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Investigating Interactions Between Water and Society on a Global Scale: Econometric Analyses of Hydroclimatic Variability and Water Policy

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INVESTIGATING INTERACTIONS BETWEEN WATER AND SOCIETY ON A GLOBAL SCALE: ECONOMETRIC ANALYSES OF HYDROCLIMATIC VARIABILITY AND WATER POLICY

A Masters Project Presented

by

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ABSTRACT

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Water-related hazards such as floods, droughts and disease cause damage to an economy through the destruction of physical capital including property and infrastructure, the loss of human capital and the interruption of economic activities, like trade and education. The question for policy makers, however, is whether the impacts of water-related risk accrue to manifest as a drag on economic growth at a scale suggesting policy intervention. In this work, we use differently specified panel regression models to estimate the average drag on economic growth from water-related hazards faced by society at a global level. In doing so, we make use of surface runoff related variables never used before. In addition, the analysis is conducted at the country-basin level. The analysis of the climate variables shows that water availability and water hazards have significant effects on economic growth, providing further evidence beyond earlier studies finding precipitation extremes were at least as important or likely more important than temperature effects. In the second part of this work, we investigate the impact of drought on economic growth and find that on average, regions in South America, Southern Africa, Middle East and South Asia are the most affected. The most strongly impact country-basin units are in the tropics where hydrologic variability is relatively high. Many of the regions with a higher vulnerability to droughts are characterized by extensive agriculture. Moving to the third part of this study, we incorporate a broad set of variables representing the areas of infrastructure, institutions and information to identify the characteristics of a region that determine its vulnerability to water-related risks. We then develop a variety of linear regression models in an exploratory analysis to characterize the relevant characteristics for determining a region's vulnerability to hydroclimatic variables. The results identify water scarcity, governance and agricultural intensity as the most relevant measures affecting vulnerabilities to climate variability effects.

Introduction

Increasing interest in sociohydrology and calls for transdisciplinary water science emphasize the need for an improved understanding of the two-way interaction between water and society. The study of these interactions, sometimes called hydromorphology (Vogel 2011) or sociohydrology (Sivapalan 2015), promotes the incorporation of the interactions and dynamics of the human-hydrology coupled system into the water resources decision-making process. Impacts of human activities on water resources are significant and are manifested in various forms including altered river flows, deteriorating water quality, and changing groundwater dynamics, to name a few. Conversely, water related impacts on society, both positive and negative, are observed regularly, most notably in the form of hazards such as floods and droughts (Lundqvist 2000). While considerable literature detailing the relationships among climate, energy and society exists, the role of water and its interactions with different facets of everyday life are far less studied (Vogel et al. 2015).

In this analysis, we investigate empirical evidence of the interactions of water and society in economic terms. There exists a growing literature of work that establishes a link between climate factors and economic growth in specific regions of the world (Fankhauser and S.J. Tol 2005). Mendelsohn et al. (1994) use cross-sectional data for the US to measure the economic impact of climate on land prices and find that while higher temperatures on average reduce farm values, higher precipitation can sometimes offset those effects. Their results suggest a considerably reduced impact of global warming on US agriculture. In an assessment of climate change impacts across agro-ecological zones in Africa, Seo et al. (2009) use panel data with fixed effects regression to estimate the relationship between revenue from crop and livestock with a set of climatic and socio-economic variables. They find climate change effects varying considerably across the continent, and in some cases, even benefiting farmers. Nordhaus (2006) examines the relationship between temperature and economic output using a large global economic activity dataset and finds larger estimates of greenhouse warming damages to economic output than previous studies.

More recently, econometric analyses using panel data have considered variability in precipitation as an additional variable (Deschenes and Greenstone 2007). While variation in mean precipitation is not found to affect economic outcomes, weather anomalies (deviations from means) are more strongly associated with growth (Dell et al. 2014). These precipitation anomalies are directly responsible for extreme weather events (storms and droughts) and thus have a more pronounced impact on the economy. In particular, precipitation extremes have been shown to have a statistically significant detrimental impact on different measures of economic growth in sub-Saharan Africa (Brown et al. 2011). A global analysis employing the same methodology also found precipitation variability to have a negative and statistically significant effect on economic growth (Brown et al. 2013). A more direct hydrologic effect on economic growth has been addressed partially in previous studies. Using dynamic economic modeling, Sadoff (2006) shows that increased hydrologic variability in Ethiopia leads to diminished economic growth. The modeling estimates that droughts and flooding combine to reduce the annual economic growth rate by 20-40%.

A recent analysis of the potential of climate induced water shocks to development, performed by the World Bank, concludes that improved water allocations and investments in infrastructure to provide security against water-related shocks are critical in decoupling water use and economic growth (World Bank 2016). The analysis uses a Computable General Equilibrium model for the world economy, where water is treated as an input to production. The model is operated under two scenarios corresponding to the Shared Socioeconomic Pathways (SSPs) from the climate-modeling literature, which project alternate global futures for demography, policy, the economy, and emissions. Each of the SSPs is associated with a water supply and demand estimate, and thus the model computes the state of the world economy for each SSP. Model simulations show that water scarcity reduces economic growth, supporting findings from previous literature (Barbier 2004), with the greatest impacts observed in the Middle East, the Sahel and Central Asia. Similar to the objective of this paper, we study the linkage between water and growth on a global level. However, the work presented in this paper differs from the World Bank study in two major ways. First, the World Bank study employs projections of future sociopolitical and economic conditions as opposed to using observed historical data. Second, the model only considers the impacts of water availability in the context of a changing climate, without incorporating water-related climate extremes.

In addition to the detrimental impact of water scarcity on economic growth, water-related hazards such as floods, droughts and disease cause damage to an economy through the destruction of physical capital including property and infrastructure, the loss of human capital and the interruption of economic activities like trade and education (Grey & Sadoff 2007; Sivakumar 2011). Some consistent findings emerge from a review of the empirical studies investigating the effect of hydrologic variability on development. Droughts have been shown to be negatively associated with economic growth and agricultural production (Brown et al. 2011; Brown et al. 2013). Multiple studies have found a statistically significant relationship between rainfall variability and economic growth (Miguel et al. 2004; Brown & Lall 2006). Further, econometric investigations of climate impacts on agricultural production in the United States have consistently found that increases in mean temperature and precipitation result in a decrease in agricultural profits of up to US$5 billion (Schlenker et al. 2006; Fisher et al. 2012).

The efficacy of investment in water resources as a tool to safeguard the economy from climatic variation has been a matter of considerable debate over the past few decades. Evidence exists from specific case studies that an appropriate combination of policy and infrastructure can potentially mitigate the negative impact of hydrology on growth, or in some cases, spur economic growth as in the case of the Tennessee Valley Authority (Kline and Moretti 2014). The Green Revolution across Asia is touted as another example where substantial public investments in agricultural water management and rural infrastructure have led to tremendous decrease in hunger and poverty (Bhutto and Bazmi 2007). Flood control measures, improvements in water sanitation and strengthening of the municipal water supply systems have been shown to bolster economic growth in Japan (Japan Water Forum 2005). At the other end of the spectrum on this debate, critics have identified examples where substantial investments in water resources development have had little to no impact on economic growth (Cox et al. 1971; Duflo and Pande 2007).

This work employs econometric techniques to assess the relationship between economic growth at the basin scale and the hydroclimatic factors that influence it using a large global dataset containing gridded economic and climatic variables. We then seek to identify characteristics of a region that influence the magnitude of effect of these exogenous factors. The study is conducted at a sub-national spatial scale, using river basin-country units as the scale of analysis, and includes surface runoff related variables never previously incorporated. The work presented comprises the most complete economic assessment of the effects of the relationship between hydrology and economic growth.

Background: Measuring Water Security

Because water is a crucial part of everyday life and its effects felt on various segments of society, it is crucial to comprehensively and objectively identify the different factors which impact our ability to extract the most benefit out of this resource. Although in recent times there have been great strides made in the improvement of water availability (UN 2012), the number of people affected from water-related disasters continues to increase (Adikari and Yoshitani 2009). There are still hundreds of millions of people without access to an acceptable quantity and quality of water (WHO 2008), and many more are hostage to climate extremes. This water insecurity continues to have a debilitating impact on the growth and development of the regions these people live in.

The concept of water security has evolved over the past few decades, and academic discourse on water security has featured four inter-related themes (Cook and Bakker 2012). The most prominent theme in the discussion has focused around the assessment of water scarcity. The quantity and availability of water are often linked to water security (Falkenmark et al 2007). A second aspect of water security commonly discussed and managed are the water related hazards and vulnerability. Human needs, covering challenges such as water accessibility and food security is another recognized facet of water security. Various development agencies, such as Food and Agricultural Organization (FAO), have made this aspect of water security as one of their main objectives (FAO Land and Water Development Division 2000). Another dimension of water security is sustainability. This is to 'ensur[e] that the natural environment is protected and enhanced' (GWP 2000) while water resources are being utilized for human needs.

