Runoff variability & Trans boundary water Management: An Assessment of Risk to Regional Agreements from Likely Climatic Change

Indrani Chatterjee

Abstract

With localised increases in water stress due to rise in population, industrialization, pollution and natural variation, states are relying more and more on sources of freshwater shared with other states, primarily on transboundary rivers governed by treaties. Climate Change may exacerbate the causes of non-compliance and hinder the ability of river treaties to manage riparian conflicts. This raises the concern whether arguments over use of a limited resource might turn into international tensions and increase the likelihood of conflicts. Most river treaties specify quantities of water allocated between the riparians according to long-term mean flows. However under adverse conditions when actual water supply falls short of the specified amount or exceeds the retaining capacity in a country, damages are inevitable. An additional source of complexity is that countries differ in their ability to resist flow variabilities and thereby face different levels of risk from natural disasters and hence are likely to have different propensities to co-operate with others. In order to fill up the gap from absence of convincing analysis of estimated losses and lack of assessment of the socio-economic impacts of such events we estimate future risks faced by each riparian from natural disasters caused by extreme surface flows and explore whether this risk inflicts the risk of breaking down of a treaty as one or more parties retract from it. In deriving our estimates we use the probability distribution of extreme surface flows for the Zambezi and Mekong basins, obtained by Blankespoor et. al. (2011) who develop a methodology of generating realistic

distributions using the BWI (Basist Wetness Index).

1 Introduction:

With the IPCC 2007 predicting rising global temperatutres, climate change has become a cause of concern for planners all over the world and there are urgent calls for immediate action. The 2010 World Development Report gives a detailed documentation of the direct effects of climate change on different types of hazards estimating the damages in terms of expected values. Global climate change models linking climate with hydrology predict large-scale fluctuations in the water cycle both spatially as well as temporally (Ellis et. al. 2008, Seager et. al. 2007). According to these studies impact of changing climatic patterns could have serious consequences. It could lead to extreme events like droughts and floods, changing sea-level dynamics, precipitation patterns and distribution of freshwater; which in turn could lead to destruction of eco-systems, mass species extinctions, tropical crop failures and so on. Achieving compliance of treaty specifications could be a difficult task to achieve even under the best circumstances, as imprecise and ambiguous terms, which room for multiple interpretations. This problem is further exacerbated as climate change complicates both the willingness and the ability of the parties to adhere to a river treaty. As the value of water increases due to shortages, it raises the incentive to violate treaty provisions that limit unilateral development of infrastructure or limit water withdrawals for consumption. Climate change could bring with it unanticipated hydrological conditions which could in turn lead to disputes regarding interpretations of appropriate actions under such circumstances and prompt one or more parties to abandon the treaty. Moreover, lack of capacity to deal with droughts could also lead to treaty violations. For instance in 1999 drought reduced Israel's ability to deliver water to Jordon according to the terms of the 1994 peace agreement (Kilgour and Dinar 2001). Fischhendler (2008a) is of the opinion that disagreements over water may spill over and set the stage for conflicts over other issues. For instance, the slow progress in implementing water related peace agreements between Israel and Jordon had spoiled the overall relation between them.

Previous literature has attempted to find the factors that lead to conflict or co-operation and has estimated the agricultural risk from climate change. However none of these studies have estimated the nationwide risk from volatile surface flows nor have they tried to derive the corresponding probability of a treaty breaking down. However, in order to avoid national as well as international strife, ensure a sustainable co-operative environment and better adapt to future uncertainties through well designed disaster mitigation strategies, it is imperative that these nations have an unambiguous notion of the individual as well as basin wide risks awaiting them if they are planning to defect from an existing treaty in the face of future hydrological uncertainties. This is what this paper attempts to accomplish.

