Assessing Economic and Political Impacts of Hydrological Variability on Treaties

Case Studies on the Zambezi and Mekong Basins

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Abstract

International river basins will likely face higher hydrologic variability due to climate change. Increased floods and droughts would have economic and political consequences. Riparians of transboundary basins governed by water treaties could experience non-compliance and inter-state tensions if flow falls below levels presumed in a treaty. Flow information is essential to cope with these challenges through water storage, allocation, and use.

This paper demonstrates a simple yet robust method, which measures gauge station runoff with wetness values derived from satellite data (1988-2010), for expanding sub-basin stream flow information to the entire river basin where natural flow information is limited. It demonstrates the approach with flow level data that provide estimates of monthly runoff in near real time in two international river basins: Zambezi and Mekong. The paper includes an economic framework incorporating information on existing institutions to assess potential economic and political impacts and to inform policy on conflict and cooperation between riparians. The authors conclude that satellite data modeled with gauge station runoff reduce the uncertainty inherent in negotiating an international water agreement under increased hydrological variability, and thus can assist policy makers to devise more efficient institutional apparatus.

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Assessing Economic and Political Impacts of Hydrological Variability on Treaties:
Case Studies on the Zambezi and Mekong Basins*

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INTRODUCTION

Climatic conditions have a direct impact on the hydrology of a river basin. Climatic change will most likely affect the variability of river flows (Jury and Vaux 2005) and have a variety of additional impacts on the hydrologic cycle (Miller and Yates 2006). The change in variability will affect populations who will no longer be able to plan according to current water availability and supply trends (Milly et al. 2008). Changes will not be uniform and each region will experience either increases or decreases in river discharge compared with present observations (Palmer et al. 2008).

Hydrologic variability creates a significant challenge especially for countries sharing international river basins. Unanticipated high flow events or low flow events may lead to flooding damage, severe drought, and/or fatalities. These events give rise to economic shocks and inter-state political tensions. Such tensions have also been found to take place in the intra-state context including even the likelihood of armed violent conflict increasing after natural disasters (Drury and Olson 1998; Nel and Righarts 2008). In the context of inter-state relations, political tensions may ensue even in basins where mitigating institutions (say, in the form of water treaties) have been negotiated. In other words, climate change could increase the probability of flow below treaty specifications and expectations, leading to non-compliance and consequent political tensions between riparians.

Consequently, when designing a water agreement or appending an outdated one, water negotiators from the respective riparian states need to identify what water flow may look like in the future, in order to design the ideal treaty. Having high quality flow data will also determine the appropriate treaty stipulations and institutional mechanisms that can deal with future challenges. Real time data can also provide policy makers with the ability to predict extreme weather events, and address their impact on an existing treaty.

Flow estimation models are already available to policy analysts, but they need improvement to increase the accuracy of the results. This paper contributes to the growing literature of methodologies with a specific application of the Basist Wetness Index (BWI), which is an index used to identify the magnitude of surface water, for the global set of international river basins. The methodology will predict natural runoff with a greater accuracy and level of significance than precipitation data alone, customary in other methodologies. The method
provides a simple and robust model with basin-relevant results for policy, which measures gauge station runoff with wetness values derived from satellite data (BWI) over the period 1988-2010, as proof of the concept on how sub-basin stream flow information can be expanded to the river basin where natural flow gauge information is limited and can provide the possibility of timely updates. Then, we demonstrate the use of the approach for monitoring various flow levels that provide estimates of monthly runoff in near real time in two international river basins, Zambezi and Mekong. We show how information from the model can strengthen the institutional capacity within the basin to understand the probability of various levels of extreme flow, has potential to realize the economic consequences of extreme flow events, and prepares or adjusts proper institutions to address it.

The paper is organized in five sections. Below we begin by couching the discussion of the BWI in a socio-political context by highlighting the links between climate change and water variability, conflict and cooperation, and the role of international institutions such as international water treaties. We also stress the importance of data availability given the uncertainties inherent in climate change and the consequences of water variability. Second, we describe a number of methodologies that have been used to derive flow data and likewise discuss the BWI and demonstrate its use in the Zambezi and the Mekong. Third, we discuss the accuracy and predictability of the BWI’s estimated flow probability models. Fourth, we develop a basin economic model that incorporates the flow probability and the existing institutional frameworks that exist in these basins to gauge economic and political impact. We compare these institutions based on their relevance, structure, and design. Fifth, and in an effort to demonstrate the applicability of the BWI to a growing research agenda on conflict and cooperation over shared rivers, we review historical political events related to floods. We conclude that the satellite data we derive may reduce the uncertainty inherent in negotiating an international water agreement and help policy makers devise more efficient institutional apparatus.

**The Socio-Political Context: Uncertainty, Institutions, and Institutional Capacity**

Although water variability and return periods for extreme events are available across river basins, climate change is predicted to increase such variability (Dai et al. 2009; Milly et al. 2008). One of the
most forceful characterizations of links between climate change and water variability came out of a 2008 Technical Report of the Intergovernmental Panel on Climate Change, claiming that increased precipitation intensity and variability will increase flooding and drought in many areas, which will affect food stability, water quality, as well as exacerbate many forms of water pollution (Bates et al. 2008: 3-4). Such environmental changes could also aggravate political tensions, increasing the vulnerability of certain regions, and present substantial challenges to water infrastructure and services (Vörösmarty et al. 2000: 287; Kabat et al. 2002: vii; IPCC 2007: 49). Climate change may have indirect negative effects that can challenge the legitimacy of governments, undermine individual and collective economic livelihood, and affect human health (Barnett 2003:9). Regions comprised of developing countries that are more reliant on climate sensitive resources may lack the capacity to adapt to climate change impacts, making them more vulnerable to these changes and may fare worse to these changes (Barnett and Adger 2007: 648). Moreover, according to Buhaug, Gleditsch, and Thiesen (2008: 6), unexpected and sudden climate induced events (such as floods and droughts) are expected to constitute a large threat to human security and the prospects of sustained peace.

The transboundary nature of rivers and shared bodies of water further complicates scenarios of climatic and environmental change as inter-state tensions may rise as water variability increases. Evidence suggests that the likelihood of political tensions is related to the interaction between variability or rates of change within an international river basin and the institutional capacity to absorb that change (Wolf, Stahl, and Macomber 2003; Stahl 2005). In this context, climate change may further act as a ‘threat multiplier’ exacerbating existing economic, social, and political problems (CNA 2007: 43) and even contributing to waves of eco-refugees as people attempt to escape ecological devastation (Reuveny 2007).

Given the links between climate change, water variability, economic development, and political tensions, the role of institutions in assuaging potential inter-state conflicts and associated economic and ecological problems seems paramount (Brochmann and Hensel 2009; Salehyan 2008: 317). Such institutions, in the form of international water treaties, may confer a certain level of resilience allowing the participating basin riparians to deal with the perturbations brought upon by environmental change (Adger et al. 2005). However, given the uncertainty that is implicit in climatic change and the consequent effects of water variability, even basins that are governed by international water treaties may be susceptible to the effects of environmental change—mainly, if these institutions were not originally designed to deal with these complex environmental changes
(Drieschova and Fischhendler 2011). As such, water variability may even raise serious questions about the adequacy of existing institutions and transboundary arrangements (IPCC 2001; Cooley et al. 2009) to deal with the economic and political consequences that are likely to follow.

The extant literature has identified a number of institutional stipulations, codified in an international water treaty, which may confer resilience on an international river basin. Most of this discussion is derived from scholars situated in the hydro-politics field. Analysts have identified such mechanisms as monitoring, enforcement, conflict resolution, issue-linkage/side-payment, and joint commission apparatus (e.g. De Stefano et al. 2012). Monitoring stipulations in transboundary settings provide some guarantee that states are complying with the treaty and not free riding. Given the availability of systematic data, a monitoring mechanism may also allow states to estimate the probability of high and low water flow, especially when the water is expected to vary under climate change (Cooley et al. 2009). In the case of non-compliance, an enforcement mechanism allows states the ability to punish defectors (Susskind 1994). Conflict resolution mechanisms provide parties with a forum for discussing resource and environmental changes not envisioned in the treaty (Drieschova, Giordano, and Fischhendler 2008). A side-payment, issue-linkage, or benefit-sharing apparatus provides a level of stability to a treaty in the sense that it restructures the incentives so the parties want to cooperate (Bernauer 1996; Bennett, Ragland, and Yolles 1998; Weinthal 2002; Barrett 2003; Phillips et al. 2006; Dinar 2009). Joint bodies such as an international joint commission or a more formal river basin organization (which brings the riparians together) aid the parties in confronting environmental uncertainties are often mandated to implement necessary projects and generally provide the organizational apparatus needed to discuss issues and problems (Dombrowski 2007; Gerlak and Grant 2009). Empirical studies have confirmed the importance of these individual (or combination of) mechanisms in explaining a variety of outcomes including the abatement of armed conflict as well as more cooperative inter-state behavior (Stinnett and Tir 2011; Dinar S., A. Dinar, and Kurukulasuriya 2011).

Related works in the hydro-politics literature have also pointed to a number of institutional stipulations that may confer resilience in particular situations and for particular treaty issues. For water allocation issues, for example, analysts have argued that when water variability is predicted to increase, a flexible allocation mechanism may fare better than a fixed allocation mechanism (Drieschova, Giordano, and Fischhendler 2008). In other words, a flexible
allocation mechanism that divides the water among the parties by percentage rather than a fixed amount may reduce possible inter-state tensions when future water flows in the basin are uncertain. Other authors have also pointed to various types of variability management schemes (De Stefano et al. 2012). In situations of drought, for example, authors have discussed the utility of stipulations such as consultations, stricter irrigation procedures, water allocation adjustments, specific reservoir releases, and data sharing (McCaffrey, 2003; Turton, 2003; Drieschova, Giordano, and Fisichendler 2008). For flood issues authors have generally argued that the mere existence of a flood-control treaty may confer the necessary resilience (Bakker 2009) while others have stressed a specific flood-control mechanism such as warning systems, channelization schemes, and levees, among other schemes, as the necessary stipulations needed to confer resilience on river basins (Arnell 2002; Drieschova, Giordano, and Fisichendler 2008).

