate the larger volume as the interannual shortfall index (ISI).

Figure 5 shows the nations with positive values of the ISI, meaning they experience annual deficits due to interannual variability. Table 3 lists the ISI volumes and as a percent of average annual precipitation. This provides an indication of the storage needed to provide water during single or multi-year droughts. The average GDP of these nations is $3443, however the median GDP is $853, showing the impact of interannual variability and the lack of ability to achieve resiliency in these countries without foreign assistance. Some of the deficits listed in Table 3 are very large in comparison with the annual average rainfall and the indicated nations should probably meet their deficits with soft water methods. For purposes of comparison, the largest total reservoir storage for single river basins in terms of percent of annual flow is the Volta River (428%) and the Colorado (250%) is the largest in North America (Nilsson et al., 2005).

South Asia stands out as a water hot spot. It needs seasonal and inter-annual storage, as well as “soft” water. Given that this is a region with some of the highest population densities on the planet, and has high rainfall variability, this is not a surprise. The interlinking of rivers, an increase in storage projects, and rampant groundwater mining continue to be current concerns in the region. China faces similar concerns, but does not emerge in the same way in our country level analysis. A higher spatial resolution would likely reveal why the country has been embarking on the South to North transfer project and the Yangtze storage projects (to deal with intra- and inter-annual variability in rainfall).

3. Summary

This study tested the hypothesis that the economic development of nations was affected by the amount and variability of rainfall. This hypothesis follows the reasoning of Sachs that difficult conditions for early agriculture significantly impacted economic development. We propose rainfall variability as a critical factor in agriculture and in early economic development. The results of this analysis find interannual and intra-annual rainfall variability are significant variables that heretofore have been overlooked in analyses of the economic development of nations. To the extent that water infrastructure (irrigation systems, dams, groundwater wells) and policy (water rights, trading, efficiency incentives) can provide resilience to rainfall variability, these are heartening results.

The variability of rainfall has been overlooked when evaluating strategies for managing current water scarcity. The physical availability of water relative to domestic water demand was used to determine whether increasing water storage with investment in infrastructure (hard water) or increasing efficiency of water use (soft water) is appropriate on a country-by-country basis. These results indicate that there are several countries facing critical water stress with current capacity only a small fraction of estimated requirements. These countries are overwhelmingly poor. While the majority of these countries are located in Africa, where the general need for infrastructure is accepted, several, such as Haiti, Nepal and El Salvador, are not often mentioned. Investments in seasonal water storage could solve these water shortages but in many cases would likely depend on foreign aid. There are many more countries that should solve water shortfalls through water efficiency gains.

The results also suggest that wealthy nations typically require soft water while those requiring hard water tend to be less developed. Development aid may be unduly influenced by soft water strategies that are more appropriate at home than in recipient countries. This study does not address the costs or benefits of dam construction in general or in any particular country. The recipe to mitigate water scarcity for any individual nation should consider the specific effects of climate variability in that nation. *A priori* paradigms of management or infrastructure should be avoided.

Given the nature of our study, industrial and drinking water demand were not considered here. Drinking water needs are typically a small fraction of the agricultural need. However, where water supply is critical, we can anticipate failures for drinking water as well. This is seen in South Asia.

This study did not address shortages due to spatial variability of water, although it is indicated as a statistically significant factor in economic development. Both India and China have ambitious plans to address this issue through the linking of rivers. The results of this study are also dependent on the quality of the data, which are likely to have errors in areas with sparse observations. Nonetheless, we are surprised at the strength of the story and the clarity of the message of these results.

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List of Captions

Figure 1. Intra-annual variability of rainfall as measured by the coefficient of variation of monthly rainfall totals (CVM). Higher values, as seen in South Asia, Australia, and western Africa indicate large variability in month to month rainfall.

Figure 2. Interannual rainfall variability as measured by the coefficient of variation of annual rainfall totals (CVI). Higher values indicate areas where the annual rainfall total varies widely from year to year.

Figure 3. Scatter plot of mean annual precipitation ($\overline{P}$, x-axis), the coefficient of variation of monthly rainfall (*CVM*, y-axis) and the (a) inverse of per capita GDP and (b) per capita GDP (size of circle). Color is for the countries that rank in the bottom half (blue) of interannual coefficienct of variation (CVI) and that rank in the top half (red). In (a) it can be seen that nations with lower GDP (large circles) tend to have higher CVM than those with high GDP (small circles). In (b) it can be seen that most wealthy nations (large circles) tend to have low CVI (blue). The three nations with high CVI, high CVM and high GDP (large red circles in figure b) are the small oil producing states Kuwait, Oman, and United Arab Emirates.