Given the various aspects of water security discussed, there is a need for a comprehensive definition of water security to encompass both the benefits and costs of water. Grey and Sadoff (2007) define water security as the "availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water related risks to people, environments and economies". This definition provides a good framework for policy decisions. To help guide the development of a more rigorous science-based measurement of water security, a redefinition using a risk based approach is required. A definition for water security rooted in risk science is proposed by Grey et al. (2013): "water security is a tolerable level of water-related risk to society". Thus a 'water secure' river basin is one which is protected from various water related risks. Impacts of water related risks can be measured in a number of ways, including direct economic impacts, health effects and social changes(Sapir and Hoyois 2013). This requires an integrative approach to water management and working across disciplines.

The recent increase in attention paid to the concept of water security has prompted many attempts of quantifying water security. Many different water security indicators have been developed, with a variety of approaches to identifying the factors critical to engendering water security. Here we briefly review a few prominent water security indicators.

One of the most thorough water risk indicators is the Aqueduct Water Risk Atlas, an interactive water-risk mapping tool. This indicator aims to assess the exposure of companies and investors to water-related risks (Reig et al 2013). Aqueduct makes use of a 'Water Risk Framework' which includes 12 water security variables grouped into three categories of water risk: quantity, quality and regulatory risk. The Risk Atlas provides 10 preset weighting profiles for variables that have been developed based on input from companies and experts in water resources. Since this indicator is specifically designed to evaluate water security for companies and impacts on their operations, it does not provide guidance on a river basin level to the basin authority for the development of a country. This is significant as the objectives of a for-profit corporation may be different than the objectives of a governmental agency. The objectives for the index determine the selection of, and weighting for, the various variables that comprise the index. For instance in the Aqueduct framework, the presence and scoring of the 'Media Coverage' variable means that there will be a *higher water risk* where there is greater public awareness of the water problems. This goes against conventional wisdom which suggests that greater public participation is beneficial as it suggests better information facilities.

Lautze and Manthrithilake (2012) develop a more straightforward index for evaluating water security at the country level. This index is additive and is comprised of five components that the authors consider to be critical to quantifying water security. These components are derived from the common strands of the various definitions of water security, focusing on *basic human needs*, *food production*, *environmental conservation*, *risk management* and *water resources independence*. Countries are ranked relative to each other on a five point scale, with five being the most desirable score for each component. The scores for each of these components are then added up to provide a final score for water security for each country. A higher score out of 25 indicates greater water security. For their analysis, the authors use data from 46 countries in the Asia-Pacific region. The scoring for the various components is subjective, and displays a lack of clarity in the indicator objectives. For instance, for the environment component, Pakistan, a country with a higher level of water resource development, scores lower than Myanmar, a country with a lower level of water resources development. This water security index thus penalizes countries for better infrastructure.

This review found the most in-depth and comprehensive existing water security indicator to be the National Water Security (NWS) indicator developed by the Asian Development Bank (ADB) for countries in the Asia Pacific region (ADB 2013). The NWS is comprised of five dimensions of water security: household, economic, urban, environmental and resilience to hazards. Each of these dimensions is comprised of several variables, including both the hydrologic conditions of the country and adaptation measures in place. With a score for each dimension calculated and reported, this indicator provides insight for a country's river basin management into the critical aspects of water security. The report also tracks scores geographically, which allows funding agencies and development organizations to focus on 'hotspots' of water insecurity. However, the calculation of the indicator involves averaging of scores across the variables in each dimension, and then rounding the scores to achieve an integer value. The averaging causes the weighting of the variables to be simply determined by how many variables are present in each dimension. Not only is the rounding up or down of scores subjective, but since the index is on a five point scale, the rounding can show a country's problems to be worse than they actually are. In addition, the comprehensive nature of this indicator means that for many measures, data availability is sparse for most countries. In such a situation, the score is assigned based on expert opinion, and diminishes the quantitative nature of this index.

This review of existing water security indicators shows general agreement on the crucial factors for water security: hydrology, infrastructure and institutions. However, existing indicators rely heavily on intuition and expert judgment for the selection of components and their relative weighting. The results tend to be linear aggregations of factors that are believed to be important. It's not clear that this extrapolation of existing beliefs provides original insight.

Three key shortcomings are observed in existing water security indicators. The first lies in the identification of the variables that have an impact on water security. Existing indicators are comprised of factors which are intuitive, but little empirical evidence exists to support their inclusion. There is an additional problem of a lack of distinction between factors that are choices (endogenous) versus inherent conditions (exogenous). This reduces the utility of the indicator for countries and aid agencies who are looking for advice regarding the best course of actions for improving their state of water security. The second major shortcoming is the subjectivity in defining the importance of any particular factor. Almost all existing indicators rely on expert judgment to determine how the different components in the water security index should be weighted. Finally, because of the evolving definition of water security, most of the existing water security indicators lack direction, regarding the objective and users of the indicator. A clearly defined objective is important in ensuring that the indicator provides information that is useful for something.

Methods

This analysis has three parts. In the first part, we use panel regressions with various specifications to investigate the relationship between economic growth and hydroclimatic variables at the basin-country level. In doing so, we use surface runoff related variables for the first time in this kind of analysis. Then, we focus on quantifying the impact of drought on economic growth. We do so by performing simulations of economic growth in countries with and without the effect of drought. In the third part, we incorporate a broad set of variables representing infrastructure, institutions and information to identify the characteristics of a region that determine its vulnerability to water-related risks. We then develop a variety of linear regression models in an exploratory analysis to characterize the relevant characteristics for determining a region's vulnerability to hydroclimatic variables.

Data sources and characterization

This analysis is performed at the river basin-country unit scale. This country-basin unit scale is the intersection of river basin delineations, obtained from the GRDC river basins database (GRDC 2007), and country boundaries. For instance, the Indus River Basin extends geographically across four different countries, resulting in four different country-basin units (only two of those country-basins is used in the analysis due to the filtering described below). In total, a dataset including 748 country-basin units is developed. For this analysis, our chosen measure of economic outcome is per capita GDP growth. Values for the per capita GDP growth for each country-basin (CB) unit were calculated from the G-Econ database. The G-Econ database provides time-series data for the gross economic value added in a specific region (Nordhaus 2006). These data are available globally at a 1-degree grid cell level, with output from 14,859 terrestrial cells. We aggregate the gridded output across all cells in a country-basin unit and calculate the percentage growth in economic output for each year. We filter the resulting dataset to include only country-basin units with a population greater than 10,000 and area greater than 100 km^2. Figure 1 shows the 502 country-basin units included in this analysis.

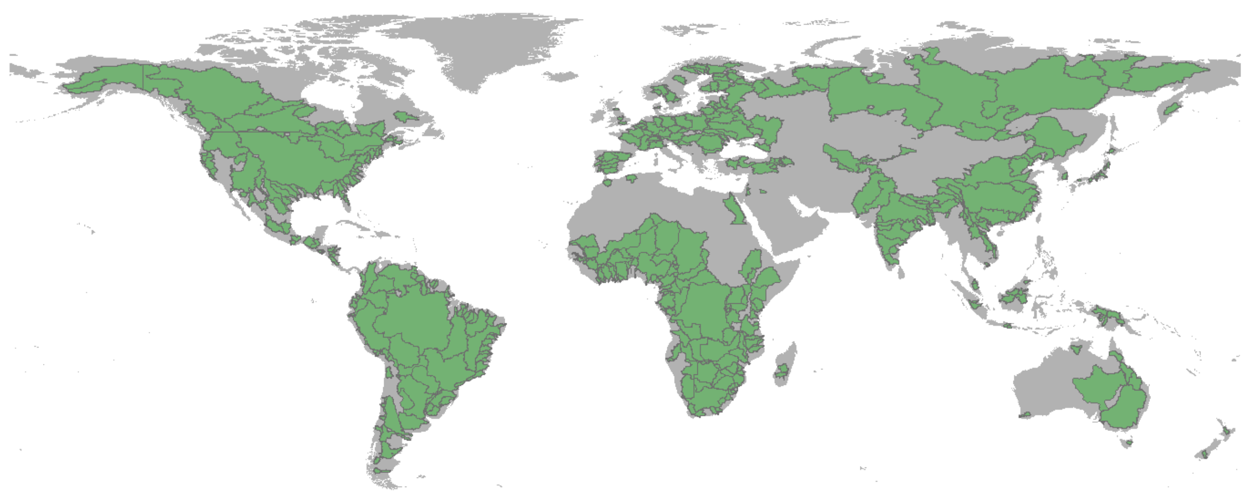

Figure 1: Map showing the 502 country-basin units included in this analysis

The independent hydroclimatic variables employed in the analysis include precipitation, surface runoff and temperature. While precipitation is generally indicative of water availability, it does not account for the effects of evapotranspiration or soil moisture storage which are important especially in the semi-arid tropics. To account for these effects, we include surface runoff data for the first time in an econometric analysis of economic growth. The runoff data were simulated by a global hydrological model, MacPDM (Arnell 1999), run at a one degree resolution. The use of surface runoff is novel and adds value because it combines precipitation and temperature effects and is posited to have more direct impact on human activities in comparison to other climate variables. Precipitation and temperature data are obtained from ERA-Interim global gridded 1^o datasets (Dee et al. 2011), with climate data on a monthly time scale from 1991-2012. Mean values for the hydroclimatic variables were calculated by spatially averaging the annual average over the domain of each country-basin unit. The hydroclimatic variables for each region were calculated based on the water year (WY), which spans October to September (e.g. WY 2005 spans October 2004 to September 2005).