Perhaps even more important in addressing the uncertainty of climate change is the ability to predict the availability and accessibility of water flow data for river basins in near real time. In fact, the above discussed treaty mechanisms and stipulations are most efficiently negotiated and devised when reliable data are available. In this manner, negotiators and water policy makers are able to make educated decisions pertaining to which stipulations to include or which mechanisms should take priority. They are able to anticipate possible shocks or extreme events and design appropriate institutions. In the next section we describe a number of these existing methodologies, used to anticipate future flows, and then discuss the BWI.

**Existing Run-off Estimation Methodologies**

Existing methods that assess global climate change in basins typically calculate river flow predictions in basins by calculating a percent change from a long-term normal base time period compared to predictions provided by the Intergovernmental Panel on Climate Change (IPCC) General Circulation Model(s) (e.g. Alcamo et al. 2003; Milly et al. 2005; Palmer et al. 2008). These methods have several shortcomings. First, global models tend to be complex and require many inputs. Second, global models are useful for global comparisons of basins; however policy work on specific treaties benefit greatly from basin specific applications. Third, the timely nature of the results does not provide continuous updates from the most current observations. Many experts see integrated monitoring systems that include remote sensing and GIS data helpful in
mitigating disaster and conflict (Coskun et al. 2006). With increasing computer processing speeds and data storage, remote sensing and GIS methods to estimate runoff accommodate increasing complexity (Schultz 1994). Finally, many global models use precipitation data as a primary input, which show considerable variance and lack accuracy, as Fekete et al. (2004) demonstrated in the six monthly datasets they analyzed.

Applications of remote sensing to hydrology have improved dramatically over the past decade. Alsdorf et al. (2007) summarize the capabilities of remote sensing to calculate the spatial and temporal variability of water stored on and near the surface of all continents, illustrating this information can be measured reliably from space. A review of the literature notes several examples of specific basin runoff applications. Scipal et al. (2005) present a Basin Water Index to estimate runoff from the Advanced Scatterometer (ASCAT) ERS microwave sensor, with a 50km spatial resolution over the Zambezi River. Papa et al. (2007) apply a multi-satellite technique including Special Sensor Microwave/Imager (SSM/I) to the Ob river basin, which allows them to account for snow parameters that impact river runoff. Finally, the Basist Wetness Index (BWI), derived from SSM/I observations, is used to estimate surface wetness and runoff (Basist et al. 1998). The BWI takes advantage of the global coverage of the SSM/I satellite to observe most of the land surface twice a day, even under various weather and environmental conditions and time of day, because the wavelength of microwave radiation can penetrate cloud cover, dust, haze and rainfall. These observations are binned into 1/3 arc degree (approximately 30 km²) monthly values.

Characteristics of hydrologic extremes vary and a variety of studies specify the distribution function in the analysis according to sample size, low or high flow, and distribution of the sample. Smakhtin (2001) and WMO (2008) provide a review of low flow hydrology, where much evidence suggests the distribution of hydrologic variables is heavy tailed (Katz et al. 2002). Among the distribution possibilities, the gamma distribution is simple and reasonably accurate for runoff models (Singh 2007).

Since future hydrologic variation is difficult to predict without an understanding of historical variation and long term normal averages, the BWI provides historical spatial and temporal coverage to quantify hydrologic variability with a globally consistent methodology and geographic coverage provided by SSM/I. Once the model is established, current observations
from the satellite can provide near real-time estimates of flow. The policy application is to provide a probability of extreme flows in these transboundary basins to inform decisions regarding water obligations and to estimate the current probability of not meeting a particular treaty obligation.

**METHODOLOGY FOR MODELING SURFACE WETNESS WITH FLOW**

**Surface wetness (BWI)**

We utilize a surface wetness index, the Basist Wetness Index (BWI), due to its strong correspondence with flow and availability of monthly time-series data. BWI is derived from SSM/I observations to estimate runoff (Basist et al. 1998). The BWI is based on the emissivity adjustment associated with water in the radiating surface and has a strong correlation with the upper level soil moisture (Basist et al. 2001). This surface wetness is sensitive to liquid water from multiple sources (i.e. precipitation, irrigation, snow melt, rivers, swamps, and lakes), yet the satellite observations are largely insensitive to clouds. This allows measurements to monitor water near the surface under almost all conditions at 30 square Kilometers across the globe (Owe et al. 1992) with accurate measures of the amount of liquid water on or near the earth’s surface (Vinnokov et al. 1999). The index ranges from zero, which represents no water detected near the surface, to all other values, which represent the percentage of radiating surface that is liquid water. The index takes the form of a linear relationship between channel measurements (Equation 1), where a channel measurement is the value observed at a particular frequency and polarization (i.e. the SSM/I observes seven channels).

\[
BWI = \Delta \varepsilon \cdot T_s = \beta_0 [T_b(v_2) - T_b(v_1)] + \beta_1 [T_b(v_3) - T_b(v_2)]
\]

where the change of emissivity, \( \Delta \varepsilon \), was empirically determined from global SSM/I measurements, \( T_s \) is surface temperature over wet or dry land, \( T_b \) is the satellite brightness temperature at a particular frequency (GHz), \( v_n \) (e.g. \( v_1, v_2, v_3 \)) is a frequency observed by the SSM/I instrument, \( \beta_n \) is an empirically derived correlation coefficient: \( \beta_0 \) and \( \beta_1 \) are estimate coefficients.
**Precipitation**

Since precipitation is an important determinant in runoff, a simple precipitation runoff model is calculated for the catchment study areas in order to compare accuracy and level of significance against the BWI runoff model. We hypothesize that the BWI regressed with gauging station flow is better than precipitation predicting flow pass a gauging station, which we test using a $R^2$ test. The hypothesis is based on the realization that runoff is compounded by many factors: such as snow melt, soil texture, irrigation, solar isolation, relative humidity, and wind speed. All these factors are difficult to measure separately and they vary spatially from in situ observations. The satellite captures the spatial structure, and the BWI integrates all the above factors into one observation at each grid point (Basist et al. 2001).

**Runoff**

We identify the correspondence between regional BWI and the rate of flow at various gauging stations. The findings allow us to evaluate the relationship between the two variables and determine if useful results can be observed from the statistical models of stream flow. In order to perform the estimates, the measuring station must have a sufficiently long observation period of record (minimum of four years – as long as possible) and the period of record corresponds with the SSM/I data, which is available from 1988 until present\(^5\), except mid-1990 through 1991.

**Integrating BWI and runoff in GIS**

Since both the BWI and runoff are geo-referenced, the model calculates the BWI over the area upstream of the gauging station. The Geographic Information System allows for the spatial delineation of the upstream area, using HydroSHEDS\(^6\) (Lehner et al. 2006) for a model of flow accumulation and direction. Since impoundments and/or diversions affect the amount and timing of water reaching the gauge, we used GIS to display the geo-referenced dam data

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\(^5\) We have used data until 2009 in this analysis.

\(^6\) HydroSHEDS is a dataset in the public domain of conditioned Shuttle Radar Topography Mission (SRTM) elevation data (90m resolution) that used a series of processing steps that alter the elevation values in order to produce a surface that drains to the coast (except in cases of known internal drainages). Further steps include filtering, lowering of stream courses and adjacent pixels, and carving out barriers to streamflow. Flow accumulation and flow direction grids (30 arc seconds) were downloaded at: http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php.
upstream of gauge stations, and exclude upstream watersheds with large-scale obstructions (e.g. dams) from the analysis

**Regression analysis variables**

Two models relating flow to current and past BWI values are presented for two basins. We regress the BWI values on the gauging station runoff per month (Equation 2) where \( Q \) is discharge at a station for month \( m \), and \( n \) is number of previous months or lag months.

\[
Q_m = g \left( \frac{\sum_{i=0}^{n} BWI_{m-i}}{n} \right)
\]  

(2)

We investigate whether lag periods improve the statistical correlation of the BWI and gauging station runoff. Lagged runoff values are the average of the concurrent and the previous month(s). We suggest that the size and topography of the catchments strongly influence the duration of the lag. First, snowmelt “captures” the accumulated precipitation and delays the flows until the melting inside the snow pack “releases” the water, which can further increase the lag time. Second, since the BWI integrates one value to represent the total area of accumulation, the size, slope and land use in the area impacts the lag time. For example, this model is much simpler in form than the model in Herold and Mouton (2006).

Like Equation (2), we regress precipitation, \( P \), of the basin on the gauging station runoff per month (Equation 3).

\[
Q_m = f \left( \frac{\sum_{i=0}^{n} P_{m-i}}{n} \right)
\]  

(3)

**Requirements for the model**

Two basic components are fundamental for successful modeling of flow: an accurate measure of the actual surface and subsurface flow on a regular time frame, and a predictive parameter that identifies how the gauge data will fluctuate due to the changes in weather and land use across the basin. The model identifies the probability function for various levels of flow and determines the explanatory accuracy and significance of the model.

