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Water and economic development: The role of variability and a framework for resilience

Casey Brown and Upmanu Lall

Abstract

The article advances 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 datasets reveals a statistically significant relationship between greater rainfall variability and lower per capita GDP. Having established this correlation, 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 according to this metric are among the poorest in the world, and the majority of them are located in Africa. The importance of securing water availability in these nations increases every day in light of current population growth, economic development, and climate change projections.

Keywords: Economic development; Water scarcity; Climate variability; Infrastructure; Water policy.

1. Introduction

The impact of climate change on water availability could have deleterious effects on large segments of human society. The IPCC Third Assessment, Working Group II, summarizes recent work on climate change and the consequences for water resources (IPCC, 2001). The report paints a complicated hydrologic picture, with many of its model projections not substantiated by observed trends, and a high degree of uncertainty regarding the interactions between temperature, precipitation, evaporation, plant water use and human population growth and development. While the magnitude and direction of regional precipitation changes, *inter alia*, are uncertain, inter-annual and intra-annual variability appears likely to increase. Changes in streamflow are likely to be small in comparison to current natural variability, except in basins where snowmelt is an important component of runoff (Barnett *et al.*, 2005). This article will demonstrate that rainfall (and streamflow) variability is correlated with the economic development of nations. Hence, increases in variability may have adverse socio-economic impacts, particularly for many developing economies already limited by climate factors. Possible water sector mitigation strategies are also explored.

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Studies of the causes of disparity in the level of economic development between the wealthiest countries and the poorest have overlooked a fundamental difference between these sets of countries: the availability of water. The amount of rainfall, and in particular its temporal variability, presents challenges to food production, trade and infrastructure development.

Although rainfall variability is most prominent in the least developed parts of the world, 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 is still overlooked.

Several studies have found institutions, broadly defined, to be the most significant variable explaining the discrepancy in the relative 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

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institutions dominate the other variables. Acemeglou *et al.* (2001) use settler mortality rates as an exogenous measure of institutions and arrive 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. Perhaps surprisingly, this literature finds that colonial domination and military conquest are not significant factors relative to the causes cited above (see Sachs, 2001).

Many other studies argue in favour of the significant impact of geography (Sachs, 2001; Masters and McMillan, 2001; Olsson and Hibbs, 2000; Mellinger *et al.*, 1999; Gallup *et al.*, 1998; Diamond, 1997). Sachs (2001) describes the tropical disadvantage in agriculture as being due to poor soils, the presence of pests and parasites, higher crop respiration rates due to warmer temperatures and difficulty with water availability and control. However, studies investigating the impact of geography on development 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 favourite choice of some authors (Rodrik *et al.*, 2004). Accordingly, the use of percentage population living within the Köppen-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 that the impacts of hydrology and rainfall variability on economic development are significant (World Bank, 2004; Grey and Sadoff, 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 (Grey and Sadoff, 2006). Losses in Kenya due to flooding associated with El Niño in 1997–1998 and the La Niña drought in 1998–2000 caused annual damage ranging from 10–16% of GDP during this period. Interestingly, the most damage was not incurred by agriculture. Transport losses represented 88% of flood losses and foregone hydropower and industrial production totalled 84% of the drought losses (World Bank, 2004).

Many parts of the world experience a high 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 season of concentrated heavy rainfall can inundate the means of transportation, which in turn limits trade potential and communication, and can flood 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 bar 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 four 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 dilemma. This sensitivity to the timing of the arrival and departure of the rainy season requires different methods than those used in regions where rainfall is more equally distributed throughout the year, and where the key variable is a more gradual temperature progression. As Sachs (2001) suggests, difficulty in food production may have been a key factor in the slower economic development of the tropics.