In addition to using mean climate conditions, for the precipitation and runoff data, we additionally calculate the weighted anomaly standardized precipitation (WASP) and weighted anomaly standardized runoff (WASR) indices respectively. These indices provide a measure of anomalous climate conditions relative to the long-term mean, while preserving the spatial and temporal variability. A threshold level of one standard deviation from the mean is used to signify anomalous conditions (Lyon and Barnston 2005). The output for these indices is percentage of area of a region that is experiencing anomalously dry (WASP(-1), WASR(-1)) or wet (WASP(+1), WASR(+1)) conditions over the time period measured. Eight hydroclimatic variables were determined for each country-basin unit: mean annual precipitation, mean annual temperature, squared mean annual temperature, mean annual runoff (streamflow), and precipitation and runoff thresholds (WASP and WASR).

Econometric analysis of hydroclimatic effects on economic growth (exogenous factors)

Panel regressions were used to identify the exogenous hydroclimatic variables that had a statistically significant impact on economic growth. The panel dataset contained cross-sectional data on 502 country-basin units over 21 years (1991-2012). This approach allows us to pool both cross-sectional and time-series data and distinguish between differences in behavior over cross-sectional units ("between" variability) as well as differences over time for a given cross-sectional unit ("within" variability). In comparison to climate data which varies considerably on a year to year basis, there are other time-invariant characteristics of each country-basin which vary relatively little over time. For example, institutions and infrastructure, among other factors, are relatively stable over time, at least in comparison to climate variables, but do vary significantly between country basins. We use individual country-basin fixed effects to control for these omitted variables that vary across individuals (in this case, country-basin units). Year fixed effects control for factors that might vary over time but affect the countries in the same way. For instance, this specification will help adjust the model for global shocks to the economy, such as the one in 2009.

The specifications of the model are shown below:

$$\boldsymbol{Y_{it} = \beta_k X_{it}^k + \alpha_i + \gamma_t + \varepsilon_{it}} \qquad (1)$$

where $\boldsymbol{\beta_k}$ is the response coefficient describing the influence of the *k*th hydro-climatic predictor $\boldsymbol{X_{it}^k}$ on economic growth $\boldsymbol{Y_{it}}$ in the *i*th watershed at time *t*, $\boldsymbol{\alpha_i}$ is the country-basin fixed effect that represents the time-invariant aspects of each basin, $\boldsymbol{\gamma_t}$ represents the year fixed effect, and $\boldsymbol{\varepsilon_{it}}$ represents the stochastic disturbance term. The disturbance is assumed to have an expected value of zero, constant variance, and to be independently and identically distributed. This panel model is quite flexible, and its assumptions can be changed to treat the coefficients as random rather than fixed.

The choice between fixed effects and random effects depends on various features of the dataset and the eventual goal of the regression. In the fixed effects model, $\boldsymbol{\alpha_i}$ are treated as fixed parameters that need to be estimated, while in the random effects, $\boldsymbol{\alpha_i}$ are incorporated into the error term. When $\boldsymbol{\alpha_i}$ are fixed, our inference is conditional on the cross-sectional units in the sample. Conditional inference is appropriate if our dataset cannot be assumed to be a random sample from a larger population. If the cross-sections in the sample can be assumed to be a random sample, and we wish to make inferences about the population, then the random effects model is more appropriate. In the random effects model, we make the strong assumption that the individual random intercepts are uncorrelated with the predictors. The Hausman test, using the residuals from both the fixed and random effects model, can be used to test whether the errors are correlated with the predictors. In this analysis, we perform regressions under the assumption of both fixed and random effects.

We perform various specification tests to determine whether the assumptions underlying the panel regression model are valid. To check for presence of individual heterogeneity, the Breusch-Pagan Lagrange multiplier test is used to determine whether the individual effects are present and significantly different from zero. To ensure valid inference, further tests are performed for this model to check the structure of the residuals and detect presence of heteroscedasticity. The panel models described above also do not take into account serially and/or spatially correlated residuals. A growing number of studies highlight the existence of substantial cross-sectional dependence in panel data. In this analysis, where our panel data consists of country-basin units and the dependent variable is economic growth, it is reasonable to expect some spatial dependence (De Hoyos and Sarafidis 2006). Statistical tests are available to determine whether spatial or temporal dependence exists in the panel model errors (Steinschneider et al. 2013). If spatial and temporal correlations in the error term are found, we perform robust covariance matrix estimation for the fixed effects model as suggested by Driscoll and Kraay (1998) to account for heteroscedasticity, serial correlation and cross-sectional dependence.

Analysis of determinants of vulnerability to hydroclimate effects (endogenous factors)

Panel regressions help identify, on a global scale, the critical hydroclimatic variables related to economic growth. However, we expect the relationship between the water-related variables and economic growth to vary across different country-basins. In the second part of this analysis, we investigate which endogenous measures are most useful in describing the 'unique' conditions in each country-basin that may contribute to the differential effects that each location reveals in the panel analysis. These factors are the attributes that represent choices, whether by design or default, regarding the policies and investments within a region or that are otherwise able to be influenced by policy. They are distinct from the exogenous factors described above in that the exogenous factors are not influenced by policy decisions. A country cannot influence the weather it bears. However, a country does make investment and policy decisions that may influence its vulnerability to water-related hazards, such as investment in infrastructure and policies that encourage economic diversification.

The *individual fixed effects* from the panel model described above represent individual heterogeneity of regions. In this exploratory analysis, we use the fixed effects parameter estimation in a second regression as the dependent variable and perform linear regressions with various specifications to identify endogenous measures most closely related to the individual heterogeneity. A cross-country dataset consisting of various adaptation measures, explained in Table 1, was developed. The available data were limited, in particular, for measures of water infrastructure which necessarily reduced the sample size in this second analysis.

Table 1: Variables included in linear regressions to identify endogenous measures most closely related to individual country-basin heterogeneity

Access to potable water	Provides a measure of the percentage of population in each country that has access to clean drinking water
Access to sanitation	Provides a measure of the percentage of population in each country that has access to sanitation facilities
Fragile States Index (FSI)	Gauges the strength of institutions in each country and is based on how the governance in public sectors is perceived
Agricultural water withdrawal	The percentage of total water withdrawals that is used for agricultural purposes.
The following indicators are taken from a dataset quantifying the impact of human activities on water security across the world (Vörösmarty et al. 2010)	
Cropland	Proportion of total land area used for growing crops
Nitrogen loading	Anthropogenic nitrogen loads to rivers calculated as the difference between contemporary and pristine nitrogen loads
Mercury deposition	Anthropogenic mercury deposition calculated as the difference between current and pre-industrial mercury levels
Human Water Stress	The ratio of river discharge to the local population
Agricultural Water Stress	The ratio of discharge to cropland area
Total impervious surface	Total constructed impervious surfaces (e.g., roads, buildings, parking lots)
Dam density	Total number of medium and large sized dams in each country-basin

In addition to obtaining cross-country data for specific endogenous variables, we explore an additional dataset, Institutional Economics of Water (IEW), pertaining to institutional strength. Due to limited spatial coverage, the variables from this dataset are not used in the regressions; nonetheless some interesting findings emerge from an analysis of the important factors in water governance. This dataset presents an analysis of the performance of water institutions for countries around the world (World Bank 2004). As part of the study, a survey of water professionals across 40 different countries was conducted focusing on all aspects of the water sector including water law, water policy, financial administration, organizational structure, water governance and rights, research in water resources and evaluations of overall performance of the water sector. Based on the survey questions, different metrics of water institution were formulated. All the metrics used are scored based on a scale of 1 to 10, with 10 being the most desired score. For this study, only countries which had a ranking for all of the metrics were used. The processed dataset thus contained scores for 22 metrics for a total of 21 countries. Tables A1 and A2 in the appendix show the metrics used along with their description, and the countries for which complete data was available.