Figure 4. Countries with positive values of the seasonal storage index (SSI), reflecting intra-annual variability (CVM). Color shading indicates the current storage capacity of each country as a percentage of the estimated storage requirement. South Asia and west Africa standout.

Figure 5. Countries with positive values of the interannual storage index (ISI), reflecting interannual variability (CVI). Color shading indicates the magnitude of the requirement.

Figure 6. Soft water requirements. Highlighted countries have water requirements that should be met through soft water, i.e., improvements in water efficiency and increasing imports of virtual water. The presence of European countries is likely due to underestimation of the water use efficiency and current trade of virtual water in Europe.

Table 1. Regression results for predictors retained by bidirectional, exhaustive stepwise regression.

Table 2. Seasonal Storage Index (SSI). The seasonal storage index indicates the volume of storage needed to satisfy annual water demand based on the average seasonal rainfall cycle. The gdp's of countries lacking adequate storage in comparison to the SSI are notably low.

Table 3. Interannual Shortfall Index (ISI). The interannual shortfall index indicates the volume of the annual rainfall deficit in comparison to the annual demand for a given country. While storage may enable some countries to meet demand by holding over water from year to year, in the cases of India, Eritrea and Armenia, soft water methods recommended since deficits occur in more than 50% of the years and the shortfalls are very large in comparison to annual rainfall volume.

Table 4. Soft Water Requirements. These countries face water shortages that should be met through soft water methods, including policy reformation and conservation. In some cases, this is additional to estimated hard water requirements (infrastructure), and the percent of the total estimated requirement represented by soft water and hard water is listed.

Figure 1. Intra-annual variability of rainfall as measured by the coefficient of variation of monthly rainfall totals (CVM). Higher values, as seen in South Asia, Australia, and western Africa indicate large variability in month to month rainfall.