Inter-annual variability, i.e., large differences in total annual rainfall in different years, may be caused by quasi-periodic phenomena, such as the El Niño/Southern Oscillation (ENSO), or longer-term climate shifts, such as those that caused the Dust Bowl in the American Midwest during the 1930s and have caused drought in the African Sahel since the 1970s. The economic impacts of such events are well documented. In the United States, drought was until recently the most costly form of natural disaster, averaging $6–8 billion annually (FEMA, 1995). Globally, drought is the largest single cause of death 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 to agriculture in any 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% (Grey and Sadoff, 2006). Therefore, countries with high intra-annual variability (rainfall concentrated in a single season) and inter-annual variability (typically symptomatic of ENSO or longer-term climate shifts) can be expected to lag in economic development. Furthermore, the affected countries typically lack the most common response to hydrologic variability in industrialized countries — water storage infrastructure.

During 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 re-evaluation 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 scepticism. 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 incorporated the role of climate variability and the impact of variability on the performance of infrastructure or management initiatives. Several studies have addressed the question of present and future water scarcity without considering variability. Postel *et al.* (1996) estimated water usage to be 54% of accessible runoff which 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 that the impacts on water availability from projected population growth and economic development are even greater than the estimated impact from climate change. Falkenmark (1997) found that, in parts of Africa and Asia, the volume of water estimated to be required for agriculture to support future populations was not available.

Annual precipitation averages, 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 statistics would characterize the level of water scarcity actually faced. However, in many parts of Africa, Asia and South America, rains arrive in excessive quantity during the rainy season and then cease, 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 scarcity due to variability. This article suggests that water scarcity due to mean normal climate conditions should be solved through water management and institutional measures, while addressing 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 inter-annual and seasonal climate forecasts (Lenton, 2002).

This study does not make a comparative evaluation of institutional approaches versus geography or climate methods. Rather, it attempts to demonstrate that climate variability in the form of rainfall variability is a significant factor in economic growth, and importantly, that its impacts can in many cases be mitigated. The authors 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 since the early 19th century. 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 country level.

The hypothesis of this paper is that climate variability is important and translates directly into a 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 a 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 inter-annual 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 ($2.5° \times 2.5°$ cells) global dataset of monthly temperature and rainfall, the NOAA Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1996) along with 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. Regression analysis of climate and GDP

A regression model was developed to explore how per capita GDP (average value of 1979–2004) of nations may

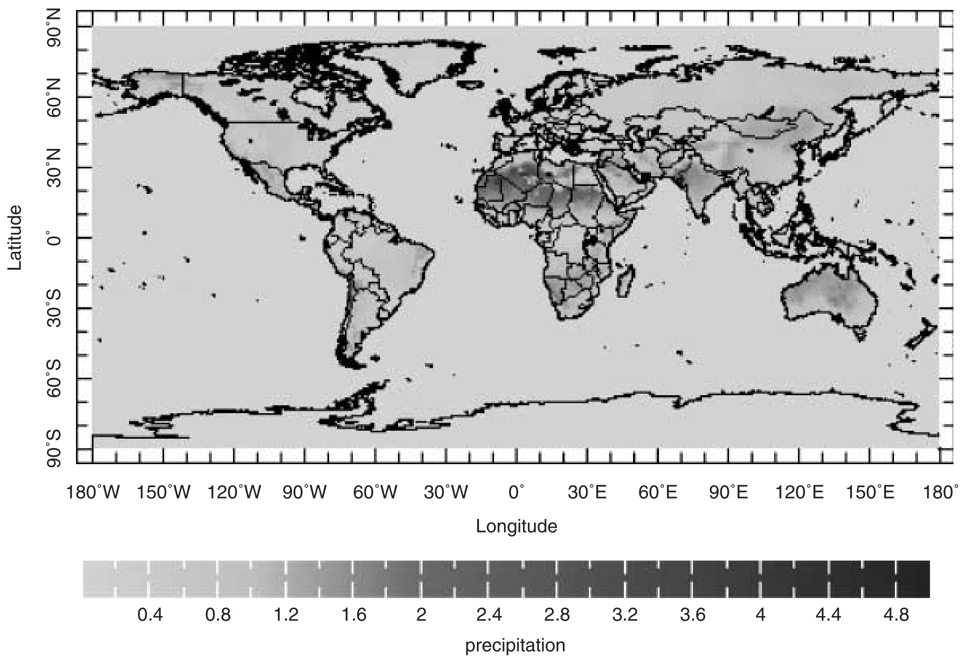

Figure 1. Intra-annual variability of rainfall as measured by the coefficient of variation of monthly rainfall totals (CVM). Higher values, as seen in South Asia, Australia, and western Africa indicate large variability in month to month rainfall.