This paper has two main research objectives. First, to make an assessment of risk for each riparian country as well as for the entire basin from uncertain water supply and second, to determine the conditional risk to the treaty between the riparians. In other words, this paper would examine if the country level risks inflict on the treaty, stability risks and if it is possible to formulate strategies that could ensure its stability in light of climate change and water supply variability. In order to address the first issue, the Expected Utility approach is adopted to model allocation decisions of an uncertain input for various productive sectors, assuming a specified level of risk averseness for each of the countries. To find the basin-wide optimum, a social planner is considered and the stochastic programming model is used for allocating water to different sectors in each of the countries sharing the basin. Subsequently, water markets are introduced as an institutional adaptation and the allocations are obtained in a similar manner. Several risk measures are introduced in order to quantify the economic risk faced by the basin countries, individually as well as jointly. Using the optimal allocations obtained from the optimization, the values of economic risk from possible extreme events caused by fluctuating flows are derived. The results are compared both under water market and non-water market scenarios to confirm if the existence of markets correspond to lower economic risks. To address the second issue, we run a discrete choice dynamic programming model, thereby obtaining the conditional choice probabilities or the conditional risk for the breakdown of a treaty. Once the probability values are obtained it is possible to generate a probability distribution indicating the likelihood of breakdown of the treaty at each level of water allocation and water flow in the river. Finally, calculation of the Shapley-Shubik Power Ratio could provide us with a measure of stability of the existing treaty between the riparians. This analytical framework would then be applied to the Zambezi and the Mekong, Since these two river basins are known for their long term sensitivity to fluctuations in water flow and for basin wide arrangements put in place to address it. The probability distribution of predicted extreme flow events are obtained from Blankespoor et. al. (2011). They use the Basist Wetness Index (BWI) as a measure to explain variability of natural flow in two international basins and found that it had a highly significant explanatory power of downstream gauge measurements. The wetness values could more accurately measure the occurrences of low flow events with a lag indicating that a prolonged dry period translates to low flows downstream. Hence the BWI can serve as an early warning sytem for decision makers, who could then mobilize resources accordingly, co-operate with the other riparians at an earlier stage and take appropriate disaster mitigation steps. (Figure 3 and 4 in the appendix show the probability distributions of flows obtained by them for the Zambezi and the Mekong river basins).

The organization of the paper is as follows. Section 1 provides a motivation and background of the issues being addressed. Section 2 provides an overview of the related literature on several dimensions of the impact of climate change and water use management. Section 3 constructs the analytical framework. Section 4 provides a description of the two basins that would be studied in our analysis. Section 5 develops the empirical strategy to be adopted. Section 6 describes briefly the data required and their sources. Section 7 mentions the expected results from the analysis and Section 8 summarizes the paper.

2 Literature Review:

2.1 *Impact of climate change on the economy and the environment:*

Mimikou et. al. (2000) assesses the impacts of climate change on the quantity and quality of water resources. Caselli and Malhotra (2004) conclude that fatalities and damage depend on the country's stage of development and not on the disaster per se. More recent studies like Hallegatte and Dumas (2009); Hallegatte and Ghil (2008) are of the opinion that these results are sensitive to the elasticities of substitution in the production function and also to its coincidence with upturns or downturns of the business cycle. Miller and Yates (2005) suggest that changes in global climatic patterns affect the hydrological cycle. Rising temperatures and decreasing soil moisture could induce forest fires, change vegetation patterns and alter the region's water balance. Mc.Donald et. al. (2010) adopt a detailed hydrologic model to predict that by 2050, highly populated urban centres would experience difficulties in maintaining ecological processes due to insufficient flows. They also find that freshwater fish populations would be impacted and that cities would need to make significant investments in order to secure functioning of freshwater ecosystems for future generations.

Tubiello and Rosenzweig (2008) conduct an extensive review of the literature studying the agricultural impacts of climate change. McCarl, Villavicencio and Wu (2008), Schlenker and Lobell (2010), Mendelsohn, Nordhaus and Shaw (1994) and Mendelsohn et. al. (2007),estimate impacts of fluctuations in climate on crop yields and land values. Hertel, Burke and Lobell (2009) explore the poverty impacts of climate change over different segments of the population.