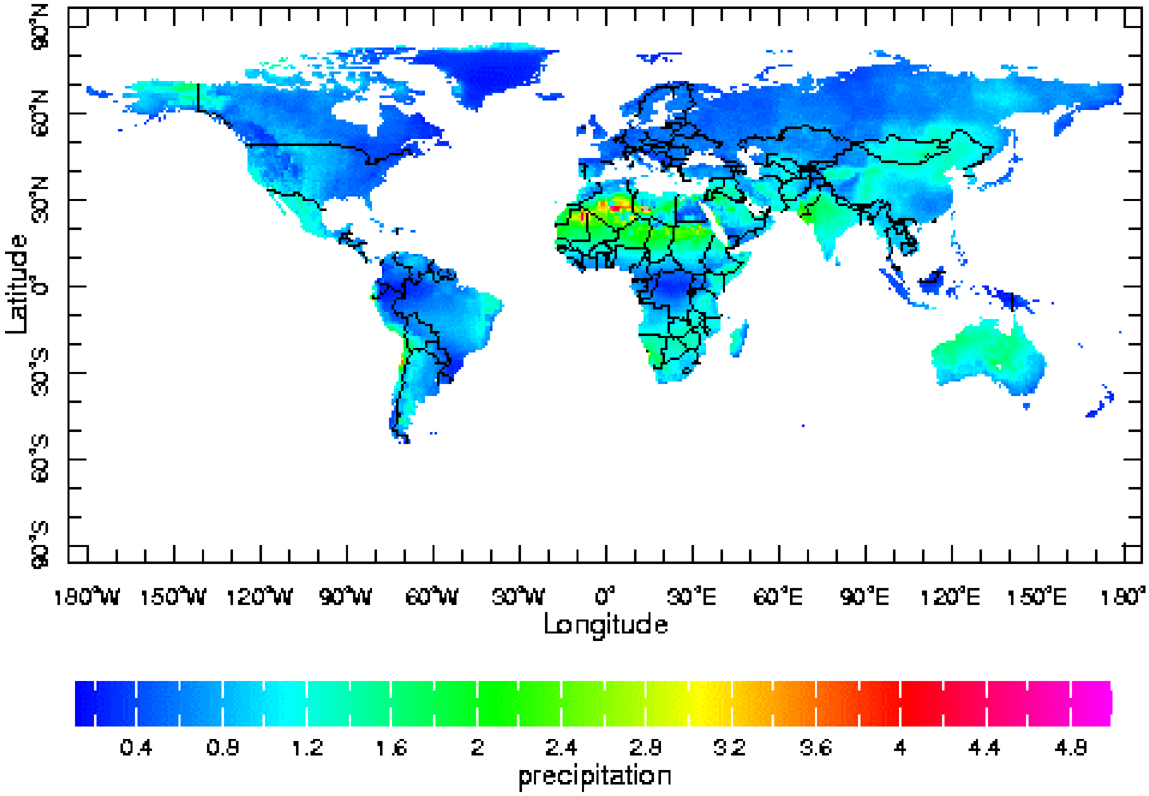

Figure 2. Interannual rainfall variability as measured by the coefficient of variation of annual rainfall totals (CVI). Higher values indicate areas where the annual rainfall total varies widely from year to year.

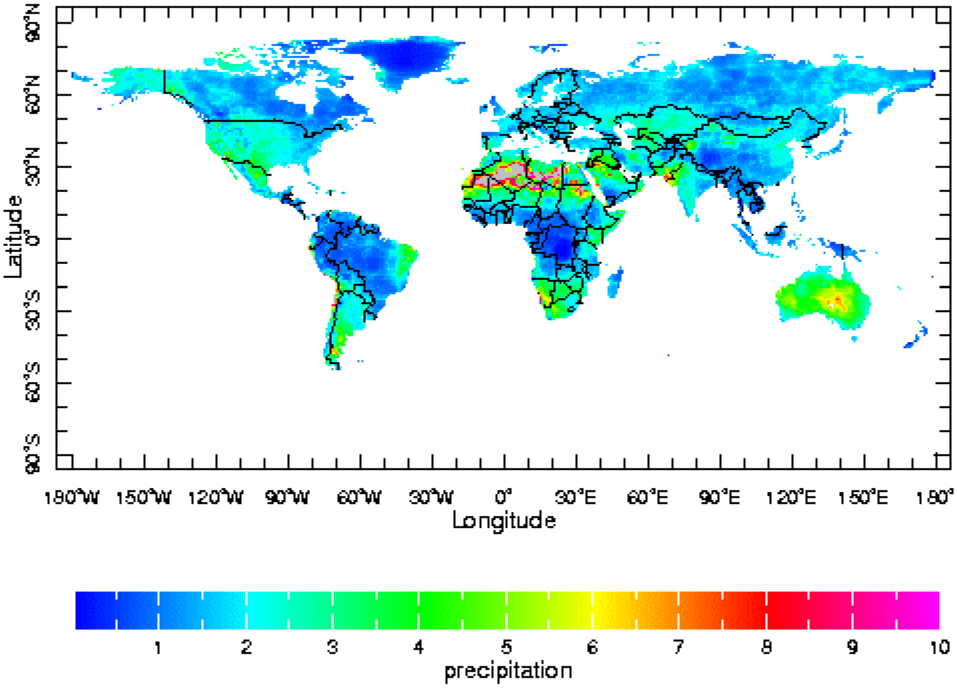

Figure 3. Scatter plot of mean annual precipitation ($\overline{P}$, x-axis), the coefficient of variation of monthly rainfall (*CVM*, y-axis) and the (a) inverse of per capita GDP and (b) per capita GDP (size of circle). Color is for the countries that rank in the bottom half (blue) of interannual coefficienct of variation (CVI) and that rank in the top half (red). In (a) it can be seen that nations with lower GDP (large circles) tend to have higher CVM than those with high GDP (small circles). In (b) it can be seen that most wealthy nations (large circles) tend to have low CVI (blue). The three nations with high CVI, high CVM and high GDP (large red circles in figure b) are the small oil producing states Kuwait, Oman, and United Arab Emirates.