Conditional Economic growth rates

The goal of this analysis was to identify the economic sensitivity of individual countries to climate variability. Our first approach based the estimation of sensitivity on the difference between economic growth rates in drought years and in all other years. This allowed the isolation of the drought effect. It also identified the degree to which a country is “set back” by a drought. The first step in this approach was to establish a threshold for declaring when drought was present. The WASP(-1) index was used with a threshold that relates to the fraction of a country’s spatial area that is in a state of drought (anomalously low precipitation). WASP(-1) was used because we believe it is the most reliable drought metric but metrics based on runoff could also be used.

This threshold is used to explore the effect of drought on economic growth over a long time period. Simulations were created that represent the growth in countries with the drought effect present and with it removed to visualize the cumulative effect over time. This approach used a static model that does not reflect any dynamic effects of drought shocks (e.g., changes in stocks or investments). The simulations used the actual non-drought and drought growth rates for each country individually to estimate the drought effect. The difference between the drought growth rate and non-drought growth rate reflects the degree to which a country is affected by drought while accounting for its baseline growth rate. As such, it may be the most informative index of the economic sensitivity of countries to drought. Based on this simulation analysis, one can determine which regions benefit most from a reduction of the drought effect in terms of economic growth rate.

Results and Discussion

We first present characterization of the World Bank dataset explored as part of this study. Then we discuss results from the global analysis of hydroclimatic variables on economic growth. In this analysis, panel regression with individual and time effects was used to identify and evaluate the impact of exogenous hydroclimatic factors on economic growth. Next, results are presented from conditioned panel regressions, on a global level, to identify key characteristics of regions that impact their vulnerability to water risks. Lastly, we explore, on a local level, which specific metrics are relevant in determining sensitivity of regions to water risks.

Characterization of datasets

Institutional Economics of Water (IEW)

The IEW (World Bank 2004) dataset was investigated using correlation tests and principal component analysis. Figure 2 shows the visualization of the correlation matrix of the water institution metrics. The first two columns of the matrix show the correlation of the median per capita gdp growth rate and the median gdp per capita (from 1991-2012) with the metrics of this dataset. Many of the metrics are found to be highly correlated.

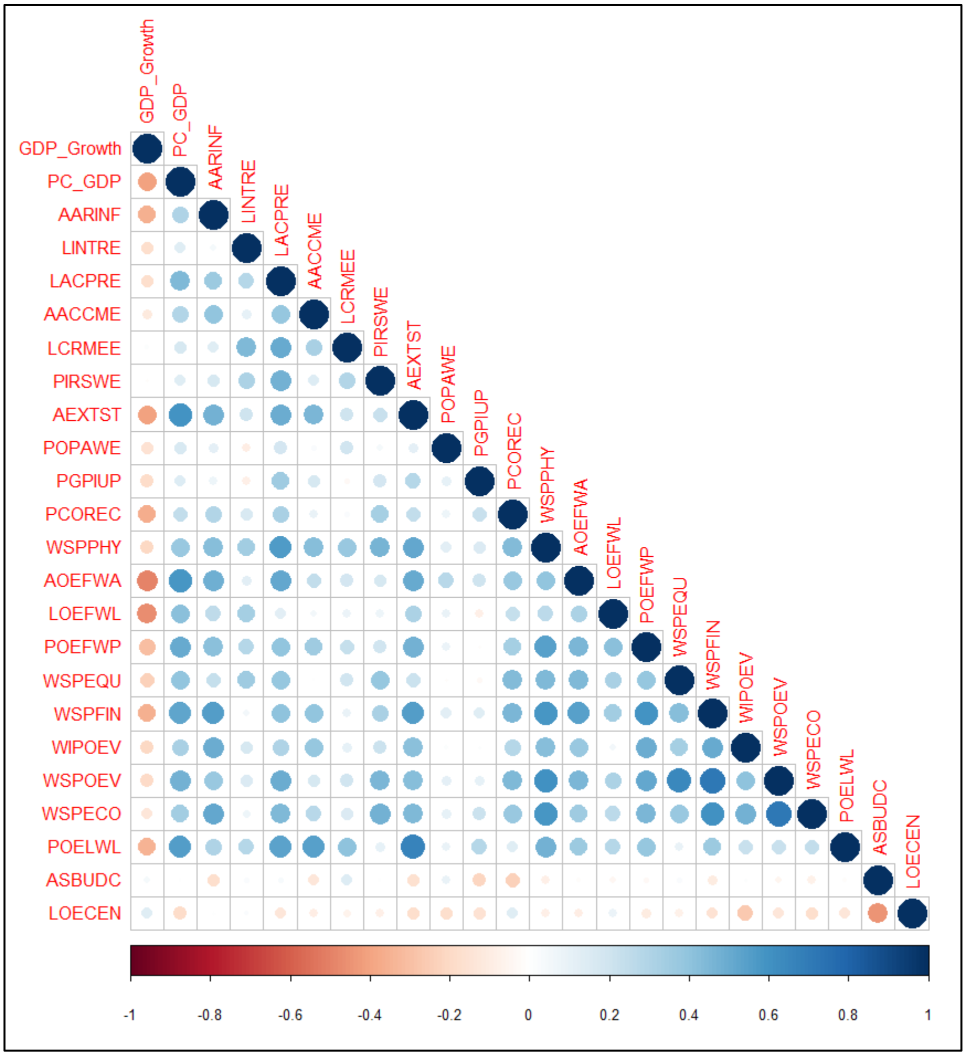

Figure 2: Visualization of correlation matrix for IEW metrics with economic indicators for 21 countries

For the per capita GDP growth rate, most of the performance metrics are negatively correlated, suggesting that a higher growth rate is correlated with poorer performance of the water institutions. A more careful look at the countries included in this dataset explains this surprising result. The countries that score highly in these performance metrics are also the ones that are generally more developed (e.g., France, Canada, Netherlands). These countries have bigger economies which have now stabilized and are growing at a steadier rate. On the other hand, countries which have smaller economies are growing at a much more rapid rate and thus have higher median pc growth rate for the period of our analysis. The countries in this dataset include (Equatorial Guinea, Namibia etc. with China being the notable exception). The positive correlation of the pc GDP with the water institutional metrics is more intuitive as countries with more developed economies also have the strongest water institutions.

To better understand the variance of the water institution metrics, a principal component analysis (PCA) was performed to help reduce the dimensionality of the data. The PCA showed that the first two principal components accounted for more than 56% of the variance in the data. The eigenvectors from the covariance matrix gives us loadings for the principal component (PC), which help identify the specific metrics which are weighted highly in that component. Table 2 shows the metrics that had the highest loadings for the first and second principal components.

Table 2: IEW metrics that have the highest loadings for the 1st and 2nd Principal Component

1st Principal Component	
LACPRE	Effectiveness of accountability provisions
WSPECO	Overall evaluation of economic performance
2nd Principal Component	
ASBUDC	Seriousness of budget constraint
LOECEN	Tendency for centralization in water law

To further investigate the results of the PCA, the scores (obtained from the eigenvalues of the eigenvectors) from the first principal component were obtained for each country. The correlation between these scores and the Corruptions Perceptions Index (CPI) and the Fragile States Index (FSI) rankings for these countries was then evaluated. Table 3 shows the correlation matrix for these three datasets. These datasets are well correlated; suggesting that performance of the water institutions is similar to overall institutional strength in a country.

Table 3:Correlation between FSI, CPI and scores from first Principal Component of IEW dataset

	FSI	CPI	PC1 of IEW dataset
FSI	1.00	-0.79	-0.50
CPI	-0.79	1.00	0.59
PC1 of IEW dataset	-0.50	0.59	1.00

Global impact of hydroclimatic variables on economic growth

Table 4 provides estimation results for three differently specified models. Each is fitted with (a) fixed effects and (b) random effects. Model 1 shows results for regressions with all climate variables included; in Model 2, three precipitation related variables are removed while in Model 3, two precipitation and the two temperature related variables are excluded from the regressions to avoid confounding effects of collinearity. The estimated coefficient for each climate variable in each model is shown along with its standard error obtained through robust covariance estimation. The asterisk on a coefficient represents its statistical significance.