2.2 *Climate Change and Conflict:*

Among researchers investigating water and international relations, one group namely the Neo-Malthusians are of the opinion that water could end up being a source of violent conflict. Homer-Dixon (1994,1999) Gleick (1993) and Rogers (2002) provide similar views that water scarcity could be a national security issue. Burke et. al. (2009) find strong historical linkage between civil war and temperature in Africa with warmer years leading to increases in the likelihood of war. Miguel, Satyanath and Sergenti (2004) attempt to understand the factors behind civil strifes and emphasise the role of economic fluctuations in shaping conflict risk. Based on accumulating evidence on potentially disruptive effects of climate change on human enterprise, like possible declines in global food production, Barnaby (2009); Hendrix and Glaser (2007) claim that climate change will worsen instability in already volatile regions. Institutionalists like Keohane and Ostrom (1994), Wolf (2002), Kalpakian (2004), Brochmann and Gleditsch (2006) on the other hand share a more optimistic view stating that the nature of water resources makes armed conflict counterproductive and hence co-operation is a more likely outcome through trade and joint membership in international organizations. Tir and Ackerman (2004), Homer and Dixon (1999) find how the level of economic development, joint membership into international organizations and water rights issue and relative capabilities between upstream and downstream riparians affect treaty formations. Dinar (2009b) suggest that scarcity and co-operation follow a hill shaped relation. There are other studies that employ game theory and experimental techniques to explore the effects of climate change and variability on treaty stability like Ansink and Rujis (2008), Dinar (2009a), Abbink et. al. (2010).

2.3 *International Water Law:*

Fairness concerns are one of the crucial issues in international efforts to avoid tensions over trans-boundary freshwater systems worldwide. The legal grounds for most of the international water agreements have been laid by globally developed norms for river basin management. For instance the Helsinski Rule proposed by the International Law Association (ILA) in 1966, states that each co-riparian is entitled to " a reasonable and equitable share in the beneficial use of the waters of an international drainage basin". The UN Convention on the Law of the Non-Navigational Uses of International Watercourses (approved in May 1998) supports the doctrine of "equitable and reasonable" utilization. Though countries tend to agree in abstract terms about fairness and equity in allocations, they usually disagree on their implications under specific real world situations. The difficulty here lies in some potentially conflicting views like absolute territorial sovereignty as opposed to total riverine integrity, the needs based view as opposed to both the historically evolved water rights and the efficiency based views. In times of scarcity, under extreme conditions this could foster intense competition and lead to a zero-sum game between the countries. These scarcity issues are compounded when environmental and future developmental aspects of the basin are considered (Wolf 2002).

2.4 *Climate Change and Risk Assessment:*

Understanding risk is important on one hand for helping producers make better decisions while on the other hand, it provides policymakers with essential information that aids them to evaluate the potency of various risk protection measures. Harwood et. al. (1999) conduct a research on the analysis and management of risk in farming. According to the Stern Review "climate change is the greatest externality the world has ever seen." It analyzes climate changes by converting future cost and benefits into present discounted values. It essentially adopts the expected utility theory accounting for risk averseness. However there remains the controversy regarding conceptualizing probabilities as objective frequencies or subjective beliefs. Critics of the paper point out that as one moves towards the tails of the probability distributions, one is increasingly moving towards subjective uncertainty where the probability estimates of probability distributions themselves become obscure since it is impossible to pin down the frequencies of rare events by past occurrences or through computer simulations. Weitzman (2007) discusses the theme of catastrophe insurance and develops the motivation for treating structural uncertainty as tail thickening of posterior predictive distributions.

3 Analytical Framework:

3.1 *Assessment of Individual and Basin-wide Economic Risk*

3.1.1 *Incorporating Uncertainty into the Production Decision:*

Antle (1983) argues that risk affects risk neutral farmers when they make sequential production decisions subject to random shocks. Letey et al. (1984) show that risk can increase optimal irrigation water use by upto 50%. Estimating the effect of climate change on production decisions entails including the uncertain nature of water availability into the modelling framework. To do this we follow Babcock and Shogren (1995) who incorporate uncertainty into agricultural decision making. For our analysis, we consider a national production function with an aggregate output y which can be sold at a price p ,

$$y = q(A)......(1)$$

The output is stochastic due to the presence of a stochastic input A which is water availability or the water allotted to the country by an agreement. The input A cannot be controlled directly by the decision maker due to random events. However, the decision maker can influence the distribution of A to a considerable extent by investment in x units of infrastructure to control the stochasticity of A (e.g. construction of dams, expanding capacity of a reservoir, investment made in order to be better informed of the weather conditions etc.) with a per unit cost of c. Thus the conditional density of A is defined as;