The optimal data conditions for the BWI necessitate natural flow upstream of a gauging station. The sensitivity of the SSM/I signal to water restricts our use of the instrument near coasts, since the wetness signal would saturate the results; it is unusable near large bodies of
water. Therefore, we limited our watershed to be at least 50 Kilometers from a large body of water. Due to the spatial resolution of the data, each observation has a diameter of about 30 kilometers. As a result, the basin needs to be greater than several hundred Kilometers in area in order to have numerous satellite observations over the river basin. Finally with regards to the hydrological cycle, the basin must contain natural inter- and intra-annual variability of flow, in order for the data to contain natural variations over the period of record. Surface wetness performs best in areas without high vegetation, yet arid regions can be difficult too, due to the intensity of the water flow (e.g. flash floods) that may not be recorded by the orbit of the satellite.

**Regression to predict ex-post river flow**

All rivers have extreme events in flow. Correlating historical record of flow with known flood events allows us to examine whether the BWI corresponds with variations in flow rates in near real-time. As an illustrative example, ex-post knowledge of a flood in a basin is used to test the statistical models’ estimate of runoff. We used both gauge data and meteorological data to validate the model’s accuracy. Results are reported in the next section.

**Estimating probabilities of extreme flow**

The probability distribution function (PDF) describes the likelihood for an amount of runoff to occur at a given time. This distribution makes it possible to provide statistics on the likelihood of low and high flow within a treaty basin. All parameters have been estimated, assuming a gamma distribution derived from the sample *L-moments* (as per Hosking 1990, 1995; Hosking and Wallis 1997) using the “lmomco” package (Asquith 2007) in R (R Development Core Team 2008). *L-moments* are summary statistics for probability distributions and data samples computed from a linear combination of the ordered data values\(^7\). It provides measures of Arithmetic mean, *L-scale*—analogous to standard deviation, skewness, kurtosis, and other aspects of the shape of probability distributions or data samples. Then, the “cdfgam” function

---

\(^7\) Gubareva and Gartsman (2010) provide a review of the advantages of the *L-moments* method.
computes the cumulative probability or nonexceedance probability of the Gamma distribution given shape and scale parameters of the distribution computed from the \textit{L-moments} parameters. In addition, the “lmomco” package is used to create 0.90 confidence intervals for BWI derived from a Monte Carlo simulation. This PDF gives estimates for both low- and high-flow.

\textbf{Risks of being below treaty supply parameters}

Applying the probability density function, a theoretical estimation of runoff can provide a probability of low flow, and, in the case with specific water requirements, this probability can be extended to estimate the probability of treaty non-compliance.

\textbf{ASSESSING THE PERFORMANCE OF THE MODEL}

\textbf{Basin selection}

One of the leading databases on international river basins, Transboundary Freshwater Dispute Database (TFDD), reports on 276 international river basins. The foundation of a defensible model has several necessary requirements that apply to the selection of gauge and satellite data (Table 1 includes a summary of these criteria and references) in order to select the basins. Natural (unimpeded) flow is a fundamental assumption of the model. Therefore regulated rivers are identified through GIS survey of TFDD international river basin. ESRI ArcGIS defined watersheds from 3535 gauging stations (GRDC) within international river basins derived from the HydroSHEDS database. The universe of unregulated multilateral basins with available

8 There is much evidence that the distributions of hydrologic variables are heavy tailed (Katz et al. 2002). This is even more pronounced in arid and semi-arid environments (Anderson et al. 1998; and Farquharson, Meigh, and Sutcliffe 1992).

5 The cumulative distribution function of the distribution has no explicit form, but is expressed as an integral:

\[
F(x) = \frac{\beta^{-u}}{\Gamma(\alpha)} \int t^{\alpha-1} e^{-t/\beta} dF
\]

where \( F(x) \) is the nonexceedance probability for the quantile \( x \). The parameters have the following interpretation in the R syntax; \( \alpha \) is a shape parameter and \( \beta \) is a scale parameter.

10 A small correction factor of up to approximately 2 Km is used to snap the location of the gauging station to the HydroSHEDS 15 second flow accumulation grid based on the highest flow accumulation value. A correction factor of 1 Km yielded several inconsistencies between the reported station catchment area from GRDC and the area
gauging station data are summarized for each watershed. This includes dam location data (Food and Agricultural Organization on Africa dams 2006; Meridian Global Dam Database 2006; and hydro power plants (CARMA 2009). Global Lakes and Wetlands Database (Lehner and Döll 2004) identified areas of large bodies of water (which are usually impoundments) within the international river basins. After possible selection, the data are loaded into Google Earth (version 5.2.1.1329) for further visual inspection of impoundments from the imagery as well as georeferenced photos. In addition, we searched for 4 years from 1988 to present of available runoff data, yet there was an extensive search for periods of records that overlapped the 20+ years of the SSM/I instruments. Since the satellite resolution and a number of observations inside the basin should have structure, a restriction was imposed that the watershed should be at least 50,000 Km².

We selected two international river basins that met the stringent set of technical assumptions and had significant previous international relations and socio-economic data upon which to draw: Mekong and Zambezi. A limited number of basins fit the technical criteria, which reinforces the notion that many international basins are significantly altered from natural flow and the other basins do not have sufficient gauging station information. More precisely, Nilsson et al. (2005) provide a global overview of dam-based impacts on large river systems that finds over half (172 out of 292) are affected by dams, including the eight most biogeographically diverse. Moreover, World’s Water report (2010) has a global total of 47,655 dams (see 1998-1999, Table 12). With regards to gauging station information, Vörösmarty et al. (2001) highlight the need for additional river discharge data (especially since the mid-1980s).

River basin characteristics

The two rivers included in this analysis vary in basin characteristics. The Mekong and Zambezi represent a magnitude of river lengths (4350 km and 2,574 km) and basin areas (788,000 km² and 1,390,000 km², respectively). These basins are international and have a critical role in the socio-economics of the riparian states including: food, water, transportation, electricity, natural resources, and cultural identity. Both basins are governed by treaties (TFDD 2008). Table 2 summarizes and compares river basin statistics including: geographic and socio-economic calculated from the watershed delineation in ESRI ArcGIS, which we suggest is due to the level of precision in the coordinates compared to the HydroSHEDS flow accumulation grid.
variables. Table 3 displays the predicted climate change for the two selected basins by Palmer et al. (2008). Due to the constraints of obtaining natural flow data, the sample areas are upstream sections of the gauging station and represent a portion of the entire river basin. They are around 25% of the entire set of tributaries of the rivers that they represent.

Data

Runoff data with location coordinates were collected from the Global Runoff Data Centre (GRDC). GRDC provided available monthly time-series gauging station data in the international river basins (approximately 3500 stations). While the GRDC is the source of comprehensive data on global gauging station data, the data are available in limited time periods and the distribution of gauge data is not even across the globe; gauges are mainly located on main stem rivers in middle and high income countries.

The model of precipitation data is from the CRU 3.0 Global Climate database downloaded from http://badc.nerc.ac.uk/data/cru/ (accessed 2010) with data from 1901 to June 2006 (in preparation, see Mitchell and Jones 2005). These data have a spatial resolution of 0.5 degree.

SSM/I derived surface wetness data description

The BWI uses observations from the Special Sensor Microwave Imager (SSM/I). It is a seven channel passive microwave radiometer operating at four frequencies (19.35, 22.2, 37.0, and 85.05) and each channel has dual-polarization (except at 22.235 GHz which is V-polarization only). The frequencies flown on the SSM/I are used to dynamically derive the amount of liquid water near the surface. Data are available from 1988 to present except mid-1990 through 1991 and this analysis uses data until 2009.

Statistical procedures and calibration of the runoff models

In order to relate the BWI to the flow gauge data, we use the XL-stat software to run a quadratic univariate regression equation. The independent variable is BWI and the dependent variable is the flow data. Initial results from a simple coincident model did not account for a natural lag that occurs between the period of time when the moisture falls on the surface and the arrival of the water at the downstream gauge in the basin. Therefore, we performed several lagged relationships, realizing that the duration of the lag would depend on the basin’s size, topography, soil type, and land-use. In performing this analysis we used monthly data, allowing lag to occur
at monthly time steps, i.e. the BWI values were the average of current and previous month(s) values, and these were regressed against monthly river flow data from a particular month. The results section highlights the best-lagged relations obtained from this process. Likewise, in order to relate the BWI to the precipitation data, we use the XL-stat software to run a quadratic univariate regression equation, with various lags.

**RESULTS**

**General model**

We tested the accuracy, significance, and explanatory power of precipitation and BWI models for each basin (Tables 4, 5, and 6). Results identify the accuracy of the flow estimates for each independent variable. The BWI has a superior relationship to the fixed effects of topography and basin area to the lag in downstream runoff, i.e. small and steep basins have a faster discharge of water with limited lag. The best relationships in the model have lagged relationships based on the speed of flow, resembling a Kinematic wave moving throughout the river basin. The accuracy of this relationship increased in the section where wetness values and gauge values were at the low end of their spectrum, which indicates that the wetness values can accurately measure the occurrences of low flow events. The lag in this area demonstrates the period of time that it takes for a prolonged dry period to translate to reduced flow downstream, or conversely, how long excessive rainfall will be detected at the gauge downstream.

**Model results by basin**

**Zambezi**

In the Zambezi model \( Q_m \) is a function of \( x(BWI) \) (Equation 2), and \( Q_m \) as a function of \( x(precipitation) \) (Equation 3), where

\[
x = \frac{\sum_{i=0}^{n} BWI_{m-i}}{n}, \text{ and } n = \text{number of months lagged}
\]

\[
x = \frac{\sum_{i=0}^{n} P_{m-i}}{n}, \text{ and } n = \text{number of months lagged}
\]

The results are:

\[
Q_m(BWI) = 749.26 - 1358.3x + 886.25x^2 \quad (R^2=0.688)
\]
Comparing the models, the Zambezi BWI flow model has higher accuracy and significance than the Zambezi precipitation model. The BWI model flow signature is clearly curved; it has a quadratic signature of high wetness values and extreme flow. High BWI values display considerable heteroscedasticity, which implies that numerous factors impact the high rate of flow past the gauge. In contrast, low BWI values (less than 1) contain a high confidence that the flow will be near the base flow. As a result, the BWI can be a quantitative indicator for periods and frequencies of flow associated with limited water – of particular interest to water obligations in treaties at the gauging station. Due to its quadratic nature and no wetness values below 0.3, the intercept is not realistic. Therefore, an approximate limit of documented flow occurs at a wetness value of 0.3. The flow at this time is around 100 to 200 m$^3$/s averaged across a month at the gauging station.