A comparison between the fixed and random effects estimates for each model shows that the sign of the parameter estimate remains consistent. This suggests a high degree of confidence in the direction of the effect of each climate parameter on economic growth. Model 1 results show that the WASP(-1), WASR(-1) and WASR(+1) coefficients are significant at the 99% confidence level with the random effects model, with only WASR(-1) significant at the 95% confidence level with the fixed effects model. Both temperature variables are not statistically significant using either modeling approach. Since the precipitation and runoff-related variables are well correlated ($r = 0.88$), in Model 2, we remove the precipitation related variables to avoid the confounding effects of collinearity in parameter estimation. With this model specification, annual average runoff is now statistically significant. We see that the temperature related variables remain statistically insignificant. The signs on the climate variables are the same as that observed in model 1. In Model 3, we drop the temperature variables from our model and re-introduce WASP(-1) to incorporate a drought-related variable. This is our preferred model specification since it includes all climate variables that have a statistically significant relationship with our dependent variable and incorporate the different aspects of water security (i.e. droughts, floods, mean water availability).

The positive coefficient of the runoff variable confirms our hypothesis that greater available runoff is associated with positive impacts on economic growth. This is the first study to show this association between runoff and economic growth using rigorous econometrics and a global panel. In addition to providing a basis for existing hydrologic conditions, the runoff variables also assimilate changes in temperature and precipitation. It is no surprise that the temperature-related variables found to be significant in previous analyses are no longer significant in these regressions. The negative coefficient associated with WASP(-1) confirms results from earlier studies (Brown et al. 2011, 2013), showing the impact of extended dry periods. The negative association between WASR(+1) and economic growth also supports the hypothesis that anomalously high runoff conditions are a drag on the economy. Significant deviations from mean precipitation and surface runoff conditions (WASP and WASR) are shown to be more important than the mean conditions, a finding Barrios et al. (2010) and Yang (2008) also support.

The positive coefficient associated with the WASR(-1) variable is initially surprising. Intuition suggests that as water availability decreases substantially, that would have a negative impact instead of a positive effect on economic growth. Indeed this is seen in the coefficients associated with average annual runoff and WASP(-1). The WASP(-1) and WASR(-1) variables (both expected to be associated with drought) are strongly correlated. It is possible that including both variables concurrently confounds estimation results due to collinearity, which may be the reason behind the unexpected sign on WASR(-1). However, in a separate regression where WASP(-1) was removed from the model, WASR(-1) still retained its positive coefficient.

Table 4: Panel regression results for 500 country-basin units for data from 1991-2012. Each column represents a different model specification. The top row shows whether (a) fixed or (b) random effects were used. Clustered robust standard errors are shown in parantheses below the parameter estimate. The dependent variable is percent GDP growth for a country-basin unit.

	Model 1		Model 2		Model 3	
	a	b	a	b	a	b
Annual Precipitation	1.025 (0.947)	0.376 (0.252)				
Temperature	5.726 (9.582)	0.334 (0.606)	7.380 (9.532)	0.371 (0.608)		
Temperature^2	-0.009 (0.017)	-0.001 (0.001)	-0.012 (0.017)	-0.001 (0.001)		
Annual Runoff	0.0001 (0.0005)	0.0003 (0.0003)	0.001* (0.001)	0.001*** (0.0002)	0.001* (0.001)	0.001*** (0.0002)
WASP(-1)	-0.848 (0.526)	-0.929*** (0.279)			-1.028** (0.496)	-1.025*** (0.274)
WASP(+1)	0.062 (0.681)	0.303 (0.317)				
WASR(-1)	1.168** (0.507)	1.093*** (0.345)	0.463 (0.316)	0.373 (0.287)	1.218** (0.550)	1.132*** (0.349)
WASR(+1)	-0.902 (0.559)	-0.919*** (0.349)	-0.726 (0.526)	-0.600*** (0.224)	-0.816 (0.591)	-0.690*** (0.225)
Constant		-46.093 (86.221)		-51.923 (86.426)		3.987*** (1.056)

Significance levels ***: > 99%, **: 95%, *: 90%

A possible reason behind the positive association of WASR(-1) with economic growth is that there may be some country-basin units where surface water runoff is extremely high, and the storage infrastructure is low. Such regions may experience frequent flooding in an average year and avoid the impacts of flooding in low runoff years. To test this hypothesis, time-series regressions were performed for each country-basin unit with the preferred model specification shown in Table 1 (Model 3); the country-basin (CB) units for which WASR(-1) was statistically significant at the 90% level are shown in Figure 3. For each of these CB units, we calculated the per capita total renewable water resources (TRWR). The average per capita TRWR for country-basin units which had a positive WASR(-1) coefficient was 30,040 m^3/year, compared to 8,555 m^3/year per capita for country-basin units with a negative WASR(-1) coefficient. These findings support the hypothesis that the positive effect of anomalously low runoff may be felt the most in country-basin units with high per capita TRWR, and manifested in terms of avoidance of the negative impact of annual flooding.

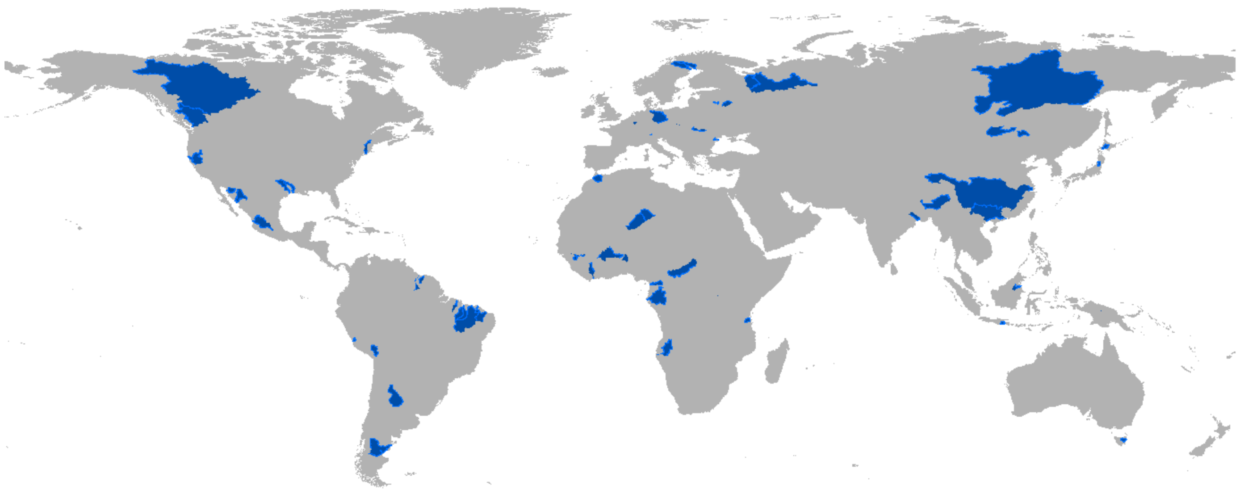

Figure 3: Map showing country-basin units (in blue) where the association between WASR(-1) and economic growth was statistically significant

It should be noted that the statistical significance of the water-related variables does not imply that economic growth is determined by water and related hazards. The total variation explained by the models is quite small. There are many factors that affect economic growth for which these models do not account. From an econometric standpoint this is a positive attribute as it shows that the model is not over-specified. The results are best interpreted as implying that water-related hazards, such as floods and droughts, act as a "headwind" on growth, reducing the economic growth that would have occurred if not for these negative factors. Also, water may be a "tailwind" for growth when it is sufficiently available.

Drought severity and economic growth

The panel regressions show that, on average, extreme precipitation and runoff conditions influence economic growth in a statistically significant manner. However, the effect on economic growth *solely* because of these anomalously low or high 'water' conditions is not immediately clear. In the next investigation, we seek to address this issue by studying economic growth in years with extreme weather conditions. In general, drought conditions are easier to identify than floods. For instance, lower than average precipitation over an extended period of time (months or years) is likely to result in droughts. However, flooding happens on a much shorter temporal scale (order of hours or days), and is thus a lot more problematic to identify with existing datasets which have coarser temporal resolution (monthly or annual). The extent of flooding is also influenced by the existing infrastructure and land use conditions, and so cannot be determined based only on weather conditions. With the climate dataset available for this study, identifying flood conditions is not possible and so we restrict our investigation to measuring drought effects.

We assess the impact of drought on economic growth by calculating the global average economic growth rate for droughts of different levels of severity, where severity is reported in return period years and is based on the threshold of spatial area in drought condition. We use the WASP(-1) index to represent drought conditions. For example, the drought return period of 5 years is observed for a WASP(-1) index value of 0.3, meaning on average 30% of a country-basin's spatial area is in drought with a frequency of approximately 5 years (Naturally the frequency is higher for some countries and lower for others). This analysis conditioned on the extent of drought, revealed a clear relationship between threshold drought levels and the resulting effect on economic growth rates as shown in Figure 4. As drought severity increased, the average global economic growth rate was seen to decrease.