$$g(A|\, x); \qquad \underline{A} \leq A \leq \overline{A} \quad ....(2)$$

The national welfare as a function of net profits is given by,

$$U(\pi) = U[p \cdot q(A) - c \cdot x] \;\; U' > 0, \; U" \leq 0...(3)$$

The expected national welfare is,

$$E[U(\pi)] = \sum_{A=\underline{A}}^{\overline{A}} U\{p \cdot q(A) - c \cdot x\} \cdot g(A|\, x) ....(4)$$

Let $\lambda(x)$ be defined as the premium that represents the country's willingness to resolve the uncertainty regarding A for a given level of x. Then,

$$U[p \cdot q\{E(A)\} - c \cdot x - \lambda(x)] = \sum_{A=\underline{A}}^{\overline{A}} U[p \cdot q(A) - c \cdot x] \cdot g(A|\, x) ....(5)$$

Let RP be the level of risk premium that a country is willing to pay to stabilize productive activities at the mean level,

$$U[p \cdot E[q(A)] - c \cdot x - RP] = \sum_{A=\underline{A}}^{\overline{A}} U[p \cdot q(A) - c \cdot x] \cdot g(A|\, x) .....(6)$$

From the last two equations (5) and (6) we get,

$$\lambda(x) = p\{q[E(A)] - E[q(A)]\} + RP.....(7)$$

Thus $\lambda(x)$ has two parts, the production premium and the risk premium. The production premium is the change in expected profits obtained by fixing A at its mean level. By Jensen's inequality this is positive if q is concave in A. This essentially implies that if expected profit is greater when uncertainty can be resolved, even a risk neutral nation will pay a premium to resolve the uncertainty. Thus production premium plays a significant role in the valuation of new technologies or investments.

RP is the Arrow-Prat risk premium which measures the willingness to pay to fix income at its mean level. A Taylor Series expansion around both sides of equation (7) provides a second order approximation to the premium.

$$\lambda(x) = p\{q[E(A)] - E[q(A)]\} - \frac{1}{2} \cdot \frac{U"}{U'} \cdot p^2 E\{q(A) - q[E(A)]\}^2 .....(8)$$

Thus $\lambda(x)$ is a measure of the value that would be derived from investment for reducing risk targeted at A and it is evident that risk preferences or tastes influence $\lambda(x)$, but risk aversion is not a necessary condition for a positive $\lambda(x)$

3.1.2 *Altered Production Decisions with the Inclusion of Water Markets:*

Institutions can help support the production process in the presence of scarcity and uncertain water supply (Venema et. a. 1997). Hurd et. al. (1999) have simulated the impacts of climate change under varying institutional scenarios and have come to the conclusion that the environment would have to absorb most of the costs of global warming unless significant institutional changes take place with regard to the allocation of resources among competing users and among competing uses. Water markets in particular have been proposed by many authors to improve water use efficiency (Easter et. al. 1998). Tisdell (2001) finds that releasing water from the agricultural system through water trading, creates non-market benefits like improvements in water quality and increased water availability for fish and other aquatic species. The results obtained by Maqsood et. al. (2003) indicate that the water allocation target falls when water trade is introduced and that the average net benefit with trading would be greater than the relevant value without trading. This means that trading would be efficient if reallocations are considered. In this subsection thus, we introduce the water market institution as one means of reducing the uncertainty of water availability. Howitt (1998) points out that uncertainty could be introduced in a water market setting as an annual scarcity cost by assuming that even in a dry year, water could be purchased from any source at some price. In the presence of a water market, the uncertainty regarding water availability can be transformed into the uncertainty regarding water prices and /or the uncertainty about water allotments (Calatrava and Garrido 2005a, 2005b). For our analysis we assume that water allotment and water price, both are random variables with known probability distributions as shown in Calatrava and Garrido (2005a 2005b). Thus, in order to incorporate this uncertainty into the decision making process, we consider several possible states of nature that might be realized in the future with a known probability distribution. In a static framework the profit function, from carrying out various productive activities, for a particular country, for the state of nature s and in the presence of a water market m is given by,

$$\pi_{ms} = \theta\pi_{sE} + (1-\theta)\pi_{sI} - P_{ms}(w - A) \qquad ......(9)$$

π_{sE} is the net benefit derived from energy production at state s

π_{sI} is the net benefit derived from irrigation at state s

θ and $1-\theta$ are the weights given by decision makers to hydro power production and irrigation respectively.