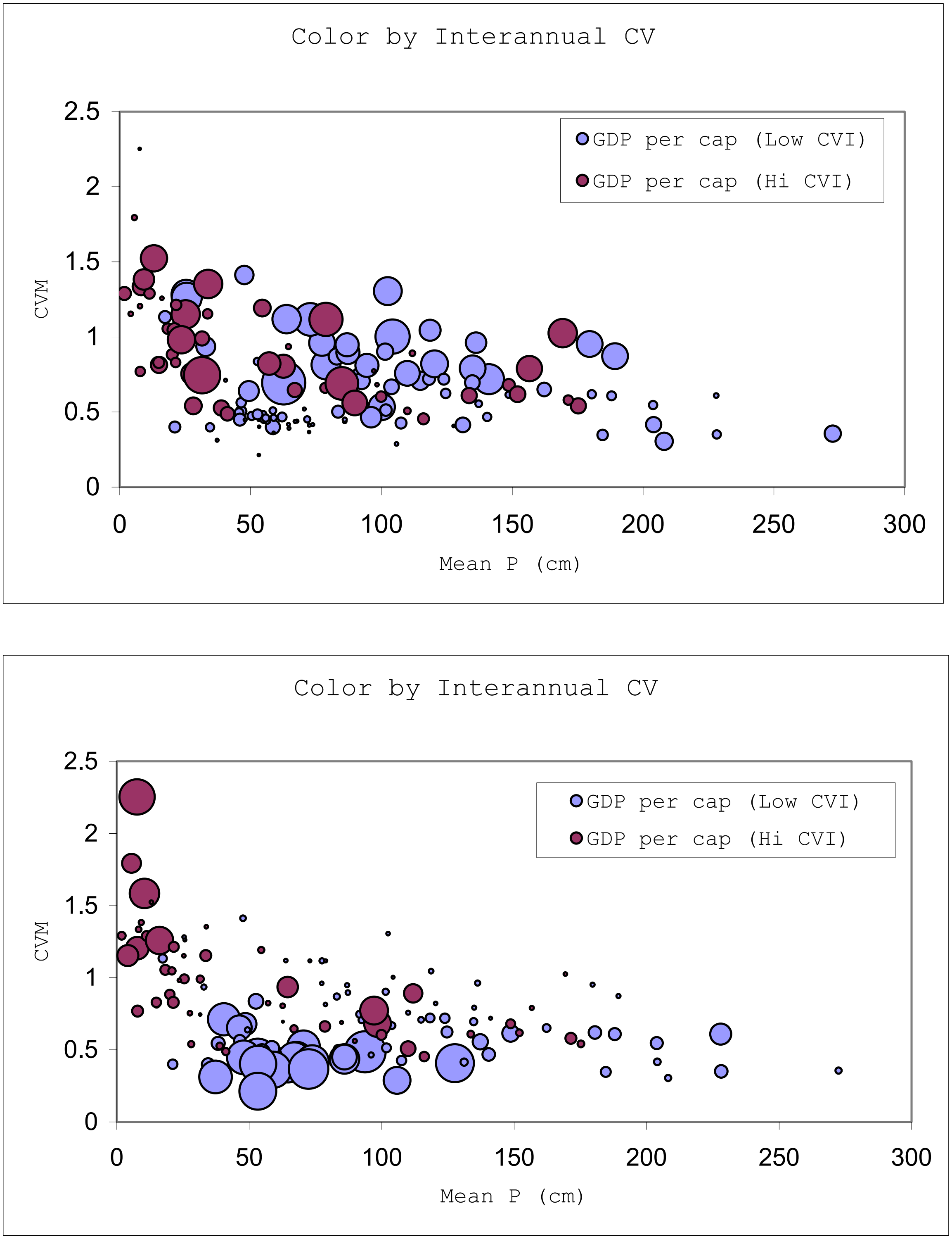

Figure 4. Countries with positive values of the seasonal storage index (SSI), reflecting intra-annual variability (CVM). Color shading indicates the current storage capacity of each country as a percentage of the estimated storage requirement. South Asia and west Africa standout.