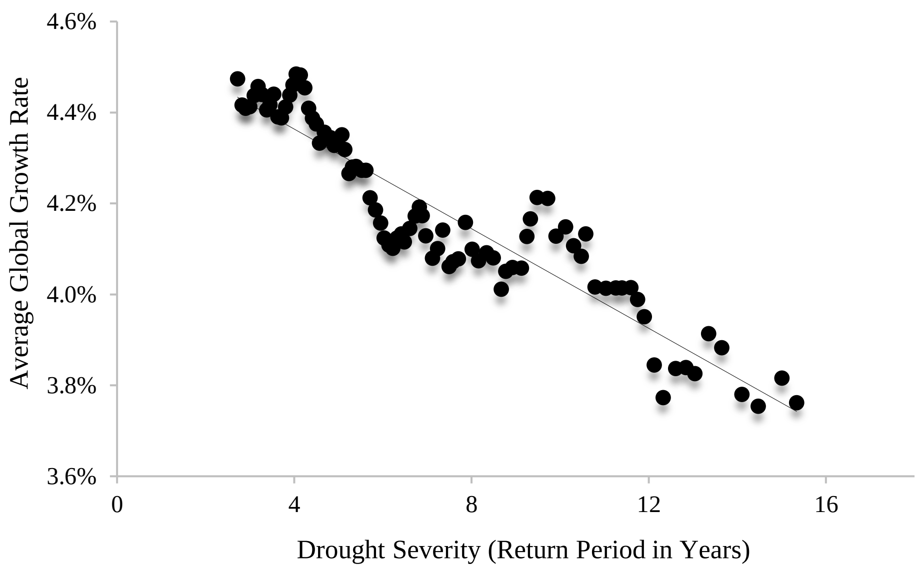

Figure 4: The global average country-basin economic growth rate for drought of a given severity where severity is reported in return period years and is based on the threshold of spatial area in drought condition

The previous analysis shows that globally, an increase in drought severity leads to reduced growth. However, the global analysis does not imply that all regions are affected in a similar manner. To glean more information on a local scale, we performed simulations to assess the cumulative impact of drought on economic growth for *each region*. These simulations compared the growth rates in years with and without drought. A WASP(-1) threshold of 0.3 was chosen to represent the drought effect of most interest, corresponding to a drought frequency of approximately 5 years. For each region, the average growth rate in years when WASP(-1) index is below 0.3 (non-drought years) and when it is above 0.3 (drought years) is calculated. Then the difference between these average growth rates is determined.

$$Drought\ Impact = Ave\ GDP\ growth_{WASP(-1)< 0.3} - Ave\ GDP\ growth_{WASP(-1)> 0.3} \quad (2)$$

Figure 5 below shows a map of the world for country-basins where the difference between the drought and non-drought growth rates is the highest. It must be noted that this investigation is not a significance test but instead shows where the drought effects are strongest. The results show that on average, country-basins in South America, Southern Africa, Middle East and South Asia experience the greatest economic impact of droughts. The most strongly impact country-basin units are in the tropics where hydrologic variability is relatively high. Many of these regions with a higher vulnerability to droughts are also characterized by extensive agriculture. Regions in grey show little difference, or even higher growth, during drought years.

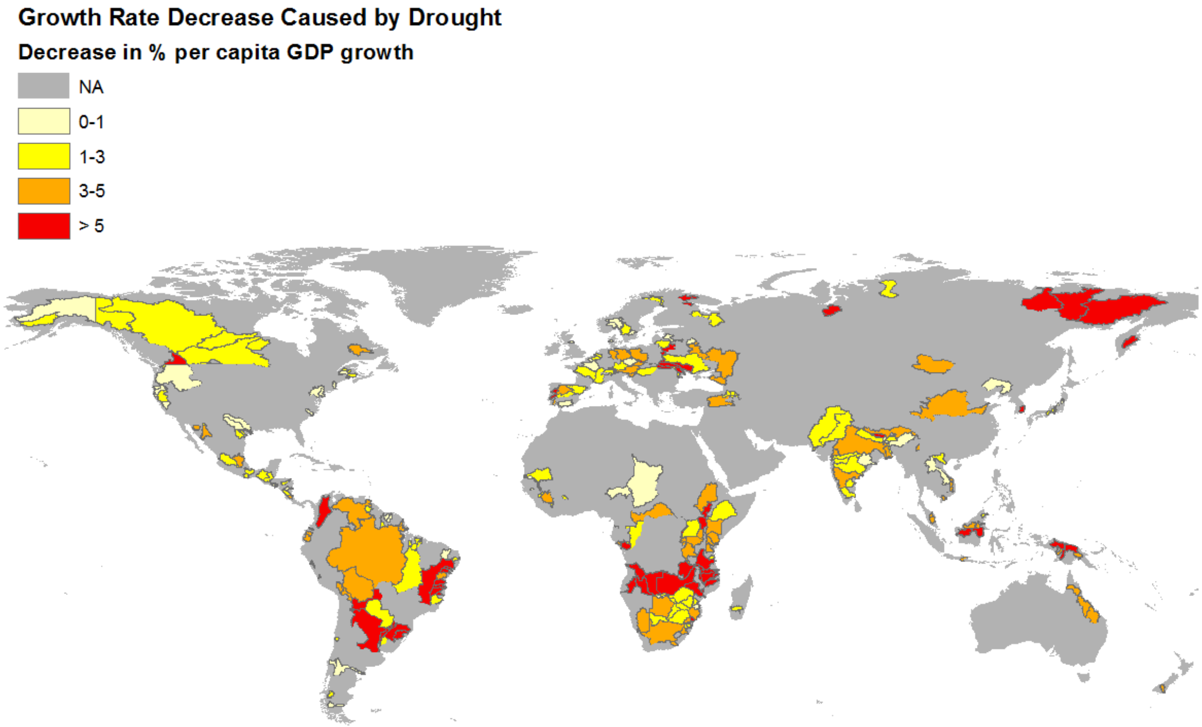

Figure 5: Map showing countries with the largest differences in economic growth between drought years and non-drought years. Drought is defined as >30% of a country's area with rainfall below the drought threshold

Factors affecting vulnerability of regions

The preceding analyses show that water-related climate variables have the most significant impact on economic growth of a region. Next, we explore the various characteristics of a country-basin unit that are hypothesized to make it less or more vulnerable to these water risks. Water risk indicators highlight level of infrastructure and the structure of the economy as important factors to consider when quantifying vulnerability of regions (ADB 2013; Lautze and Manthrithilake 2012). Studies on the economic impact of drought further corroborate the hypothesis that the role of agriculture in the overall economy influences the link between climate variables and economic growth (Schewe et al. 2013). Level of current economic strength, as a proxy for gauging state of infrastructure and institutions, is another factor thought to influence how growth is impacted by climate variables.

To test our hypotheses on possible explanatory factors, we evaluate the impact of climate variables for country-basin units on two differently specified dependent variables. One accounts for varying levels of *economic strength,* the other measures *economic dependence on agriculture* in a new set of panel regressions. Each measure of the dependent variable is matched with the Model 3 predictor variables, and a new set of panel regressions is estimated. In both of these conditioned panel regressions, individual and year fixed effects were used, with the climate variables from the preferred model included in the model.

Classification of countries based on economic level was done using the 2014 World Bank country classification which groups countries based on per capita gross national income (GNI). Countries were divided into three groups: low income (LI), middle income (MI) and high income (HI). For economic dependence on agriculture, countries were divided into two groups based on the percentage of total GDP that agricultural output contributes. Figure 7 shows the cumulative distribution of economic dependence on agriculture for country basins. Based on the dataset, we choose a threshold level of 20% so countries where agricultural output forms more than 20% of total GDP have a high dependence on agriculture. The map in Figure 6 shows the classification of the country-basins, for both economic strength and dependence on agriculture.