π_{ms} is the total profit in the presence of a water market at state s

P_{ms} is the price of water in the presence of water market at state s

$(w-A)$is the demand for water w in excess of the allotment A

Anderson et. al. (1977) show that when utiliy has a single argument (in this case profit) it can be approximated by a Taylors series expansion of the utility, as a function of the moments of the probability distribution of the argument around its mean. Thus the national welfare function can be represented as,

$$U(\pi_m) = U[E(\pi_m)] + \frac{U[E(\pi_m)]M_2(\pi_m)}{2} + ... + \frac{U[E(\pi_m)]M_n(\pi_m)}{n!} \quad .....(10)$$

Considering the first three terms of the Taylors series expansion, the utility becomes a function of the mean $E(\pi_m)$, variance $V(\pi_m)$ and the skewness $M_3(\pi_m)$ of the profit function as shown below,

$$U(\pi_m) \backsimeq U[E(\pi_m), V(\pi_m), M_3(\pi_m)] \quad ....(11)$$

The F.O.C obtained by maximizing this utility with respect to w is:

$$\frac{\partial U}{\partial w} = \frac{\partial U}{\partial E[\pi_m]} \cdot \frac{\partial E[\pi_m]}{\partial w} + \frac{\partial U}{\partial V[\pi_m]} \cdot \frac{\partial V[\pi_m]}{\partial w} + \frac{\partial U}{\partial M_3[\pi_m]} \cdot \frac{\partial M_3[\pi_m]}{\partial w} = 0 \quad ......(12)$$

Dividing (12) by $\frac{\partial U}{\partial E[\pi_m]]}$ we have,

$$\frac{\partial E[\pi_m]}{\partial w} + \left\{ \{\frac{\partial U}{\partial V[\pi_m]}\} / \{\frac{\partial U}{\partial E[\pi_m]}\} \right\} \cdot \frac{\partial V[\pi_m]}{\partial w} + \left\{ \{\frac{\partial U}{\partial M_3[\pi_m]}\} / \{\frac{\partial U}{\partial E[\pi_m]}\} \right\} \cdot \frac{\partial M_3[\pi_m]}{\partial w} = 0 \quad ...(13)$$

Equation (13) can be expressed as,

$\frac{\partial E[\pi_m]}{\partial w} - REDQ \cdot \frac{\partial V[\pi_m]}{\partial w} - MSQ \cdot \frac{\partial M_3[\pi_m]}{\partial w} = 0$ .....(14)

$REDQ = -\{\frac{\partial U}{\partial V[\pi_m]}\}/\{\frac{\partial U}{\partial E[\pi_m]}\}$ is known as the Risk Evaluation Differential Coefficient

$MSQ = \{\frac{\partial U}{\partial M_3[\pi_m]}\}/\{\frac{\partial U}{\partial E[\pi_m]}\}$ is known as the Marginal Skewness Coefficient

For a risk averse decision maker, $REDQ$ is positive while MSQ is negative. This is because for a risk averse person, $\frac{\partial U}{\partial E[\pi_m]} > 0$, $\frac{\partial U}{\partial V[\pi_m]} < 0$ and $\frac{\partial U}{\partial M_3[\pi_m]} > 0$, since he always prefers a higher average profit, a lower variability in profit, and a positively skewed profit function, as it implies higher chances of getting higher values of profit.