This relationship of the gauge reading and BWI has a gamma distribution, i.e. there is a much higher probability that flow will occur in the low rate, however, the vast majority of the water moving through the basin occurs in the limited periods of high flow (this relationship is central to the reason why societies invest in dams and reservoirs on rivers.) Using the gamma distribution, this probability of a limit flow (BWI = 0.3) occurs 7% of the time. For the Zambezi River at the Katima Mulilo station, approximately 25% of the time the flow is greater than 277 m$^3$/s per month, and this value corresponds to an equivalent BWI value of 1 (Figure 1.1-1.9).

Since a strong correspondence between the wetness and gauge values is present, the wetness anomalies can be used to identify the probability of various levels of flow. In areas where there are accuracy and high significance levels in predicting the wetness, it can represent the functional form of the probability distribution, and help derive the return period$^{11}$ of extreme events. Predictive accuracy and high significance levels in the models also substantiates its value as a real time monitoring tool, in order to support mitigation.

\[ Q_{m(\text{precip})} = 255.07 + 8.996x - 0.001x^2 \quad (R^2=0.346) \]

---

$^{11}$ The return period is a statistical measurement denoting the average recurrence interval over an extended period of time.
**Mekong**

In the Mekong model $Q_m$ is a function of $x(BWI)$ (Equation 2) and $Q_m$ as a function of $x(\text{precipitation})$ (Equation 3), where

$$x = \frac{\sum_{i=0}^{n} BWI_{m-i}}{n}, \text{ and } n = \text{number of months lagged}$$

$$x = \frac{\sum_{i=0}^{n} P_{m-i}}{n}, \text{ and } n = \text{number of months lagged}$$

The results are:

$$Q_m(BWI) = 384.66 + 124.5x + 504.48x^2 \quad (R^2 = 0.597)$$

$$Q_m(\text{precip}) = 640.87 + 22.521x + 0.00593x^2 \quad (R^2 = 0.624)$$

The Mekong BWI flow model has nearly the same accuracy and significance as the Mekong precipitation model. The best correspondence occurred with two month lags in both models. Based on the data and the BWI model, the results exhibit a high confidence that when the average wetness value drops below 1.0 the flow will be below 1000 cubic meters per second. The best explanatory model had a quadratic function quite similar to the Zambezi; once again it implies that the runoff has a positive non-linear relationship with the mean wetness value. It also states that flow below 800 cubic meters per second (0.8 in the wetness index) is rare (Figure 2.1-2.9).

**Predicting runoff from currently available monthly BWI: Zambezi Case**

Since the satellite with SSM/I is currently operational, it is possible to use the fitted model to predict recent runoff from the SSM/I monthly wetness values to date. Due to the higher accuracy and significance of the model and larger period of record of the Zambezi results compared to the Mekong, we highlight the Zambezi basin to demonstrate the ability of the BWI derived model to predict seasonality, low flow, and high flow events (e.g. floods) in order to explore the utility of these models to serve as an early warming indicator.

The model for the Zambezi river basin captured the seasonality compared to previous years, since this basin has a clear wet and dry season each year. More importantly, the model identified and predicted a flood in 2007, which according to the model is the highest since the extreme flood of 2004 (Figure 3). Numerous sources confirm these model predictions of severe
flooding (e.g. NASA 2006) that the flood impacted close to 285,000 people, who are living in the Zambezi valley (AFROL.COM 2009). These findings demonstrate that the model can be used to emulate the various and inter-seasonal flow in the Zambezi. Furthermore, findings illustrate the potential application of the BWI to predict extreme events in numerous basins around the world, particularly when precipitation and gauge data are limited.

DEMONSTRATING USE OF THE MODEL FOR ECONOMIC AND INSTITUTIONAL ANALYSIS

How can the results of the flow probability be utilized for policy purposes in each of the basins? We first discuss a framework to incorporate economic considerations for dealing with flows above and below normal (or in other words, above and below the long term mean flow level that is the basis of the treaty). The framework builds on Peck and Adams (2012).

In this simple framework, countries rely on water for their economic development. Annual water allocation decisions are made in two stages a basin, where a water treaty regulates the water allocation of water by country. Water flows much below and above the mean may inflict damage to socio-economic infrastructure (noted as the first stage), or conversely, the over capacity cost of infrastructure to regulate water resources can put economic pressure on the society (noted as the second stage). Policy makers can reduce the damage by considering different allocation policies and the cost and benefits of these two decision making solutions (i.e. first and second stage). The simple country level model is:

\[
\text{(4) } \quad \text{Max}_{x,y} \pi = - \sum_i c_i x_i + \sum_i \sum_n (r_{in} y_{ln}) \cdot p_n
\]

\[\text{s.t.}\]

\[
\text{(5) } \quad \sum_i x_i \leq R
\]

\[
\text{(6) } \quad \sum_i a_{ik} y_{lk} \leq W_n \quad \forall k
\]

\[
\text{(7) } \quad y_{lk} \leq b_{ki} x_i \quad \forall k, i
\]

\[
\text{(8) } \quad x_i, y_i \geq 0
\]

where,

\[\pi = \text{the welfare from water use}\]
$x_i$ = a first-stage decision variable for the $i^{th}$ activity (e.g. water storage for activity $i$, irrigated agriculture or hydropower).

$c_i$ = cost associated with $x_i$ (e.g. cost associated with storing water for $i$); at the time $x_i$ is chosen

$k$ = state of nature of water availability (e.g. if water supply is the random variable, then $n =$ below mean, mean, above mean flow)

$y_{ik}$ = a second-stage decision variable for the $i^{th}$ activity given that the $k^{th}$ state of nature occurs (e.g. acres of crop $i$ to irrigate or units of hydropower to produce, given state $n$ has been realized)

$r_{ik}$ = a coefficient associated with activity $y_{in}$ (e.g. revenue per acre of crop $i$ or unit of hydropower generated, given the $k^{th}$ state of nature is realized)

$p_k$ = the probability of the $k^{th}$ state of nature occurring (taken from the BWI analysis)

$R$ = resource availability in the first stage (e.g. total land available, or area of sites for storage)

$\alpha_i$ = a coefficient associated with activity $y_{in}$ (e.g. acre-inches of water required per acre of crop $i$ given the $k^{th}$ state of nature is realized)

$W_k$ = resource availability when given the $n^{th}$ state of nature is realized (e.g. total irrigation water available)

$\beta_i$ = a coefficient linking second-stage activity levels to first-stage activity levels (e.g. acres of crop $i$ planted in the second-stage cannot exceed acres prepared for crop $i$ in the first stage, or storage used cannot exceed available storage, in which case $\beta_i = 1$).

Kuhn-Tucker conditions of the Lagrangian of (4)-(8) provides:

$\alpha = c_i + \gamma \cdot \beta_i$, and

$\gamma = r_{ik} \cdot p_k + \beta \cdot \alpha_i$

where $\alpha$, $\beta$, $\gamma$ are the shadow values of constraints (5)-(7), respectively.

By combining and re-arranging we get $p_k \cdot r_{ik} = \frac{\alpha - c_i}{\beta_i} - \beta \cdot \alpha_i$. This means that in the optimal solution the expected value from an additional unit of activity in the second stage should
be equal to the difference between the opportunity cost per unit of land used and the opportunity cost of water used in the second stage on that land. As clearly seen, the higher $P_k$ the higher $\alpha$ and the lower $\beta$, as $c_i, b_i,$ and $a_i$ are constants.

Assuming that the information related to all parameters of the model is available we can use $p_k$ (probability of the water flow) to calculate the optimal solution. The probability distribution of the water flow is provided in Figures 1.6 and 1.8 for the Zambezi and 2.6 and 2.8 for the Mekong. The results suggest that the mean flow (range) is $750\pm100$ and $1900\pm200$ $\text{m}^3/\text{second/month}$ for the Zambezi and Mekong, respectively. Therefore, the probability of having below mean, mean, and above mean flows respectively is .65, .15, and .20 for the Zambezi, and .30, .20, and .50 for the Mekong. These values can be used in an empirical analysis to evaluate the impact of stochastic flow on the economy of each of the basin states.

Flow probability information provides valuable information to policy makers. Nonetheless, the nature of a treaty and its institutional content are important to support the resilience of the riparian countries dealing with extreme flow events. Extreme flow events produce economic losses, hardships, and damages, which are reflected in grievances and complaints by or cooperation among the basin riparians. How can the basin riparian states prepare better treaties to address such possible deviation from the mean flow? What kind of institutional arrangements could be put in place to address such events? Are treaties ‘equipped’ with such regulations and are institutions more resilient? In an effort to answer at least one of the above questions with implications for the other queries posed we review historical political events related to river flows (droughts and floods) identified by the BWI. In this context, we also highlight BWI’s utility for research on conflict and cooperation over water.