relate to a suite of climate attributes. Factors considered included:

- mean annual temperature;
- mean annual precipitation;
- intra-annual rainfall variability;
- inter-annual rainfall variability; and
- 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. Data for 163 nations was analyzed.

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 (k), defined as $CVM_k = \sigma(\bar{P}_{j,k})/\mu(\bar{P}_{j,k})$; i.e., as the ratio of the standard deviation of calendar month (j) 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 inter-annual 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 $CVI_k = \sigma(P_{t,k})/\mu(P_{t,k})$ where $P_{t,k}$ is the total annual rainfall in year t for country k. Figure 2 shows the global distribution of inter-annual rainfall variability as measured by the coefficient of variation of annual rainfall totals. Higher values indicate areas with greater variation in the total amount of rainfall 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 climate variability index (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 North-East of Brazil, one of the poorest regions of the country, also bears the mark of strong inter-annual rainfall variability. Mexico, Australia, Argentina, Pakistan and southern Africa also exhibit high CVI values.

Spatial variability of rainfall within a country was computed as $CVS_k = \bar{\sigma}(P_{n,k})/\mu(\bar{P}_{n,k})$ 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 inter-annual variability (*CVI*) and

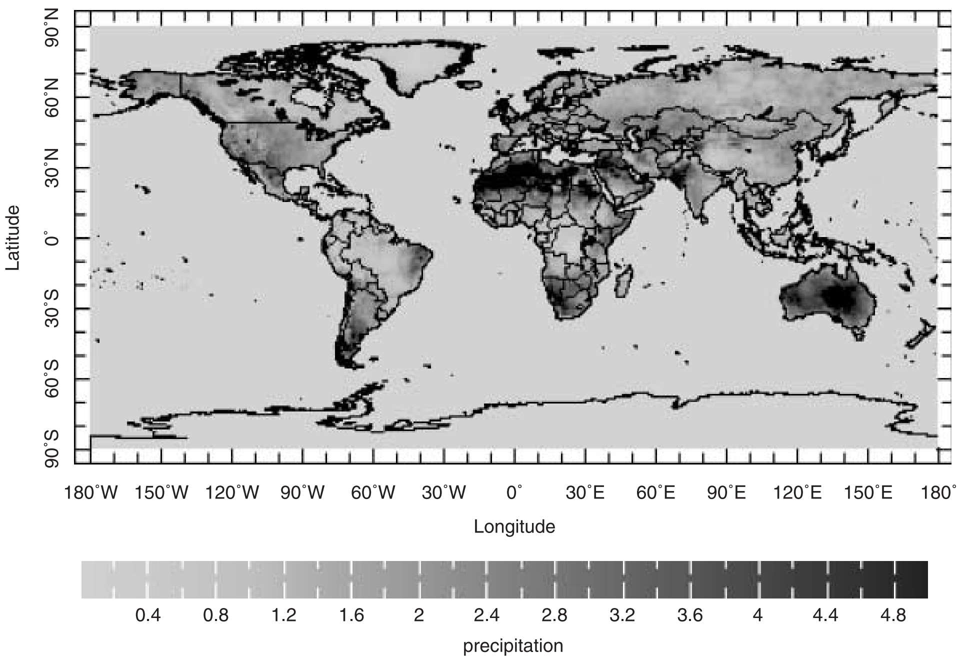

Figure 2. Inter-annual rainfall variability as measured by the coefficient of variation of annual rainfall totals (CVI). Higher values indicate areas where the annual rainfall total varies widely from year to year.