The mean variance and the skewness of the total profit assuming both A and P_m to be random variables can be obtained from (9) as,

$$E[\pi_m] = \theta\pi_E(w) + (1-\theta)\pi_I(w) - E(P_m)w + E(P_m)E(A) \quad ...(15)$$

$$V[\pi_m] = [E(P_m)]^2 V(A) + E(w-A)^2 V[P_m] + V(P_m)V(A) \quad ...(16)$$

$$M_3[\pi_m] = [E(P_m)]^3 M_3(A) + E(w-A)^3 M_3[P_m] + M_3(P_m)M_3(A) \quad ...(17)$$

Differentiating (15), (16) , (17) w.r.t w,

$$\frac{\partial E[\pi_m]}{\partial w} = \theta\pi'_E(w) + (1-\theta)\pi'_I(w) - E(P_m) \quad ....(18)$$

$$\frac{\partial V[\pi_m]}{\partial w} = 2[w - E(A)]V[P_m] \quad ....(19)$$

$$\frac{\partial M_3[\pi_m]}{\partial w} = -3[w - E(A)]^2 M_3[P_m] \quad ....(20)$$

where $\pi'_E(w)$ is the marginal productivity of water in the energy production sector.

and $\pi'_I(w)$ is the marginal productivity of water in the agricultural sector.

Substituting (18), (19) and (20) into (14) we have,

$\theta \cdot \pi'_E(w) + (1-\theta)\pi'_I(w) - 2[w - E(A)]REDQ \cdot V(P_m) + 3[w - E(A)]^2 MSQ \cdot M_3(P_m) = E(P_m)$...(21)

In a static framework, water demand functions for each country at each perios, can be simulated using a stochastic programming model with recourse (SPR). The SPR methodology was developed by Cocks (1968) and Rae (1971) and applied by Turner and Perry (1997) and Keplinger et. al. (1998) in modelling uncertain water availability for irrigation. Once the water demand functions are obtained using SPR, the water market can be simulated using an endogenous price model that maximizes the surplus value of all sectors using water. Thus if we obtain the inverse demand function $f_i(w_i - A_i)$ for sector i using w_i amount of water, then the problem is reduced to,

$$Max \sum_i [\int_0^{(w-A)_i} f(w_i - A_i) d(w-A)_i] \quad .....(22)$$

$$s.t. \quad \sum_i (w_i - A_i) \leq 0$$

$$-(w_i - A_i) < A_i \forall i$$

The first constraint ensures that the demand is met by supply and the second constraint ensures that each user will not sell more than it is allotted. The water market model yields the optimal allocation of water for each level of water availability A_i that is, the amount of water bought or sold by each farm m_i and the equilibrium price[1] for water Pm. Profit from water use is calculated from the previously estimated profit functions,

3.1.3 *Determining optimal allocations in a dynamic framework - the planners problem:*

In this subsection, we extend the model into a dynamic framework. The criticism against static expected utility (EU) modeling has been its reliance on the "independence axiom" [Epstein (1992); Quiggin (1993)]. The theoretical problems of EU modeling in an intertemporal framework as noted by Zacharis (1993) are first, the reliance on and possible

[1]It is assumed that water market is present within each country. However, there is no trade in water between the countries. This means there are two sets of prices P_m^1 and $P_m^2$and $A_1 = w_1$; $A_2 = w_2$.

violations of the von Neuman-Morgenstern independence axiom; and second, the indifference of the decision maker to the timing of uncertainty resolution. The inability of expected utility modeling in seperating out risk aversion from intertemporal substitution was pointed out by Mossin (1969) and Spence and Zeckhauser (1972). According to Epstein and Zin (1989), in order to plan consumption better, decision makers could prefer an earlier resolution of uncertainty than later. In order to overcome this drawback of the EU modeling, Koopmans (1960) introduced recursive utility functions in a deterministic setting. This approach is extended by Kreps and Porteus (1978a, 1978b, 1979) to include stochastic problems. This paper follows the stochastic representation of Kreps and Porteus to take into consideration the random flow events. For simplicity only two countries are considered - country 1 and country 2 and a social planner is considered, who gives equal importance to each of the riparian countries facing several constraints related to their land and water usage. Thus the social welfare function with recursive preferences can be expressed as,

$$W_t = G[\bar{U}_t, E_t(W_{t+1})] \quad .....(23)$$

where, $\bar{U}_t = U_t^1 + U_t^2$ is the sum of the national welfares generated in country 1 and country 2 respectively at period t,

U_t^1 and U_t^2 are the of the national welfare functions of country 1 and country 2 respectively[2],

W_t is the social welfare function[3] in period t and it is a function of the sum of national welfares in period t and the certainty equivalent of future welfare values.