**BWI’S VALUE FOR RESEARCH ON CONFLICT AND COOPERATION OVER WATER**

The river flow data provided in the BWI provide hydrological and physical data required to investigate the links between water scarcity/variability and conflict and cooperation over water. To date, scholars have used national measures of water availability per capita as well as precipitation and drought to explore how physical water scarcity affects inter-state conflict (Toset et al. 2000; Hensel et al. 2006; Gleditsch et al. 2006). A similar methodology has been
used by scholars investigating inter-state cooperation over water (Brochmann and Hensel 2009; Tir and Ackerman 2009; Dinar et al. 2011). Most recently, scholars have also considered the role of water variability across time on hydro-political relations between states (e.g. Dinar et al. 2010; De Stefano et al. 2012). Given some of its advantages (e.g. ability to predict natural runoff with a higher accuracy and high significance levels than precipitation and measure the magnitude of extreme events particularly when precipitation and gauge data are limited), the BWI, therefore, provides another measure of water flows that scholars can utilize in their socio-political studies. In particular, the data provided by the BWI befit recent calls by scholars for better measures of “dynamic scarcity” which make better use of satellite imagery and meteorological data to account for time-varying measures of water availability (Buhaug et al. 2008).

To illustrate the utility of the BWI for the cooperation and conflict analysis, we show how actual past water related political events are distributed over time relative to the extreme weather events (particularly floods) which the BWI identifies in this study. To that extent, we utilize the Basins at Risk Data Base (TFDD website n.d.), which contains a database of historical water relations (such as events) documenting historical incidents of international water cooperation and conflict, and comb the databank for relevant flood-related events that transpire around the flood periods identified by the BWI. This exercise is not intended to confirm any type of causation between hydro-political events and extreme weather events as this will require a much more robust econometric approach utilizing control variables. We simply wish to demonstrate the value of the BWI (among the other measures of water variability and supply) for systematic and empirical research.

Various studies have already used the TFDD Basins at Risk database to make certain arguments about conflict and cooperation over water (Wolf, Stahl & Macomber 2003; Yoffe at al. 2004; Stahl 2005) and the application of the BWI can prove useful for ascertaining how physical phenomenon (such as droughts and floods) interact with political, economic, and social variables to explain some of these political events. An analysis of Mekong and Zambezi Treaties with regards to types of complaints and analysis of Mekong and Zambezi Treaties with regards to the water regulation mechanisms and existing institutions is provided in Tables 7 and 8, respectively. Below we begin with the Mekong and proceed to the Zambezi.

In regards to the flood events pertaining to the Mekong, the BWI predicted heavy flooding in August through October 1988, August and October 1989, and August through
September of 1993. Table 9 depicts all of the events that pertain to flooding after 1988. As there are a large number of events pertaining to the Mekong, we arbitrarily limit our event enumeration to events that took place within a three year span of time after the last flood identified. In total we present 30 events. The majority of the events are cooperative in nature (with only one event considered conflictive in nature). One of the events also represents an international water treaty signed in the basin. Although only an anecdotal finding, we note that the various floods in the region have elicited a relatively high number of cooperative events among the riparians.

In regards to the flood events pertaining to the Zambezi, the BWI predicted a flood in 2007. Floods (of the 2007 magnitude) were also identified in 1989, 1993, 1998, 1999, 2000, 2001, and 2003. A flood was also identified in 2004 but of a slightly more severe magnitude than 2007. A look at the water related socio-political data as it pertains to events associated with the Zambezi River Basin reveals six cooperative (interestingly, rather than conflictive) events associated with these flood events. Table 10 presents these events from The Basins at Risk Database (TFDD, n.d.) following the first major flood reported by the BWI—1989. These cooperative events, with one event constituting an international water treaty, are (like the Mekong case) perhaps one indication that the severity of the floods led the parties to different forms of cooperative action.

**CONCLUDING DISCUSSION**

The paper introduces an analytical framework to assess the impact of variability of river flow on international river basin treaty stability, which includes economic, social and political impacts. Policy makers can use these probabilities to assess mechanisms that impact treaties, thereby allowing institutions to develop mitigation to extreme events. The probability of non-compliance of a treaty obligation can help policy makers identify the relative risk and economic impacts. In addition, the estimated hydrological variability and flow probabilities provided by the BWI can be used to forewarn of future extreme events, thus minimizing their vulnerability and stress during periods of low or high water levels. Finally, we believe that the BWI provides appropriate and more accurate water variability data, compared to other predictive variables such
as precipitation. Therefore, it can provide more accuracy in socio-political studies investigating conflict and cooperation over water.

In particular, results from this paper demonstrate that the BWI and rainfall runoff models did have a highly significant explanatory power of down-stream gauge measurements; however the BWI model has higher accuracy and significance level compared to rainfall in the Zambezi, while a negligible difference exists in the Mekong. Moreover, the accuracy of the BWI increased under low flow conditions, which reveals its utility in high risk situations, allowing it to serve as an independent measure of risk and its probability of occurrence. Results from the modeled flow in the Zambezi illustrate its potential value as a predictive tool for many river basins around the world. Specifically, the BWI-based model accurately predicted from a satellite the magnitude of floods months in advance. It accomplished this result by measuring the magnitude of water entering the watershed upstream of the lower basin.

Building on the results from this study, future work will refine the methodology and applications. Specifically, the methodology can be extended beyond the stringent set of assumptions in this paper thereby allowing policy makers to monitor flow in regulated rivers. In addition, the basin economic model can benefit from further development and expansion of the model to other river basins.

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| Parameter                                      | Data source                                                                 |
|------------------------------------------------|------------------------------------------------------------------------------|
| No impediments to natural flow upstream       | FAO Africa dams; Meridian Global Dam Database (2006); and powerplants - CARMA (www.carma.org) |
| Gauging station data: location, discharge, and year (minimum of 4 in between 1988-2009) | Global Runoff Data Centre                                                   |
| Greater than 100 Km from major water bodies  | Global Lakes and Wetlands Database (2004)                                    |
| Sufficient amount of rain for detection      | SSM/I                                                                        |
| International River Basin                    | Transboundary Freshwater Dispute Database (TFDD, 2008)                      |
| Catchment area upstream of gauging station is as large as possible to provide many observations and degrees of freedom for the model | 15 second accumulation and flow direction grids (HydroSHEDS, 2006) |

**Table 1**: Selection of river basins criteria and catchment upstream of gauging station data source.

| Parameter                              | Mekong   | Zambezi   |
|----------------------------------------|----------|-----------|
| Length (km)                            | 4,350    | 2,574     |
| Area (km²)                             | 787,836  | 1,390,000 |
| WB Region                              | EAP      | SSA       |
| Population density / km²               | 71       | 21        |
| Population²                            | 55,800,000 | 28,800,000 |
| Treaty with water quantity             | Yes      | Yes       |
| River basin organization               | Mekong River Commission | Zambezi River Authority |
| Riparians                              | China, Burma, Thailand, Laos, Cambodia, and Vietnam | Zambia, Angola, Namibia, Botswana, Zambia, Zimbabwe, and Mozambique, |
| Snowmelt                                | No       | No        |

**Table 2**: Selected river basins have a range of physical and socio-economic characteristics

| Mekong | Zambezi |
|--------|---------|
| -1.0   | -12.6   |

**Table 3**: Palmer et al. predict the relative change (%) of discharge in selected river basins from 1960-1990 (km³ yr⁻¹) compared to 2050s (km³ yr⁻¹)

12 The selection is based on greater or equal to 50,000 Km²
13 Population statistics based on Landscan 2000 estimates summarized by basin (TFDD, 2008).
### Table 4: Geographic results of BWI and Precipitation models for Mekong and Zambezi

| Variable                  | Unit                  | MEKONG       | MEKONG       | ZAMBEZI      | ZAMBEZI      |
|---------------------------|-----------------------|--------------|--------------|--------------|--------------|
|                           |                       | BWI          | PRECIPITATION| BWI          | PRECIPITATION|
| Sample area (km\(^2\))   | 189,000               | 189,000      | 334,000      | 334,000      |
| Basin area (km\(^2\))    | 787,836               | 787,836      | 1,390,000    | 1,390,000    |
| Sample area of basin (%)  | 24.0                  | 24.0         | 24.0         | 24.0         |

### Table 5: Descriptive statistics of variables used in regression

| Variable                  | Unit                  | MEKONG       | MEKONG       | ZAMBEZI      | ZAMBEZI      |
|---------------------------|-----------------------|--------------|--------------|--------------|--------------|
|                           |                       | BWI          | PRECIPITATION| BWI          | PRECIPITATION|
| Precipitation             | mm per month          | 70.229       | 50.028       | 800.871      | 6158.064     | 50           |
| Wetness value             | Index                 | 1.725        | 0.580        | 0.774        | 3.031        | 50           |
| Lagged runoff             | m³/s per month        | 2266.331     | 1487.285     | 800.871      | 6158.064     | 50           |

**MEKONG** (1988-1990, 1992-1993) at Chiang Saen

**ZAMBEZI** (1988-1990, 1992-2006) at Katima Mulilo
| Parameter | Value |
|-----------|-------|
| **Mekong – BWI model** | | |
| pr1 | 384.660 (0.314) |
| pr2 | 124.496 (0.087) |
| pr3 | 504.480 (1.302 *) |
| Lag time (months) | 2 |
| Observations | 50 |
| DF | 47 |
| RMSE | 963 |
| R² | 0.597 |
| **Mekong – Precipitation model** | | |
| pr1 | 640.873 (1.844 **) |
| pr2 | 22.521 (2.072 **) |
| pr3 | 0.00593 (0.0915) |
| Lag time (months) | 2 |
| Observations | 50 |
| DF | 47 |
| RMSE | 930 |
| R² | 0.624 |
| **Zambezi- BWI model** | | |
| pr1 | 749.262 (3.379 ***)|
| pr2 | -1358.335 (-4.054 ***)|
| pr3 | 886.249 (8.009 ***)|
| Lag time (months) | 3 |
| Observations | 201 |
| DF | 198 |
| RMSE | 611.915 |
| R² | 0.688 |
| **Zambezi – Precipitation model** | | |
| pr1 | 255.066 (1.914 **) |
| pr2 | 8.996 (3.024 ***)|
| pr3 | -0.001 (-0.0440) |
| Lag time (months) | 3 |
| Observations | 201 |
| DF | 198 |
| RMSE | 886.463 |
| R² | 0.346 |