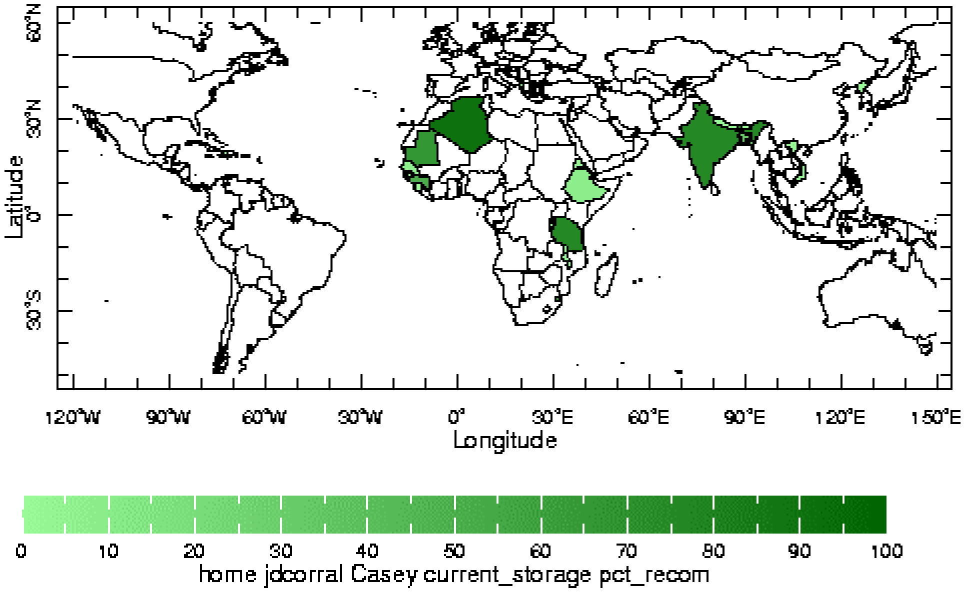

Figure 5. Countries with positive values of the interannual storage index (ISI), reflecting interannual variability (CVI). Color shading indicates the magnitude of the requirement.

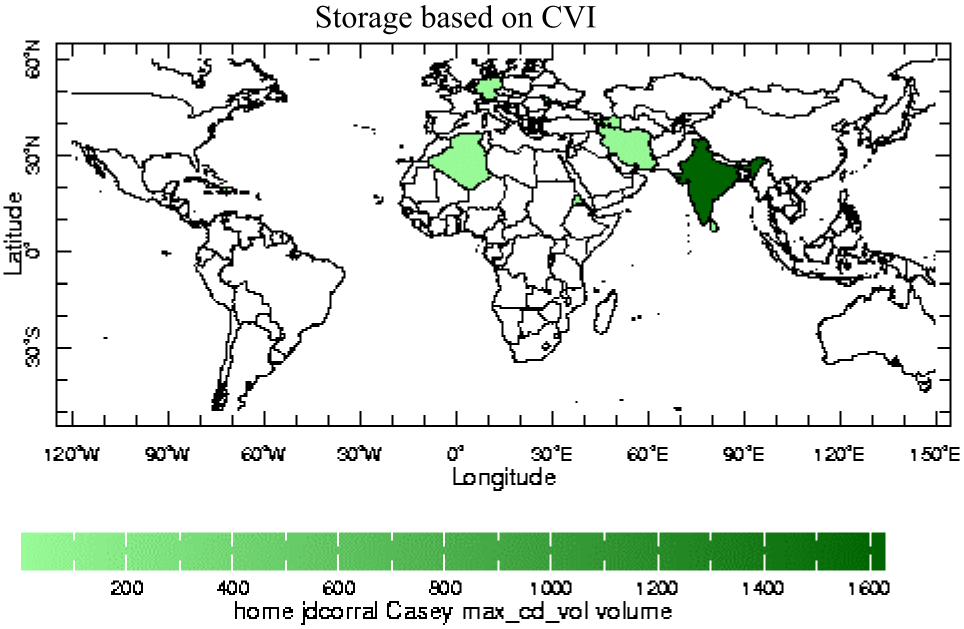

Table 1. Regression results for predictors retained by bidirectional, exhaustive stepwise regression

Regression Statistics	
R Square	0.52
Standard Error	1.03
Observations	163

Independent variable	*Coefficients*	*t Stat*	*P-value*
Intercept	11.41	24.44	0.0000
Mean Monthly Precipitation	-0.011	-5.67	0.0000
CV - Monthly Precipitation	-2.63	-5.87	0.0000
CV - Annual Precipitation	-0.14	-0.67	0.5
War/Revolution	-1.45	-7.26	0.0000
Spatial CV	-2.13	-5.02	0.0000
Interaction CV annual and spatial	0.523	4.15	0.0001

Table 2. Seasonal Storage Index (SSI). The seasonal storage index indicates the volume of storage needed to satisfy annual water demand based on the average seasonal rainfall cycle. The gdp's of countries lacking adequate storage in comparison to the SSI are notably low.