The recursive preferences can be represented following the Epstein and Zin (1989) parameterization as,

$$W_t = [(1-\beta) \centerdot \bar{U}_t + \beta \centerdot E_t(W_{t+1}^r)^{\alpha/r}]^{1/\alpha} \qquad 0 \neq \alpha \leq 1, \quad 0 < \beta < 1$$

where β is the subjective discount factor,

[2]utility function is a function of profits as defined in section 3.1.1

[3]W_t represents the social welfare function whereas, w_t is the water usage which is the same as the market allocation A_t in the absence of water markets

$\gamma = \frac{1}{1-\alpha}$ is the constant elasticity of intertemporal substitution

and r reflects the risk aversion.

The optimal value function $J(Q_{c,t})$ is defined as optimal welfare[4] over the horizon as a function of the state variable which is water flows or the volume of water available at each node c. Thus the Bellman equation, in the unknown value function is,

$$J(Q_{c,t}) = \underset{A_{1it}, A_{2it}}{Max} \quad G[\bar{U}_t, E_t[J(Q_{c,t+1}]]$$

There are several constraints faced by the basin countries like land constraints, capacity constraints and hydrological balance constraints shown in the empirical strategy section. Since recursive preferences have a built in structure as that of standard dynamic programming models, this problem can be solved using dynamic programming methods as discussed in Stokey and Lucas (1989), Kreps and Porteus (1979a) and Boyd (1990) among others. The welfare maximization problem can also be performed for different levels of α to compare between outcomes under various cases with different combinations of risk preference between the countries. Using this methodology we can obtain the welfare values for different levels of water allotment for a given level of risk aversion i.e. the distribution of welfare for a given level of risk aversion.

3.1.4 *Analyzing Risk Exposure with and without water markets* :

The literature provides three types of quantitative risk analysis methods or probabilistic assessment methods (Vose 1996; Cullen and Frey 1999;). The first are the analytical methods that calculate mathematical exact solutions for the model outcome but are difficult to implement with complex models. Secondly, there are the approximation methods based on Taylor series expansion, which provide statistical moments of the model outcome variables (Manfredo and Leuthold 1999). This method usually requires strong statistical assumptions and calculates only some parameters of the distribution.

[4] $J(Q_{c,t})$ is obtained by maximizing $W_t = G[\bar{U}_t, E_t(W_{t+1})]$ with respect to A_{it} , i.e. the water allocations in each sector within each country.

The third method is the statistical simulation method, which involves randomly sampling the probability distributions of the random variables (a possible scenario) and then running the model for each scenario. The analytical and statistical methods are known as "full valuation" methods in the risk analysis literature as they enable us to derive a probability distribution of the model outcome. We would employ the statistical simulation method as it allows for complex mathematical functions within the model and is easy to implement from a computational point of view.

Hypothetical values of the random variable in our model or the water allotment values, are randomly generated from a probability distribution fitted to past recorded allotments. These values are used as parameters in the water market model, from which the probability distribution of profits can be calculated using simulation techniques. In order to quantify economic risk, we would be using various indices like the variance, coefficient of asymmetry and "value at risk" of the welfare probability distribution, representing different dimensions of risk to which each of the riparian countries are exposed as a result of uncertain water availability. Each risk averse nation selects the mean-variance strategy that best fits its preferences. When risk originates from uncertain flows, its asymmetry is highly negative and the coefficient of asymmetry and the value at risk of welfare are appropriate measures of capturing this downside risk of that country. The Value at risk is defined as the level of welfare, to the left of which is a probability mass equalling $1-\tau$, where τ is the level of confidence (Linsmeier and Pearson, 1996). Using the value at risk index is advantageous for risk analysis since it takes into account the extreme events that occur in at the left tail of the profit probability distribution (Manfredo and Leuthold 1999). A risk averse nation would prefer a welfare distribution which is as less negatively asymmetric as possible and also one with higher levels of value at risk.