Table 6: Parameters of the BWI and Precipitation models for both basins: Mekong and Zambezi. In parentheses are t-values. *** (p<0.01); ** (p<0.05); * (p<0.10).
Table 7: Analysis of Mekong and Zambezi Treaties with regards to types of complaints

| Type                                                                 | Mekong                  | Zambezi                |
|----------------------------------------------------------------------|-------------------------|------------------------|
| Agreement year and context                                          | 4/1995 Multilateral     | 7/1987 Multilateral    |
|                                                                      | 8/1965 Multilateral     | 7/1987 Zambia-Zimbabwe  |
|                                                                      | 4/1995 Multilateral     | 7/1987 Zambia-Zimbabwe  |
|                                                                      | 5/1987 Multilateral     | 5/1987 Multilateral    |
| Strong verbal expressions displaying hostility in interaction         | 0                       | 0                      |
|                                                                      | 1                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
| Mild verbal expressions displaying discord in interaction             | 17                      | 17                     |
|                                                                      | 6                       | 6                      |
|                                                                      | 11                      | 11                     |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
| Total conflicting events                                              | 17                      | 17                     |
|                                                                      | 7                       | 7                      |
|                                                                      | 11                      | 11                     |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
| Neutral or non-significant acts for the inter-nation situation        | 6                       | 6                      |
|                                                                      | 1                       | 1                      |
|                                                                      | 6                       | 6                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
| Minor official exchanges, talks or policy expressions, mild verbal support | 94                      | 94                     |
|                                                                      | 19                      | 19                     |
|                                                                      | 90                      | 90                     |
|                                                                      | 3                       | 3                      |
|                                                                      | 1                       | 1                      |
|                                                                      | 1                       | 1                      |
|                                                                      | 3                       | 3                      |
| Official verbal support of goals, values, or regime                   | 16                      | 16                     |
|                                                                      | 7                       | 7                      |
|                                                                      | 12                      | 12                     |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 31                      | 31                     |
| Cultural or scientific agreement or support (nonstrategic)            | 4                       | 4                      |
|                                                                      | 2                       | 2                      |
|                                                                      | 16                      | 16                     |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
| Non-military economic, technological or industrial agreement          | 33                      | 33                     |
|                                                                      | 7                       | 7                      |
|                                                                      | 32                      | 32                     |
|                                                                      | 1                       | 1                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 1                       | 1                      |
| Military economic or strategic support                                | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
|                                                                      | 0                       | 0                      |
| International Freshwater                                             | 6                       | 6                      |
|                                                                      | 2                       | 2                      |
|                                                                      | 6                       | 6                      |
|                                                                      | 18                      | 18                     |
|                                                                      | 2                       | 2                      |
|                                                                      | 2                       | 2                      |
|                                                                      | 21                      | 21                     |

35
Treaty; Major strategic alliance (regional or international)  

| Total cooperating events<sup>b</sup> | 143 | 37 | 156 | 22 | 3 | 3 | 56 |

<sup>a</sup>Source: Dinar et al (2011)

<sup>b</sup>In multilateral treaties the number of events is a sum over complaints between all relevant riparians.

**Table 8 : Analysis of Mekong and Zambezi Treaties with regards to the water regulation mechanisms and existing institutions**

| Type of BAR | Mekong | Zambesi | Mekong | Zambesi | Mekong | Zambesi | Mekong | Zambesi |
|-------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Agreement year and context | 4/1995 Multilateral | 8/1965 Thailand - Laos | 4/1995 Multilateral | 5/1987 Multilateral | 7/1987 Zambia-Zimbabwe | 7/1987 Zambia-Zimbabwe | 5/1987 Multilateral |
| Water Regulation | | | | | | | | |
| ALLOCATION METHOD (0/1) | 1 | 0 | n/a | 0 | 1 | 1 | n/a |
| TYPE OF ALLOCATION METHOD | | | | | | | | |
| ADDITIONAL CODING FOR ALLOCATION METHOD | Percentag e | 0 | n/a | 0 | Fixed, recouped in next period | Fixed, recouped in next period | n/a |
| ADDITIONAL CODING FOR ALLOCATION METHOD | Fixed, recouped in next period | 0 | n/a | 0 | Fixed, varies by water availability | Fixed, varies by water availability | n/a |
| SPECIFIC FLOOD CONTROL MECHANISM (0/1) | n/a | n/a | 1 | n/a | n/a | n/a | 0 |
| Institutions (0/1) | SELF-ENFORCEMENT MECHANISMS | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| MONITORING | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| ENFORCEMENT | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| CONFLICT RESOLUTION | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| COMMISSION /COUNCIL | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| ADAPTABILITY MECHANISM TO DROUGHT (0/1) | 1 | 0 | n/a | 1 | 0 | 0 | n/a |
### Table 9: Basins At Risk (BAR) events: Mekong

| BAR Event Index Measure | BAR Event Description |
|-------------------------|-----------------------|
| **1** (Minor official exchanges, talks or policy expressions, mild verbal support) | January 16, 1990  
The delegation of the International Interim Mekong Committee (IIMC) of Laos, headed by Vongsaid (the deputy minister of trade & foreign economic relations & president of the committee) attended the 30th session of the committee held on 1/8-10. The delegation discussed various matters pertaining to the development of the Mekong Basin, especially projects for developing water resources in Lao PDR, the 1st proposed comprehensive project, multipurpose development at Nam Ngok & Nam Koua, & the protection of rare wild animals. Some projects relating to other member countries were raised at session. The committee will also addressed development of hydrologic & meteorologic network, flood forecasting & reduction of its damages, data collection, relocation of people, & socio-economic & environmental effects. Lao & Vietnam delegates considered including some projects in the action plan of the IIMC for 1990-92, but the Thai delegation requested time for thorough consideration & will make its decision by 3rd session over 4/24-27/90 |
| **1** (Minor official exchanges, talks or policy expressions, mild verbal support) | 2/7/1990  
A workshop on cooperation between Lao PDR & the International Mekong Committee was opened on 2/6/90. In opening address, Bounnaphon pointed to main tasks of the committee. These tasks include the interaction, recommendation & follow-up of planning & study of water resources development in the lower Mekong basin. The committee's role in the region, the Mekong Committee & Lao PDR's development & planning in the lower Mekong area, & water resources development in Lao PDR were also discussed. |
| **2** (Official verbal support of goals, values, or regime) | November 19, 1990  
Thailand Foreign Minister Pinkhayan will propose a joint venture project on dam & reservoir construction on the Mekong River during a visit to Vientiane on 11/18-19. The minister was received a positive response (i.e., an agreement) from Lao & Vietnamese ministers to his proposal to revive the Mekong Interim Committee projects on cooperative power development in the lower basin. Even though much money has been spent on feasibility studies for these projects & projects on Mekong tributaries have been implemented, none on the main river have been started. Regarding the Pha Mong dam project between Nong Khai & Laos & the Nam Tuen dam project in Laos, Subin said he didn't mind which project was chosen. He told Lao Minister Phoun that water resources development (i.e., construction of reservoirs & dams) is an obvious area of Thai-Lao cooperation for mutual benefits. |
|   | November 22, 1990 |   |
|---|---|---|
| 1 | The Interim Mekong Committee welcomed proposal to cooperation with China in exchanging technical information on the Mekong River, Thai Foreign Ministry source said today. The Committee will meet on 11/28 to further discuss details about cooperation with China. The idea was proposed by Thai Foreign Minister Pinkhayan during a trip to China early this month as part of a plan to include China & Myanmar in Committee. China was receptive to Pinkhayan's proposal & expressed willingness to extend all kinds of cooperation to the Committee, which comprises countries in the river's lower region (i.e, Thailand, Laos, Cambodia, & Vietnam). Exchange of info will enable the Committee to get access to info on the upper Mekong River, including information on water levels & current flows which directly affect the hydrography of the lower part of river. |
|   |   |   |
| 2 | January 1, 1991 | Cambodia requests reactivation of Mekong Committee. |
|   | January 1, 1992 | Thailand cancels Mekong Committee Plenary meeting. Thailand requests that UNDP remove its Executive Agent from the Mekong Committee. UNDP complies. |
|   | February 5, 1993 | The governments of Vietnam and Laos, in addition to Cambodia's Supreme National Council, have approved agreement for cooperation in development of the Mekong River that is to be signed here on February 5. Two preparatory meetings called by UNDP in October and December made this possible after a long absence of Cambodia in participating in developing the river's resources. |
|   | February 5, 1993 | The Agreement on Cooperation and Development of the Mekong River was signed on February 5 in Hanoi. Thailand Deputy Foreign Minister Surin, who attended signing ceremony, expressed his hope that the agreement will pave the way for closer cooperation among four Mekong Committee countries, allow Burma and China to be included in the committee, and lay a foundation for future cooperation along the entire length of the Mekong River. After signing, the working group will set up |
| Date       | Event Description                                                                                                                                 |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| February 5, 1993 | Senior Thailand and Vietnam officials will be joined by counterparts from two other main riparian states of Mekong River--Cambodia and Laos--in a 2-day working group session continuing through tomorrow. The four countries' vice ministers of foreign affairs tomorrow will sign cooperation agreement that provides legal basis for endeavor. The respective governments in recent weeks have endorsed the agreement being signed tomorrow. The agreement consists of a joint communique in which the countries reaffirm their continued cooperation for sustainable use of the river's resources and guidelines are established for the working group on future cooperation framework. Issues addressed were largely organizational. It is clear that Hanoi (Vietnam) is not in favor of expanding membership to include China and Burma. |
| August 19, 1994 | Thailand, Burma, Cambodia, China, Laos, & Vietnam yesterday took a major step toward development of science & technology by drafting guidelines on further cooperation. The countries discussed 2 guiding principles on the 1st day of the 1st International Congress on Science & Technology for Cordial Relationships among Neighboring Countries: (1) fairness, transparency, & consensus of opinion; & (2) development of science, technology, & human resources to improve economic & social well-being. Science, Technology, & Environment Minister Mulasatsathon (Thai ?) identified water resources & rice as important issues that need joint development. Vietnam Science, Technology, & Environment Minister Huu cited environmental pollution, exploitation of natural resources & other adverse impacts as examples that the region should try to prevent. |
| November 1, 1994 | Last November, an agreement on cooperation for sustainable development of the Mekong River Basin was initiated by Cambodia, Thailand, Laos, & Vietnam, possibly after a compromise between Thailand, which controls a large part of the upper stretches of the river, & Vietnam, which contains the Mekong delta. |
| November 17, 1994 | China & Thailand researchers will join hands in a study of the Langang-Mekong River valley. According to a 3-day seminar on regional & economic cooperation & sustainable development, which ended |
| Event | Date | Details |
|-------|------|---------|
| Wednesday, verbal support | | Wednesday, an agreement was reached by the 2 sides to conduct research from 1995-2002. Research will relate to 4 topics: nationalities & cultures, history & population distribution, regional cooperation & trade, management of natural resources, & environmental changes. Money will be provided by the Asian Development Bank & US Ford Foundation. US, Japan, & Canada scholars participated in the seminar. |
| 1 (Minor official exchanges, talks or policy expressions, mild verbal support) | January 8, 1995 | In early April, Chiang Rai will host historic signing ceremony for an agreement on use of water resources by 4 countries in the lower Mekong basin. The agreement re-established the Mekong River commission, ending 3 years of mutual mistrust, said a senior official from the Foreign Ministry. The most important part of the draft agreement is the change in regulations governing the use of river water which say a country only has to seek permission from members for inter-basin projects--schemes to divert water from the main body of river in dry season. The new framework will permit Thailand to continue the Kok-Ing-Nan water diversion project (as it is on a tributary) & will bring development of infrastructure & hydroelectric generation. See article for more details. |
| 2 (Official verbal support of goals, values, or regime) | April 5, 1995 | The Thai government yesterday approved a draft agreement on cooperation between the 4 lower Mekong River states which will allow Thailand to proceed with previously controversial water development projects. The agreement is scheduled to be signed on 4/5, & once signed will give birth to the Mekong River Commission (which replaces the Mekong Committee established in 1957). The agreement deals with rules & criteria for water use & diversion & allows greater freedom for implementation of water development projects. The only project needing agreement is diversion of water from mainstream in dry season. None of Thailand's proposed projects need agreement. The new agreement also encourages the countries to cooperate on mainstream projects, which include the revised Pha Mong Dam across the Mekong between Thailand & Laos & construction of a bridge across the river. |
| 6 (International Freshwater Treaty; Major) | April 5, 1995 | Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin |
| Strategic Alliance) | April 5, 1995 |
|-------------------|--------------|
| 4 (Non-military, economic, technological or industrial agreement) | The 4 downstream Mekong riparian countries signed an agreement on Wednesday on cooperating to sustainable development of the Mekong River basin. Under the agreement, the Mekong Council & joint committee were set up to coordinate cooperation on matters relating to the development of the Mekong basin, especially on water diversion & hydropower projects. |