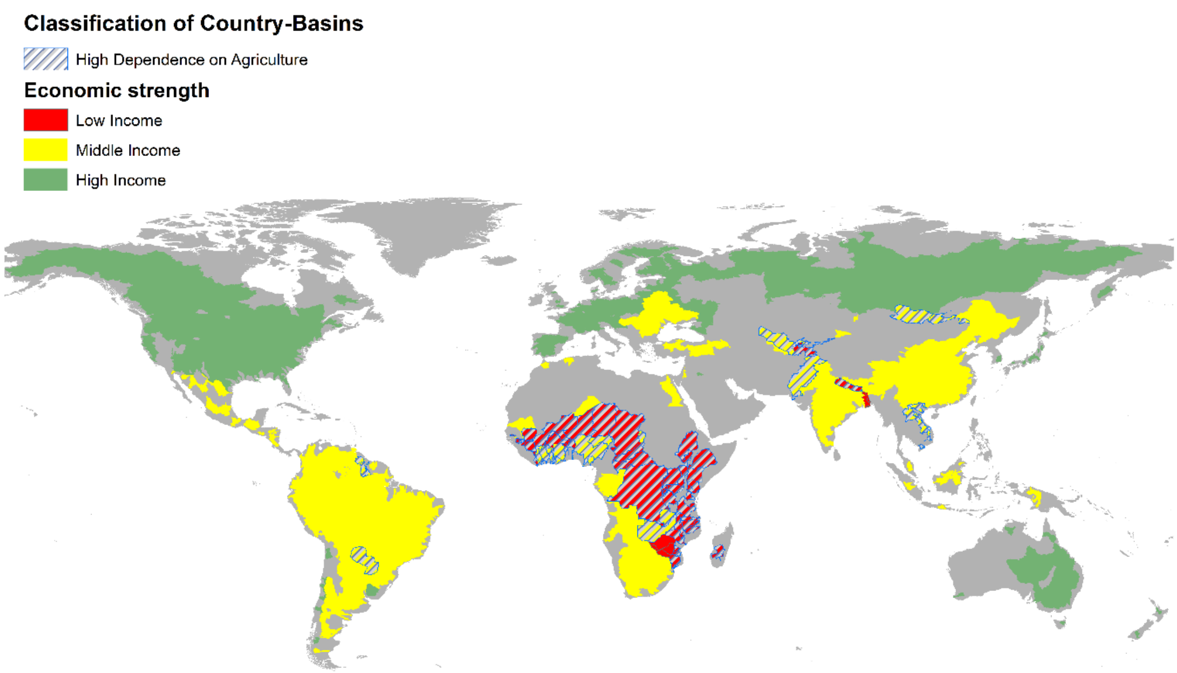

Figure 6: Classification of country-basins included in the conditioned panel regressions. The shade of the region represents the economic strength. The hatched regions represent countries with a relatively high dependence on agriculture. Almost all the CB units with low income are also highly dependent on agriculture. Regions in grey were not included in these regressions

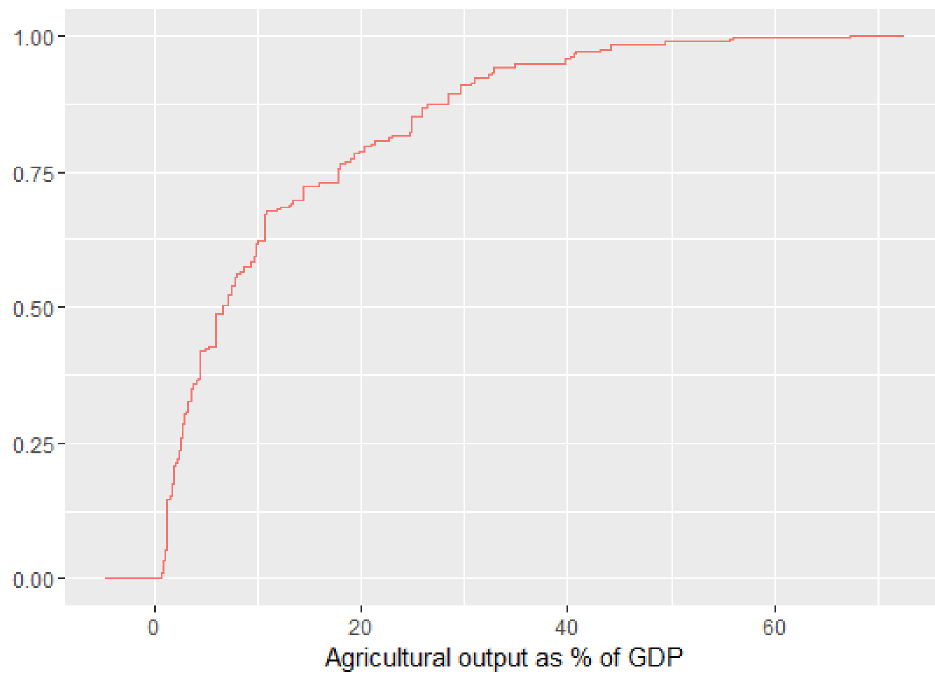

Figure 7: Cumulative distribution of economic dependence on agriculture for country basins

Results from the panel regressions conditioned on income levels and agricultural dependence are shown in Table 5. The results in panel (a) show a few interesting insights. Climate variables have different effects on economic growth when delineating the panels by income level. For CB units in high income countries, none of the climate variables have a statistically significant impact on economic growth. The significance of climate variables is greatest for country-basin (CB) units in low income countries. These results support the hypothesis that CB units in countries that have stronger economies have a greater resilience to hydroclimatic variables and are more water secure. For the CB units in low income countries, the WASR(+1) coefficient is significant and is negative as in previous regressions while the WASP(-1) coefficient is not statistically significant. For the middle income countries, the coefficients for water-related extremes, both floods and droughts, are significant while that for mean runoff is not. This seems to support the hypothesis that some economies are "hampered by hydrology" meaning these countries have made investment in water infrastructure to adequately manage their water resources, yet still remain vulnerable to climate extremes due to their unique hydrology which can have major impact on growth (Grey and Sadoff 2007).

Results in panel (b) of Table 5 show that dependence on agriculture causes differences but to a lesser degree. Hydro-climatic effects on economic growth are stronger in agriculture-dependent countries. Economic growth in such regions is more sensitive to runoff. Regions with less dependence on agriculture (below 20 percent) still show an association with runoff, albeit at a lower magnitude.

Table 5: Country and year fixed effects panel regression results for country-basin units conditioned on (a) income levels, and (b) dependence on agriculture

	(a) Income Level			(b) Dependence on Agriculture	
	Low	Middle	High	Low	High
Annual Runoff	0.006*** (0.002)	0.001 (0.001)	0.002 (0.003)	0.001* (0.001)	0.002*** (0.001)
WASP(-1)	0.414 (0.571)	-1.603** (0.757)	-1.083 (0.767)	-0.936* (0.495)	-1.559 (1.086)
WASR(-1)	0.914* (0.538)	1.933 (1.227)	0.686 (0.445)	1.033** (0.464)	2.986* (1.635)
WASR(+1)	-2.048* (1.206)	-1.721** (0.878)	-1.015 (0.691)	-1.052 (0.749)	-0.233 (0.589)
Country-Basins	75	246	180	385	104

Significance levels ***: > 99%, **: 95%, *: 90%

Factors explaining individual heterogeneity

Next, we try to identify specific metrics that contribute to the sensitivity of regions to water-related climate variables. A lack of time series data for the measures representing water quality, agricultural intensity, governance and extent of infrastructure, prevents their inclusion in the initial analysis since fixed effects regressions do not allow the use of time-invariant measures. These attributes, however, may be the source of some of the heterogeneity among the different CB units. In this exploratory analysis, we use linear regressions to identify characteristics of a region that are most closely associated with its heterogeneity and may be responsible for its different response to hydroclimatic factors.

We use the estimated individual fixed effects ($\boldsymbol{\alpha_i}$) for all CB units from our preferred model (Model 3) as the dependent variable, and regress them against several endogenous measures (Table 1), using the equation shown below. The individual fixed effects, $\boldsymbol{\alpha_i}$, represent the baseline economic growth in each country-basin, with the hydroclimatic variability effects removed. The estimated coefficients, $\boldsymbol{\beta}$, represent the effect of each measure, $\boldsymbol{X_i^k}$, on baseline economic growth rate in a country-basin unit. To account for income effects on the relationships between some of the dependent and predictor variables, per capita GDP and squared per capita GDP variables are included in the models. The predictor variables are standardized.

$$\boldsymbol{\alpha_i = \beta^k X_i^k + \varepsilon_i} \qquad (3)$$

Table 6 shows results of the different regressions performed. The model shown in column (1) includes all the time-invariant predictor variables available to us. Then, we use step-wise regression with two different criteria to select the measures most closely associated with the individual heterogeneity of country-basins. Column (2) shows the model obtained from step-wise regression where the criterion is to maximize the AIC. The variables omitted from this model are not necessarily unrelated to the dependent variable; they are found to provide little additional explanatory effect beyond the measures already selected in the model. In column (3), only the predictor variables significant at a 90% confidence level are included in the model.