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

spatial variability (*CVS*). This is likely due to the effects of extended droughts on economic activity and rural livelihoods. Inter-annual variability is not statistically significant on its own, probably 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 countries that are well off 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 suggest a climate of low *CVI*, low *CVM* and moderate rainfall favours prosperity. These results are consistent with the hypothesis that rainfall variability is a determining factor in economic development.

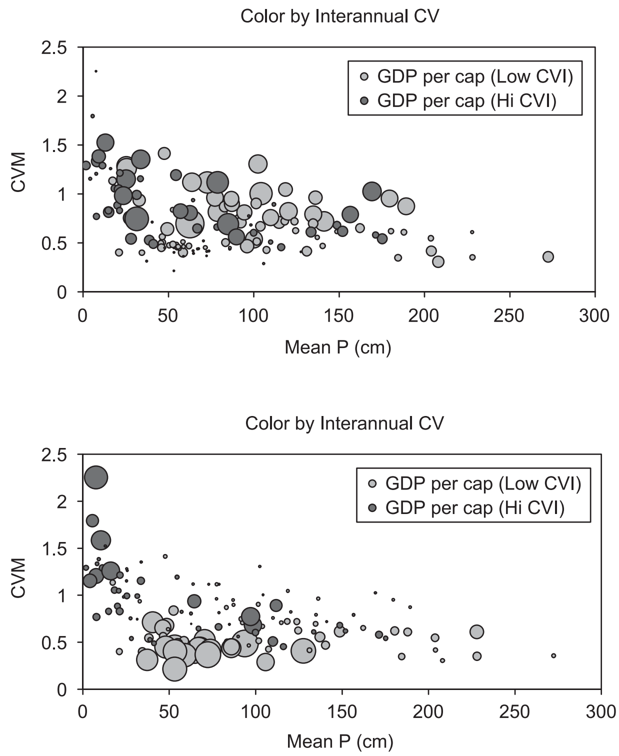

Figure 3. Scatter plot of mean annual precipitation ($\bar{P}$, x-axis), the coefficient of variation of monthly rainfall (*CVM*, y-axis) and the (a) inverse of per capita GDP and (b) per capita GDP (size of circle). Colour is for the countries that rank in the bottom half (light) of inter-annual coefficient of variation (CVI) and that rank in the top half (dark). 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 (light). The three nations with high CVI, high CVM and high GDP (large dark circles in figure b) are the small oil producing states Kuwait, Oman, and United Arab Emirates.

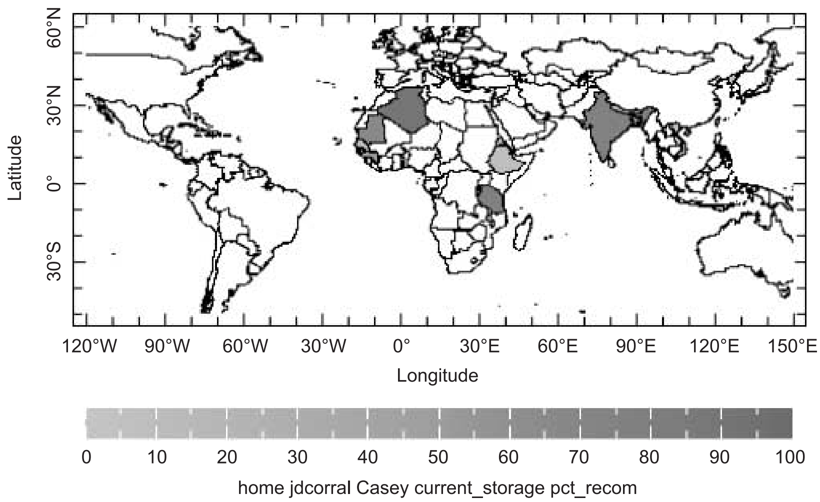

Figure 4. Countries with positive values of the seasonal storage index (SSI), reflecting intra-annual variability (CVM). Colour shading indicates the current storage capacity of each country as a percentage of the estimated storage requirement. South Asia and west Africa standout.