	Seasonal Storage Index (km3)	SSI as % of Annual Volume	% Hard Water (of total)	Current Storage (% of SSI)	GDP ($, 2003)
India	356.60	21%	17%	76%	555
Bangladesh	62.28	41%	40%	33%	385
Ethiopia	40.99	10%	100%	8%	91
Nepal	29.86	47%	100%	0%	233
Vietnam	27.64	10%	100%	3%	471
North Korea	23.32	45%	100%	0%	494
Senegal	22.30	40%	100%	7%	641
Malawi	18.98	34%	100%	0%	158
Algeria	6.60	6%	100%	91%	2049
Tanzania	5.50	1%	33%	76%	271
El Salvador	5.45	37%	100%	59%	2302
Haiti	3.73	25%	79%	0%	300
Guinea	3.71	2%	100%	51%	424
Eritrea	2.75	11%	15%	3%	305
Burundi	2.64	19%	27%	0%	86
Albania	2.64	23%	100%	21%	1915
Guinea-Bissau	2.48	11%	100%	0%	208
Sierra Leone	2.21	3%	100%	0%	197
The Gambia	2.14	56%	100%	0%	224
Rwanda	1.38	9%	3%	0%	185
Mauritania	1.34	2%	100%	66%	381
Swaziland	0.98	15%	100%	59%	1653
Bhutan	0.40	1%	13%	0%	303

Table 3. Interannual Shortfall Index (ISI). The interannual shortfall index indicates the volume of the annual rainfall deficit in comparison to the annual demand for a given country. While storage may enable some countries to meet demand by holding over water from year to year, in the cases of India, Eritrea and Armenia, soft water methods recommended since deficits occur in more than 50% of the years and the shortfalls are very large in comparison to annual rainfall volume.

	Interannual Shortfall Index (km^3)	Annual Water Available (km^3)	Shortfall as % of Ann Ave	% deficit years (1979-2004)	Current Storage (% of index)	Soft Water
India	1,630	1,704	96%	52%	17%	x
Eritrea	51	24	211%	56%	0%	x
Armenia	23	7	312%	68%	5%	x
Germany	21	138	15%	20%	20%	
Haiti	11	15	74%	32%	0%	
Algeria	10	113	9%	8%	46%	
The Gambia	0.58	4	15%	8%	0%	

Figure 6. Soft water requirements. Highlighted countries have water requirements that should be met through soft water, i.e., improvements in water efficiency and increasing imports of virtual water. The presence of European countries is likely due to underestimation of the water use efficiency and current trade of virtual water in Europe.

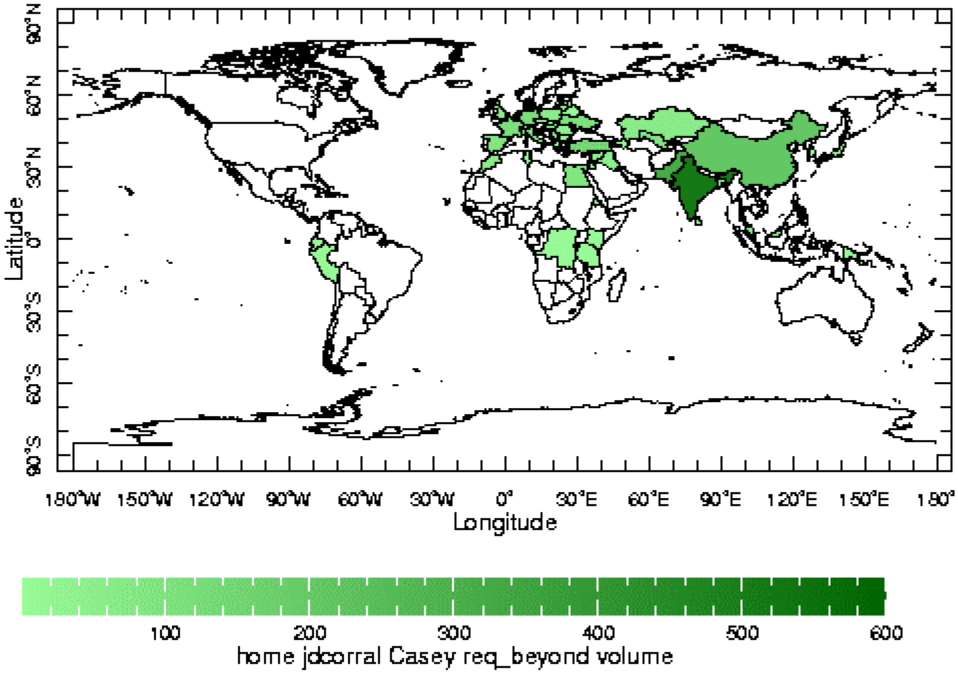

Table 4. Soft Water Requirements. These countries face water shortages that should be met through soft water methods, including policy reformation and conservation. In some cases, this is additional to estimated hard water requirements (infrastructure), and the percent of the total estimated requirement represented by soft water and hard water is listed.