The estimated coefficients show a consistent direction of relationship with the dependent variable across all the regression approaches, which is an indication that these estimates are not impacted by multicollinearity. One of the strongest associations seen across all three models is the negative impact of human water stress on baseline economic growth. Human water stress is a measure of water availability relative to population with a higher score representing greater scarcity. These results propose that water scarcity is linked to slower economic growth, a finding supported by a recent study (World Bank 2016) looking at the impact of water on economic growth using a global Computable General Equilibrium (CGE) model which showed that water scarcity propagates through a country's economy and *"remains a significant obstacle to growth and development in the context of a changing climate"*.

The negative coefficient on the per capita GDP term suggests, as expected, that regions with already strong economies grow at a slower rate (when measured in percent terms). The results also show that baseline economic growth is negatively associated with FSI, a measure of strength for water institutions in a country-basin (a higher FSI score means weaker institutions). This correlation between water governance and a country's level of economic development has been recognized previously (Araral and Yu 2013; Saleth and Dinar 2004), and has been emphasized in many development-focused programs (OECD 2015). However, the gains from improvement in water institutions are shown to be linked with the existing water infrastructure (Araral and Wang 2015). Dam density, a proxy for level of water infrastructure in a country-basin, is not statistically significant, and does not feature in either of the refined models.

Another consistent message that emerges is the positive relationship between measures of agricultural intensity and baseline economic growth. Both nitrogen loading, and agricultural water withdrawals are statistically significant in all three models, with a consistent direction of the coefficient, suggesting that regions with high levels of agriculture experience higher economic growth. Access to potable water and sanitation are not observed to be associated with baseline economic growth; these variables are strongly associated with per capita GDP which weakens their statistical significance in the results. When considered collectively, results of the different linear regressions highlight measures of water stress, institutional strength and agricultural intensity as the most relevant in explaining the individual heterogeneity of the country-basins, and thus their sensitivity to hydroclimatic variability.

Table 6: Results from regressions of individual fixed effects from the panel regressions on the endogenous variables. Data for 422 country-basin units was used.

	(1)	(2)	(3)
Access to potable water	0.047 (0.204)		
Access to sanitation	-0.197 (0.227)		
Fragile States Index	-1.375*** (0.297)	-1.400*** (0.255)	-1.348*** (0.253)
Agricultural Water Withdrawal (as % of total water withdrawal)	1.016*** (0.132)	0.945*** (0.124)	0.916*** (0.123)
Agricultural Water Stress	-0.445 (0.32)	-0.338 (0.206)	
Cropland	0.17 (0.295)		
Dam Density	-0.314 (0.23)		
Human Water Stress	-0.815** (0.325)	-0.952*** (0.292)	-1.066*** (0.211)
Total Impervious Surface	0.547* (0.32)	0.558** (0.23)	0.449** (0.208)
Nitrogen Loading	0.836*** (0.183)	0.892*** (0.167)	1.005*** (0.15)
Mercury Deposition	0.344* (0.176)	0.252 (0.161)	
Agricultural per capita GDP	-0.307 (0.197)		
per capita GDP	-3.135*** (0.495)	-3.414*** (0.464)	-3.449*** (0.458)
squared per capita GDP	0.810*** (0.215)	0.881*** (0.21)	0.943*** (0.205)
Adjusted R^2	0.364	0.365	0.362

Conclusions

Water security can be defined as a tolerable amount of risk to water hazards. With the increasing attention being paid towards water security recently, several water security indicators have been developed. While most of these existing indicators are in agreement regarding the important factors determining water security, the formulation of these indicators involves subjective weighting of the importance of different factors and use of expert judgment to assign values for these factors for different countries. While the creation of an empirically-based index is appealing for its credibility there are a number of concerns that accompany the approach. One concern is that the relationships between the variables of interest, although statistically significant may be relatively weak and confounded by random noise that makes statistical inference difficult to conduct successfully. This was found to be true to a certain extent and the methods were adjusted to better account for the noise. Second, being data driven the analysis is limited by the quality of the data. In the present case the data related to climate variables and economic growth are believed to be relatively sound. The remaining data has been collected from a large variety of sources and it is difficult to assess it collectively. For any surprising results a look at the relevant data and sources is a likely starting place. Finally, the analysis is focused solely on economic aspects of water security and in particular negative economic effects. In our view this is the logical starting point given previous work and confidence in the data. However, the analysis approach can be applied to other aspects of water security with the time available and interest in doing so.

A recent review of the field of the water resources systems analysis proposes that future development of the field needs to focus on providing broader fundamental insights about challenges in water management, rather than focusing solely on "methodological peculiars" (Brown et al. 2015). This analysis provides insight into the relationship between hydrology and society, at both the local and global scales. The analysis of the climate variables showed that water availability and water hazards have significant effects on economic growth that are at least as important or likely more important than temperature effects. These results have far-reaching implications for economists assessing the potential economic costs of climate change, emphasizing that water-related impacts should be considered, and studies that neglect water may underestimate the economic consequences of climate change. The results also imply that reducing dependence on water flows and vulnerability to water hazards supports economic growth. Based on the regressions focusing on the endogenous factors, the strongest insight relates to the importance of water scarcity in considerations of economic growth. Water governance and agricultural intensity emerge as the other most significant endogenous factors. Relating to the growing field of sociohydrology, these results represent an important contribution to the understanding of water and society interactions based on empirical evidence.

Returning to the original questions framing this work, the findings indicate that on average, economies are linked with hydrology and suffer negative consequences. Governments have a critical role to play in regulating these linkages between society and hydrology (Lundqvist et al. 2003). It is not clear whether the negative impact of hydrology on economies is due to ignorance, i.e., policy-makers are not aware of this effect, or due to gaps in current approaches to managing risks, i.e., policy makers are aware but using the ill-formed policy (project-based instead of systematic risk management), or due to other pressing needs that are more significant (e.g., education, health, privatization). Regardless of the true cause, better information for policy makers about the economic effect of water-related hazards and the potential benefits of systematic approaches to risk management is warranted and will lead to better informed policy.

Availability of datasets for the level of information services and water infrastructure development in countries worldwide would be essential in formulation of a water security indicator. Such datasets would also be helpful in evaluating and comparing performance of water sector institutions in different regions. This sharing of knowledge could help provide real-world examples of pathways to achieve water security for countries that are water insecure. Another avenue in the development of the water security indicator, one which was not included in this study, could be the inclusion of a dynamic component to water security. This component would enable the water security of a region to be updated in real time based on the changing climate conditions and governance scenarios for that region.

The second framing question relates to the qualities of an economy that influence its vulnerability to water hazards. Unfortunately, the analysis of endogenous factors is limited by the availability of a homogenous, longitudinal dataset that is required to achieve more conclusive results. Further efforts to investigate the results described here will inevitably confront that fact. A more promising investigative direction is the evaluation of specific interventions using the longitudinal panel regression techniques applied here. That is, there is a strong need for longitudinal and pooled analysis of the effectiveness of categories of investments based on large datasets of such projects. For example, there is a surprising paucity of research using rigorous econometric approaches that investigate the effectiveness of investments in water infrastructure that extend beyond cost-benefit analysis of individual projects. Comprehensive investigations based on the available data related to past investments, in some cases requiring the compilation of that data, are likely the best approach for assessing their effectiveness for achieving water security.

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Supplemental Material

Table A1: IEW water institution metrics included in the analysis

Metric	Description
AARINF	Adequacy of information
LINTRE	Degree of integration within water law
LACPRE	Effectiveness of accountability provisions
AACCME	Effectiveness of administrative accountability
LCRMEE	Effectiveness of conflict-resolution provisions
PIRSWE	Effectiveness of water transfer policy
AEXTST	Extent of science and technology application
POPAWE	Impact of other policies on water policy
PGPIUP	Impact of user participation policy
PCOREC	Level of cost recovery
WSPPHY	Overall evaluation of physical performance
AOEFWA	Overall effectiveness of water administration
LOEFWL	Overall effectiveness of water law
POEFWP	Overall effectiveness of water policy
WSPEQU	Overall evaluation of equity performance
WSPFIN	Overall evaluation of financial performance
WIPOEV	Overall evaluation of water institution performance
WSPOEV	Overall evaluation of water-sector performance
WSPECO	Overall evaluation of economic performance
POELWL	Overall linkage between law and policy
ASBUDC	Seriousness of budget constraint
LOECEN	Tendency for centralization in water law

Table A2: Countries for which complete IEW metrics data was available

1	**Australia**
2	Bangladesh
3	Brazil
4	Canada
5	Chile
6	Egypt
7	France
8	India
9	Indonesia
10	Israel
11	Italy
12	Japan
13	Mexico
14	Morocco
15	Namibia
16	Netherlands
17	Poland
18	South Africa
19	Spain
20	Sudan
21	United States