| 2 (Official verbal support of goals, values, or regime) | April 7, 1995 |
|------------------|--------------|
| The Mekong Council agreed yesterday to invite China & Burma to participate in the council's 1st formal dialogue in Phnom Penh in an attempt to draw cooperation of all riparian countries for sustainable development of Mekong River, after Thailand responded to gestures from Cambodia, Laos, & Vietnam in their welcoming messages on Wednesday for participation of the two other nations of the upper Mekong River Basin. China & Burma will be invited to participate in the 1st formal meeting of Mekong Council & the joint committee, said a Thailand delegate. |

| 1 (Minor official exchanges, talks or policy expressions, mild verbal support) | April 18, 1995 |
|------------------------|--------------|
| China has indicated willingness to involve itself in subregional cooperation among countries of the Mekong River Committee. Foreign Ministry statement released yesterday said China welcomed agreement among Mekong countries, which was designed to serve as a framework for sustainable development of the Mekong basin. China Science & Technology Minister Hui said China is interested in promoting cooperation between upstream & downstream countries. The agreement to cooperate involves jointly developing natural resources, transportation, agriculture, fisheries, commercial navigation, & culture along the Mekong, especially in south Yunnan province, Hui said. |

| 2 (Official verbal support of goals, values, or regime) | April 20, 1995 |
|------------------|--------------|
| Construction of new dams in China will help prevent Thailand from abruptly disastrous floods, a Thailand expert said today. Maiklad, the inspector-general of the Ministry of Agriculture & Cooperatives, was quoted by a Thailand news agency as saying that China's plan to construct 9 dams on the Mekong River will help hold water in the rainy season & reduce risk of floods. New dams will prevent flooding in Cambodia, Vietnam, & Laos as well. New dams will also help these countries have enough water in the summer. |
|   | Neutral or non-significant acts for the international situation |   |
|---|----------------------------------------------------------|---|
| 0 | October 24, 1995                                         |   |
|   | The officials of 6 Mekong Basin countries - Vietnam, Laos, Cambodia, Thailand, Myanmar, Burma, & Yunnan province of China - began a 2-day meeting on Monday aimed at unifying development of infrastructure & introducing the opportunity to investors in development of the Mekong region. Participants promised to continue cooperating in the sub-region, but complained about the lack of funding for important projects. On Tuesday, highlights in the discussion were procedures for project approval, project assistance, environment priorities, & avoidance of double taxation. |   |

|   | Neutral or non-significant acts for the international situation |   |
|---|----------------------------------------------------------|---|
| 0 | October 24, 1995                                         |   |
|   | Beijing is considering its level of participation in the upcoming Mekong River Commission (MRC) meeting, but stressed that its presence shouldn't be taken as a commitment to becoming a member. China's plan for construction of 9 dams on the upper Mekong in south Yunnan province posed no harm to downstream Vietnam, said Zhang, the subcommittee member of development for Regional Cooperation. Zhang said recent visit by officials from Hanoi to 1 of the dam sites in Yunnan had cleared up "misunderstandings" about environmental impacts. He said no conflict exists between China & Vietnam over use of the river. If there is any conflict, it's between Thailand & Vietnam, he added. China projects detailed in article also. Zhang said China would expect its relationship with the group to be a forum for technical & economic cooperation. To accept principles of water usage under MRC is still beyond Beijing's expectation however. |   |

|   | (Minor official exchanges, talks or policy expressions, mild verbal support) |   |
|---|-------------------------------------------------------------------------|---|
| 1 | November 9, 1995                                                        |   |
|   | Thailand will support Laos' bid to host Secretariat Office of Mekong River Commission (MRC) in Vientiane, Foreign Minister Kasemsi announced yesterday prior to his departure to Vientiane to attend the 5th Thailand-Laos Commission. MRC is re-creation of 38 year-old Mekong Committee, established last April by the Foreign Ministers of Thailand, Vietnam, Cambodia, & Laos. The four countries signed a framework agreement on sustainable development of water resources from the Mekong River. Now, the Commission is considering the location of the MRC Secretariat. |   |

|   | (Minor official exchanges, talks or policy expressions, mild verbal support) |   |
|---|-------------------------------------------------------------------------|---|
| 1 | November 9, 1995                                                        |   |
|   | Burma & China have both expressed interest in Mekong River Commission itself, but fall short of becoming members for fear of losing sovereignty over right to use the river's water. |   |
| Date       | Event                                                                 | Description                                                                                                                                                                                                 |
|------------|----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| January 5, 1996 | The Prime Minister issued a decision defining the function, obligation, scope of activities & organizational structure of Vietnam's National Mekong River Committee (VNMRC) on 12/30/95. The Minister has the control to manage the Committee's cooperation activities with the Council of the Mekong River Commission (MRC), Mekong nations, NGOs, & domestic units to reasonably exploit & protect water resources & other natural resources in basin. VNMRC is to cooperate with its counterparts from other member-countries of the MRC to organize implementation of an agreement on cooperation & sustainable development of the Mekong River Basin. It will supervise & manage water & other resources, protect Vietnam's interests through master plans & cooperation projects, & cooperate with others to protect & develop the basin. |
| March 20, 1996 | The Mekong Joint Committee agreed that the next session will be held in 3/97. At the 3rd session which closed yesterday, the Committee discussed plans & measures relating to the development of the Mekong River basin, draft regulations on the use of river's water, the 1997 action program for the International Mekong River Commission & UNDP-funded projects for Mekong River basin. The Commission held the working session with 2 observers - China & Myanmar. |
| May 5, 1996 | In reply to questions from Thailand journalist at a meeting with representatives from the Thai media, visiting China Vice Premier Zhu Rongji, who is on a week-long official visit to Thailand, said the 2 countries have a long history of friendship & no disputes. Regarding future Sino-Thai economic cooperation, Zhu cited hydroelectric power generation, development of the upper reaches of Mekong River basin, etc. |
| July 22, 1996 | China Vice Premier & Foreign Minister Qichen said today that China supports exploitation of the Mekong which will benefit economic development of region. During a meeting with Laos Foreign Minister Lengsavat, Lengsavat said development of bilateral relations is going well. Lao has set up a joint committee for Lao-China economic & trade relations. Lengsavat also thanked China for its positive attitude towards the development of Mekong River & hoped that cooperation will |
April 1996

August 5, 1996

Vietnam & Thailand should cooperate in implementation of Mekong development projects, with the aim of turning region into land of prosperity, said Vietnam Prime Minister Kiet. During Cold War, cooperation in development of utilization of the Mekong River region was hampered by political factors. Under new framework & name, the Mekong River Commission encompasses new spirit of cooperation between Thailand & Vietnam & other riparian countries, Kiet said, noting they've now pledged to increase cooperation & have brought in nonriparian countries to help plan development programs.