	Soft Water Index (km3)	Virtual Water (km3)	Requirement beyond virtual water (km3)	% Hard Water	% Soft Water (of total need)
India	504.11	(9.06)	513.16	41%	59%
Pakistan	321.05	4.50	316.55	0%	100%
China	219.20	12.93	206.28	83%	17%
Turkey	146.79	7.37	139.42	0%	100%
Germany	121.50	8.38	113.13	0%	100%
France	114.33	5.26	109.07	0%	100%
Ukraine	84.84	(18.16)	103.00	0%	100%
Italy	97.83	9.04	88.79	1%	99%
Egypt	115.21	27.71	87.51	0%	100%
Uzbekistan	87.05	0.45	86.60	0%	100%
Spain	89.15	5.50	83.66	0%	100%
Bangladesh	70.68	7.36	63.32	50%	50%
Kazakhstan	57.54	(5.01)	62.55	0%	100%
Morocco	66.68	8.46	58.22	0%	100%
United Kingdom	65.51	10.67	54.84	10%	90%
Poland	52.00	(2.03)	54.04	0%	100%
Malaysia	4.62	(45.57)	50.19	0%	100%
Rwanda	47.40	0.12	47.29	3%	97%
Iraq	54.19	7.94	46.25	0%	100%
Syria	43.90	2.54	41.36	0%	100%
Romania	34.00	0.68	33.32	0%	100%
Yugoslavia	32.98	0.10	32.88	0%	100%
Japan	148.57	116.46	32.11	0%	100%
Hungary	15.54	(9.72)	25.27	0%	100%
South Korea	57.00	40.45	16.55	40%	60%
Eritrea	16.03	NA	16.03	15%	85%
Czech Republic	15.74	0.32	15.42	0%	100%
Bulgaria	13.76	0.15	13.61	0%	100%
Azerbaijan	14.64	1.08	13.55	0%	100%
Sri Lanka	14.19	2.26	11.92	0%	100%
Belgium	15.52	5.54	9.97	2%	98%
Kenya	11.31	2.80	8.52	0%	100%
Israel	14.93	6.82	8.12	0%	100%
Belarus	8.91	1.59	7.32	4%	96%
Jordan	10.94	3.90	7.04	26%	74%
Burundi	6.98	0.00	6.98	27%	73%
Tunisia	12.08	5.16	6.92	0%	100%
Moldova	6.76	(0.12)	6.87	0%	100%
Lebanon	7.41	1.31	6.10	3%	97%
Lithuania	5.95	0.21	5.74	0%	100%
Peru	9.27	3.56	5.71	0%	100%
Latvia	4.83	0.28	4.55	0%	100%
Armenia	4.75	0.25	4.50	11%	89%
Papua New Guinea	3.51	(0.78)	4.29	0%	100%
Greece	3.14	(0.76)	3.90	51%	49%
Slovakia	3.35	(0.47)	3.81	6%	94%
Denmark	7.01	3.28	3.73	0%	100%
Bhutan	2.7	NA	2.74	13%	87%
Tanzania	4.21	1.55	2.66	67%	33%
Ecuador	3.71	1.27	2.44	0%	100%
Congo, DRC	2.0	0.31	1.64	0%	100%
Macedonia	2.0	0.44	1.61	13%	87%
Switzerland	3.06	1.56	1.50	0%	100%
Haiti	2.6	1.62	1.01	79%	21%
East Timor	0.3	NA	0.28	0%	100%

APPENDIX

Regression

Regression variables were developed using global datasets of climate data and GIS analysis performed with the IRI Data Library.
Regression Model (evaluated Stepwise)
The spatial average of precipitation and temperature over a nation's borders was calculated using monthly totals. Mean monthly temperature ($\overline{T}_m$) and mean total monthly precipitation ($\overline{P}_m$), mean total annual precipitation ($\overline{P}_A$), the standard deviation of monthly total (σ_{P_m}) and annual total precipitation (σ_{P_A}) and finally the coefficient of variation on monthly (CVM), and annual (CVI) timescales and also the spatial coefficient of variation (*CVS*) were calculated for each country. An interaction term (*CVI*CVS*) between *CVI* and *CVS* was introduced due to the expected smoothing effect of averaging rainfall in large countries. These climate statistics were evaluated as explanatory variables for the log of mean per capita GDP over 1979 to 2004. The initial regression model listing each potential predictor is shown below. An index variable (*W*) was introduced to indicate countries that had experienced significant wars or revolutions during the 25 years of analysis, such as Iraq, Rwanda, and the former Soviet republics. The regression model summarized in Table S1 includes the 6 predictors retained after stepwise linear regression. Mean temperature, used to parameterize climate in previous studies (e.g., Masters and McMillan) is not retained, while the variables retained were mean monthly precipitation ($\overline{P}_m$), the monthly coefficient of variation (CVM), the annual coefficient of variation of rainfall (CVI), the spatial variation of rainfall (*CVS*), an interaction term between the CVI and the *CVS*, and the index variable for nations that experienced war or revolution during the 25 year period of analysis.