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 the building of dams. The preceding analysis implies that mean annual precipitation and intra-annual variability are key 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.

This section presents water storage requirements and water efficiency needs calculated on a country-by-country basis and identifies those countries that are most in need of action. The calculations were based on rainfall and agricultural data and some simple assumptions to develop a framework for identifying which approach is favoured in each country analyzed. The model is described fully in the Appendix. We proceed by:

- estimating water demand on a national basis;
- calculating the intra-annual water balance;
- calculating the annual water balance; and
- 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 inter-annual 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 method allows for calculating water demand independently of use efficiency and socio-economic status of the users. Annual per capita water demand for each nation based on food requirements was calculated using standard assumptions for caloric need, crop water requirements and crop yield data. Since the vast majority of water is used for the evapo-transpirative 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 of precipitation, that is the average monthly precipitation. The storage requirement is then calculated as the volume of water needed to be transferred from wet months to dry months. This volume is termed the seasonal storage index (SSI). The storage requirement is based fundamentally on the food requirement for the population, the agricultural land area and the rainfall. Need for storage is identified when a nation does not have enough land area to grow all the food requirements during the seasons that have enough rainfall. In cases where more agricultural area is not available, storage is required to make another season possible on the existing agricultural area. Nations with positive seasonal storage indices 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. Additional storage could be obtained by constructing surface

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 (km^3)	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%	2,049
Tanzania	5.50	1%	33%	76%	271
El Salvador	5.45	37%	100%	59%	2,302
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%	1,915
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%	1,653
Bhutan	0.40	1%	13%	0%	303

water reservoirs or by exploiting groundwater, 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 satisfy their water needs solely through seasonal storage. The average GDP of countries with hard water requirements is US$ 601. In contrast, the average GDP of countries with soft water needs is US$8,477. The soft water requirement is the volume of water that is needed in excess of what can be captured from internal renewable water sources. This need can be met either by improving the productivity of water, or by importing 'virtual water', i.e., grain, cereal, maize and other necessities that require water for their production (Allan, 1993). Nations that do not have sufficient renewable water resources can relieve their water scarcity through imports. Barriers to such imports include trade restrictions, subsidies and an inability to afford imports. Political considerations, such as a policy of self-sufficiency in food supply and other concerns may also bar such imports. In fact, there are cases of water-scarce countries exporting water. The value of exports may justify it. At a minimum, a comparison of the value of water in exports versus the opportunity cost of water in competing demands should be computed. Table 3 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 percentage of estimated storage requirement achieved and average GDP is 0.55 for countries requiring hard water. This implies that there is a connection between a nation's wealth and its infrastructure inventory relative to need. For this reason, the construction of infrastructure to create hard water is often funded by development aid from wealthy nations. However, our estimates imply that the strategies appropriate for building resilience to water variability in these less wealthy countries, listed in Table 2, may be quite different than methods used in wealthier countries, mainly oriented towards soft water. Funding provided by wealthy nations is often geared toward soft-water strategies, rather than towards hard water solutions, reflecting a choice of strategy appropriate in the donor country, but not necessarily for the recipient. In many water-scarce nations, such as those listed in Table 2, hard water strategies may be more appropriate.

The storage required to satisfy the drought-year water deficits characteristic of areas with high inter-annual variability by capturing surpluses in years relatively more abundant, has been calculated 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 and the maximum cumulative (consecutive year) deficit were calculated. We designate the larger volume as the inter-annual shortfall index (ISI).