August 31, 1996

Cambodia Planning Minister Chea Chanto urged help to remedy siltation in the Mekong River & shallowing of the Tonle Sap Lake.

October 25, 1996

Laos & Cambodia agreed that a decision on the site of the Mekong River Commission (MRC) headquarters, which they both want, should be made by the body's ministerial council, in consultation with donor countries. Like other international development organizations, the MRC resolves matter through consensus. This approach enabled the eventual resolution of drawn-out squabble between Thailand & Vietnam over a rule for water utilization, a controversy that threatened to torpedo the only multi-state river organization in Southeast Asia until 1995.

Table 10: Basins At Risk (BAR) events: Zambezi

| BAR Event Index Measure | BAR Event Description |
|-------------------------|-----------------------|
| 6 (International Freshwater Treaty; Major Strategic Alliance) | August 28, 1995
Protocol on Shared Watercourse Systems |
| 1 (Minor official exchanges, talks or policy expressions, mild verbal support) | October 14, 2002
Mozambique’s director of the Zambezi Valley Planning Office has called for basin countries to meet and jointly manage the water resources of the valley. |
| Event                                                                 | Date          | Details                                                                                                                                                                                                                                                                                                                                 |
|----------------------------------------------------------------------|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 4 (Non-military economic, technological or industrial agreement)     | July 9, 2004  | Water ministers from the eight basin countries met to sign the agreement on the establishment of the Zambezi Water Course Commission (ZAMCOM). The collaborative management strategies include strategic efforts towards sustainable development and flood control.                                                                                           |
| 2 (Official verbal support of goals, values, or regime)              | December 6, 2007 | The Zambezi Action Plan 6, a Southern African Development Community initiative, was designed and discussed. The initiative focuses on efforts to mitigate unnecessary flood damage that frequently devastates basin countries by increasing data sharing, communication, and cooperative water management between basin countries. |
| 2 (Official verbal support of goals, values, or regime)              | December 6, 2007 | Zambezi basin countries met at the third Zambezi Stakeholders Forum to address sustainability and development. Officials committed to addressing the loss of wetlands as a major focus of a Joint Management strategy. The implementation of a Joint Management commission has yet to be ratified.                           |
| 1 (Minor official exchanges, talks or policy expressions, mild verbal support) | October 25, 2008 | The eight countries that share the Zambezi River met to discuss technical water management strategies, including data sharing that will improve Joint Management efforts. Leaders also pushed for ratification of the establishment of the Zambezi Commission. The commission will jointly manage the basin but requires the support of two thirds of the basin countries. |
Figure 1.1: Average of estimated flow (m³/s per month, y-axis) and precipitation (mm per month, x-axis) in sample catchment area of the Zambezi river basin in a nonlinear regression.

Figure 1.2: Predicted flow (m³/s per month, x-axis) versus calculated average flow (m³/s per month, y-axis) in sample catchment area of the Zambezi river basin from the precipitation model.
Figure 1.3: Average of all flow (m³/s per month, y-axis) and wetness index (index, x-axis) in sample catchment area of the Zambezi river basin in a nonlinear regression.

Figure 1.4: Predicted (m³/s per month, x-axis) versus calculated average flow (m³/s per month, y-axis) in sample catchment area of the Zambezi river basin from BWI model.

Figure 1.5: Observations in years (x-axis) and the residuals (m³/s per month, y-axis) of the Zambezi river basin BWI model. SSM/I data is not available from mid-1990 through 1991, thus no residuals are in the figure.
Figure 1.6: Zambezi Probability Distribution of Flow using a gamma distribution (percent, y-axis) and flow (m³/s per month, x-axis) of the Zambezi river basin sample area.

Figure 1.7: Zambezi PDF plot of 90% confidence intervals generated from a Monte-Carlo simulation (n=1000). Log10 (Confidence interval) on the y-axis and non-exceedance probabilities. Green is the upper bound of the CI and red is the lower bound of the CI.

Figure 1.8: Cumulative Distribution of Flow using a gamma distribution (percent, y-axis) and flow (m³/s per month, x-axis) of the Zambezi river basin sample area.

Figure 1.9: Map of Zambezi basin (grey) with the selected gauge data (point), international border (line), and respective catchment (hatched).
Figure 2.1: Average of all flow (m³/s per month, y-axis) and precipitation (mm per month, x-axis) in sample catchment area of the Mekong river basin in a nonlinear regression.

Figure 2.2: Predicted flow (m³/s per month, x-axis) versus calculated average flow (m³/s per month, y-axis) in sample catchment area of the Mekong river basin from precipitation model.
Figure 2.3: Average of all flow (m³/s per month, y-axis) and wetness index (index, x-axis) in sample catchment area of the Mekong river basin in a nonlinear regression.

Figure 2.4: Predicted (m³/s per month, x-axis) versus calculated average flow (m³/s per month, y-axis) in sample catchment area of the Mekong river basin from BWI model.

Figure 2.5: Observations in years (m³/s per month, x-axis) and the residuals (m³/s per month, y-axis) of the Mekong river basin model. SSM/I data is not available from mid-1990 through 1991, thus no residuals are in the figure.
Figure 2.6: Probability Distribution of Flow using a gamma distribution (percent, y-axis) and flow (m³/s per month, x-axis) of the Mekong river basin sample area

Figure 2.7: Mekong PDF plot of 90% confidence intervals generated from a Monte-Carlo simulation (n=1000). Log10 (Confidence interval) on the y-axis and non-exceedance probabilities. Green is the upper bound of the CI and red is the lower bound of the CI.

Figure 2.8: Cumulative Distribution of Flow using a gamma distribution (percent, y-axis) and flow (m³/s per month, x-axis) of the Mekong river basin sample area

Figure 2.9: Map of Mekong basin (grey) with the selected gauge data (point) and respective catchment (hatched).
Figure 3: The Zambezi values of runoff (m³/s per month, y-axis) and time (month / years, January 1988 through August 2009) display seasonality with both the observed gauging station data (blue) and the estimated values from the Zambezi runoff model (pink) (see Equation 4). The dashed line represents no SSM/I data.
1. **Annex: Agreements related to extreme flow events (water allocation, hydropower and flood) in the Mekong and Zambezi**

1.1. **Mekong; August 12, 1965; Laos and Thailand (hydropower)**

The Mekong is governed by one agreement that pertains to hydropower and is signed by both Laos and Thailand. This agreement was signed on August 12, 1965. Although this is a hydropower sharing agreement no specific allocation stipulations are set in the agreement. The only institutional mechanisms this particular treaty includes are a self-enforcement mechanism (such as side-payments or issue linkage, or a specific benefit-sharing apparatus) and a commission or council. A monitoring, enforcement, or conflict resolution mechanism is not included. In addition, an adaptability mechanism to deal with possible drought is also not included in the treaty.

1.2. **Mekong; April 5, 1995; Laos, Thailand, Vietnam, and Cambodia (water quantity and flood control)**

In 1995 another treaty is negotiated. While the 1965 treaty on the Mekong is bilateral in nature and pertains strictly to hydropower, the 1995 agreement is multilateral (signed between Thailand, Laos, Cambodia, and Vietnam) in nature and pertains to water quantity and flood control. The 1995 agreement embodies a specific water allocation mechanism that can be described as dividing the water among the riparians by way of consultations. Specifically, the duty of deciding water allocations was given to the Mekong River Commission. Although the agreement did not stipulate a self-enforcement mechanism it did include a monitoring mechanism, an enforcement mechanism, a conflict resolution mechanism, and commission or council mechanism. Finally, the agreement also stipulated some specific initiatives for dealing with drought in future years. As for the flood portion of the agreement, the treaty stipulated a specific flood-control mechanism so as to deal with the potential effects of flood.
1.3. Zambezi; May 28, 1987; Botswana, Mozambique, Tanzania, Zambia, Zimbabwe (water quantity and flood)

This agreement is a general multilateral agreement. It does pertain to water quantity but no specific allocation method is stipulated. Among its institutional mechanisms the treaty boasts a self-enforcement mechanism, a commission or council mechanism, and an adaptability mechanism to deal with drought. However, remaining institutional mechanisms such as an enforcement and conflict resolution stipulations are not included. As for the flood portion of the agreement, the treaty did not stipulate a specific flood-control mechanism so as to deal with the potential effects of flood.

1.4. Zambezi; July 28, 1987; Zambia, Zimbabwe (water quantity and hydropower)

This agreement negotiated between Zambia and Zimbabwe most likely codifies a more specific water allocation stipulation between these two countries based on the more general May 28 agreement. The water allocation mechanism stipulated is one that divided the waters according to percentages (rather than, say, a fixed allocation). A similar allocation mechanism divides the hydropower generated by percentage. The agreement also included a number of institutional mechanisms including a self-enforcement, monitoring, enforcement, conflict resolution, and commission or council stipulation. Despite the various institutional mechanisms, an adaptability to drought mechanism is not included.