Table S1

Model: Log GDP = $\beta_i x_i + \varepsilon$
x_i: $\overline{P}_m \quad \overline{P}_A \quad \sigma_{P_m} \quad \sigma_{P_A} \quad CVM \quad CVI \quad CVS \quad \overline{T}_m \quad W \quad CVI*CVS$

Final Regression Model

Log GDP =	$\beta_0 +$	$\beta_1 \overline{P}_m$	$+ \beta_2 CVM$	$+ \beta_3 CVI$	$+ \beta_4 CVS$	$+ \beta_5 CVI*CVS + \varepsilon$
p value		(1.8×10^{-4})	(7.92×10^{-16})	(2.42×10^{-10})	(2.23×10^{-9})	(1×10^{-4})

Calculation of Water Demand

The water requirement is based on a 3000 kcal/day diet and an average nutritive value for cereal crops (wheat, rice, maize, barley, sorghum, rye and millet) of 3400 kcal/kg (FAO, Source: Aquastat online database, http://www.fao.org/ag/agl/aglw/aquastat/dbase/index.stm). An average water requirement for these crops of 550 mm/ha was used. Crop yield was specified by country using FAO data based conservatively on a low input scenario. The number of required growing seasons to meet annual national food needs was compared with long term average precipitation for each calendar month. Assuming a 4 month growing season, four consecutive months of rainfall above the crop requirement was counted as a season. The number of growing seasons required was calculated by dividing the annual national food requirement by the yield and then again by the area of cropland and assuming a 4 month growing season for cereals.

$$Seasons_i = pop_i \times Nutreq \times Nutval \times \frac{season}{yield_i} \times \frac{1}{crop\ area_i}$$

$$Demand_i = Seasons_i \times \frac{crop\_watreq}{season}$$

The calculation of water requirement on this basis reveals a trade-off between providing water for an additional growing season on existing cropland or converting non-cropland to agricultural uses. Since most arable land is already in production, the latter alternative poses dire consequences for the natural environment (Tilman et al., 2001). Lack of water availability may be an incentive for this potentially destructive livelihood alternative.

Calculation of Water Balance and Storage Requirement

The seasonal water balance (SB) is the difference of water needed per season to meet crop demands and the maximum total rainfall for a 4 month period. If the number of seasons with adequate water (on a monthly basis) exceeds the number of seasons required to feed the population, the amount of estimated storage or management/efficiency gain is zero. Otherwise, water storage or efficiency requirements are calculated.

The seasonal water balance is calculated by comparing the water demand to the four month (season) period with maximum available water. This is repeated for the number of seasons required by a nation. Positive values indicate excess water that may be stored. Negative values indicate water deficits; these may be met with excess water from other seasons if storage is available. Available water is quantified as the rainfall multiplied by a factor representing the available fraction, α ($\alpha = 0.49$, X and X).

$$SB_i = \max_{k \in [1,9]} \left[\left(\sum_{j=k}^{j+3} \overline{P}_j \cdot \alpha \right)_i - Demand_i \right]$$

The interannual water balance was calculated as the difference between available fraction of total annual rainfall and the annual water demand. This was calculated using average values and monthly values from 1979 to 2004.

$$AB_{ave_i} = \left(\sum_{j=1}^{12} \overline{P}_j \cdot \alpha \right)_i - Demand_i$$

$$AB(t)_i = \left(\sum_{j=1}^{12} P_{t_j} \cdot \alpha \right)_i - Demand_i$$

In general, SB is negative but the annual balance (AB_{ave}) is positive, then seasonal storage that captures the excess rainfall in wet months may provide the necessary water in the dryer months.

The potential water storage is the cumulative total of excess water from each month. If the annual balance is not adequate to provide excess water during dry months, then storage will not alleviate water scarcity and other mechanisms must be considered. The volume of water that must be gained through efficiency measures is the shortfall between the annual demand and the annual water input from rainfall minus losses.