Figure 5 shows the nations with positive ISI values that indicate they experience annual deficits due to inter-annual variability. Table 4 lists the ISI volumes and shortfall as a percent of average annual precipitation. This provides an indication of the storage needed to provide water during

Table 3. 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 percentage of the total estimated requirement represented by soft water and hard water is listed

	Soft Water Index (km^3)	Virtual Water (km^3)	Requirement beyond virtual water (km^3)	% 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%

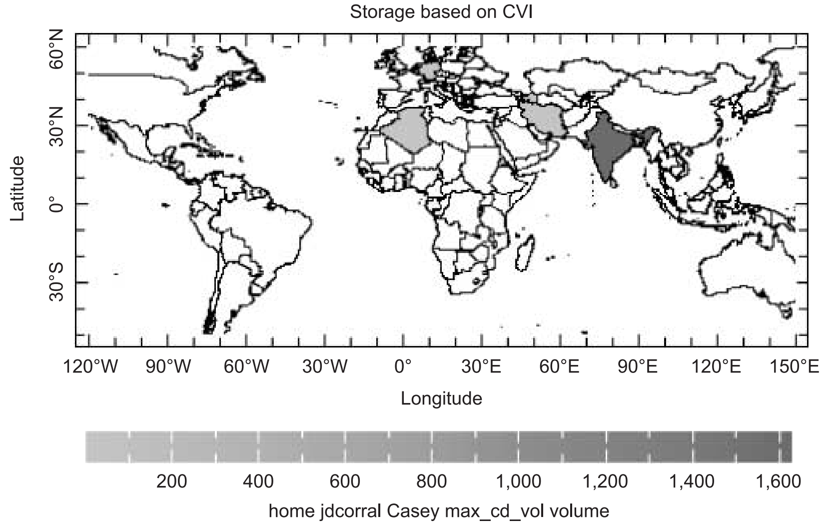

Figure 5. Countries with positive values of the inter-annual storage index (ISI), reflecting inter-annual variability (CVI). Colour shading indicates the magnitude of the requirement.

Table 4. Inter-annual Shortfall Index (ISI)

	Inter-annual Shortfall Index (km³)	Annual Water Available (km³)	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%	

Note: The ISI 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.

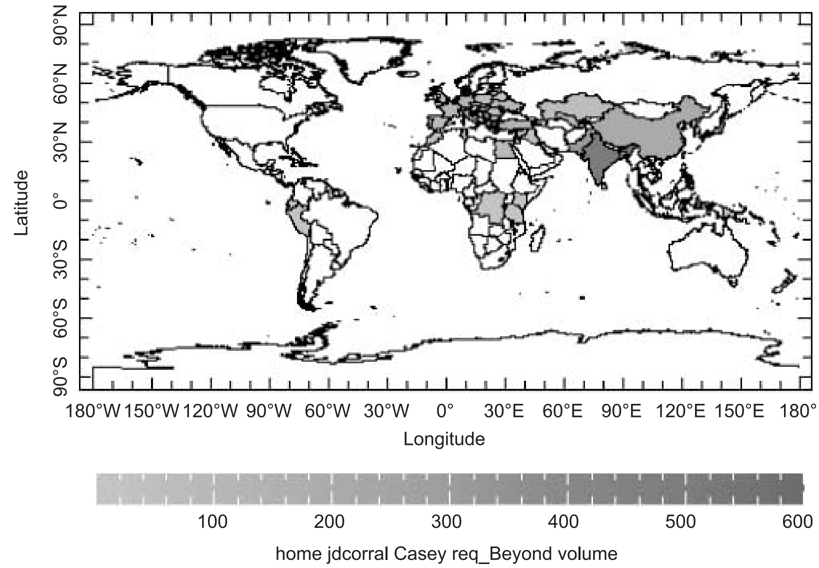

Figure 6. Soft water requirements. Shaded countries have water requirements that should be met through soft water, i.e., improvements in water efficiency and increasing imports of virtual water. The presence of European countries is likely due to underestimation of the water use efficiency and current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

single or multi-year droughts. The median GDP of these nations is US$853. Several of the nations with the greatest need for resilience to rainfall variability are among the poorest in the world, and therefore do not have the financial resources to take the necessary measures. Some of the deficits listed in Table 4 are very large in comparison with the annual average rainfall, and the indicated nations may need to consider meeting their deficit with soft water methods. The construction of storage volume that greatly exceeds the annual average flow risks significant environmental impacts and evaporative losses. 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%). The Colorado (250%) is the largest in North America (Nilsson *et al.*, 2005).

South Asia stands out as a water hot spot. It needs both seasonal and inter-annual storage, as well as "soft" water. Given that this is a region with some of the highest population densities in the world, and high rainfall variability, this is not a surprise. The interlinking of rivers, an increase in the number of storage projects, and rampant groundwater mining continue to be approaches currently considered in the region. Groundwater has provided a precious buffer to climate variability in the past, but the withdrawal of water at rates much greater than recharge is reducing the resilience of this resource (Singh and Singh, 2002). China faces similar concerns, but does not emerge in the same way in our country level analysis. A higher spatial resolution would probably reveal the differences in water availability and its variability between regions and might explain China's ambitious infrastructure investments, such as the South to North transfer project and the Yangtze storage projects.

3. Conclusion

This study has provided insight regarding the potential impact of increased climate variability on national economies and priorities for mitigation of adverse effects. Increased rainfall variability is an expected impact of climate change. We tested the hypothesis that the economic development of nations was affected by the amount of rainfall and its variability. This hypothesis follows the reasoning of Sachs (2001) that difficult conditions for early agriculture have impacted economic development significantly. This article proposes that rainfall variability should be considered as a critical factor in agriculture and in early economic development. The results of this analysis support that inter-annual 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 solutions are available in the form of water infrastructure (irrigation systems, dams, groundwater wells) and policy (water rights, trading, efficiency incentives), these are heartening results, for they imply that increased resilience to rainfall variability is likely to enhance economic development and also to mitigate some expected impacts of climate change.

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, on a country-by-country basis, whether the most appropriate way to mitigate climate variability would be to increase water storage through investment in infrastructure (hard water), or increase the efficiency of water use (soft water). These results indicate that several countries face critical water stress, as their current capacity is only a small fraction of their estimated requirements. These countries are also 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. Investment 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 could solve water shortfalls primarily through water efficiency gains. In all cases, we recommend that the principles of integrated water resources management be applied (see www.gwpforum.org), especially in view of the uncertainty of future climate change.

The results also suggest that wealthy nations typically require soft water while those less developed tend to require hard water solutions. Development aid may be unduly influenced by soft water strategies, which are more appropriate in the donors' home countries 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 that industrial water needs (4%) and drinking water needs (2%) are typically a small fraction of the human water consumption (Postel *et al.*, 1996), they were not considered in this study. However, where water supply is under stress, failures in industrial and drinking water supply may also be anticipated. Examples of this are seen in South Asia. Instream requirements were not considered as consumptive water use, although in many nations there will be demand to do so. Where this is true, our methods underestimate water requirements.

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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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 ($\bar{T}_m$) and mean total monthly precipitation ($\bar{P}_m$), mean total annual precipitation ($\bar{P}_A$), 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 ($\bar{P}_m$), 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: $\bar{P}_m$ $\bar{P}_A$ σ_{P_m} σ_{P_A} *CVM CVI CVS* $\bar{T}_m$ *W CVI*CVS*
Final Regression Model

Log GDP = β_0 +	$\beta_1 \bar{P}_m$	+	$\beta_2 CVM$	+	$\beta_3 CVI$	+	$\beta_4 CVS$	+ $\beta_5 CVI*CVS + \varepsilon$
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 four 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.

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

$$Demand_i = Seasons_i \times \frac{crop - watreq}{season}$$

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 four 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 ($\alpha = 0.5$, assumption based on references such as Postel *et al.*, 1996 and Falkenmark and Rockstrom, 2006).

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

The inter-annual 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.

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

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

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.