A probability distribution can be fitted from the series of water allotments to represent uncertainty in water availability. Following Calatrava and Garrido (2005) , the water allotment value can be sampled using the fitted beta probability function and the "Latin Hypercube Sampling" option of @Risk for Windows (Palisade Corporation 1997). The water market model can be run for each allotment value and welfare values for each nation can be computed both with and without the water market. From these two welfare series the empirical welfare probability distribution can be obtained under each institutional setting. In order to analyze whether the calculated statistics are significantly different with and without a market, bootstrapping techniques for statistical inference would be used. Bootstrapping or resampling, a simulation-based computational method is generally used to assess the statistical accuracy of statistics other than the mean (Efron and Tibshirani 1993). From the beta distribution of water allotments, a series of 100 water allotment values will be simulated, using the proposed model in section 3. The two series of welfare, with and without water markets, can be obtained from each bootstrap sample for each country. From each of these series, we can obtain the bootstrap replication of the estimated statistics. These can be used to assess whether differences in the value of each statistic are statistically significant.

3.2 *Assessing the risk to the treaty*

3.2.1 *Conditional risk of the treaty breaking down:*

From the previous subsections, we can obtain the allocations for each country and for each sector under different flow levels. Using these allocations we can model the cooperation decision of each country. In order to model the country decision, whether to co-operate or not, given the information they have at a particular point of time, we use a discrete choice dynamic programming model and solve it following Aguirregabiria and Mira (2002) to obtain a sequence of estimators of the structural parameters called the k-stage Policy Iteration Estimators (PIE). It is essentially a dynamic programming version of Mc Fadden conditional logit model. (Mc Fadden 1984).

At each discrete time period indexed by t, the decision maker within a country observes a vector of state variables A_t, and he chooses an action $D_t \epsilon (0,1)$, which is the decision whether to co-operate or not with the other riparian nation such that it maximizes his expected sum of current and discounted future pay-offs given by,

$$E[\sum_{l=0}^{\infty} \rho^l B(D_{t+l,} A_{t+l} | D_t, A_t)$$

In this case the quantity of the allocations to a country can be interpreted as the state variables A_t and the action to be chosen would be the decision whether to co-operate with the other country. In this case since we have two countries, the choice variable can take only two values as follows:

$$D = \left\{ \begin{array}{cc} 1 & cooperation \\ 0 & non-cooperation \end{array} \right\}$$

$B(D_t, A_t)$ represents payoff at period t from state of nature $A_t$and the decision D_t . The vector $A_t$consists of two components, an observable variable $a_t$which has a discrete and finite support and an unobservable variable ε_{Dt} which has 2 components $\{\varepsilon_{Dt} : D_t \in (0, 1)$ and it is independently and identically distributed over the choice alternatives having an extreme value distribution with zero mean and dispersion σ.

The payoff function $B(D_t, A_t)$ or equivalently $B(D, a_{t,}\varepsilon_{Dt})$ is additively seperable in its observable and unobservable components, and multiplicatively seperable in $a_t$and the structural parameters in preferences and can be expressed as:

$$B(D_t, a_t, \varepsilon_{Dt}) = \eta z_t(a_t) + \varepsilon_{Dt}$$

where η is a vector of structural parameters and $z_D(a_t)$ is a vector of functions of a_t

Future values of some state variables are uncertain for the decision maker at the time he makes the decision. His belief about uncertain future states can be represented by a Markov transition probability,

$$P(a_{t+1}, \varepsilon_{Dt+1}|a_t, \varepsilon_{Dt}, D_t) = g_\sigma(\varepsilon_{Dt+1}) \cdot f_\delta(a_{t+1}|a_t, D_t)$$

where $g_\sigma$is the density of $\varepsilon_{Dt}$and $f_\delta$is the conditional choice transition probability at a_t, that depends on the vector of parameters δ .

Based on the above assumptions the model is a stationary Markov decision problem with state variables a_t and ε_{Dt}.

Let $\varphi = \{\eta, \sigma, \delta, \rho\}$be the vector of the structural parameters in the model and let $v_\varphi(a_t, \varepsilon_{Dt})$ be the value function. According to Bellman's optimality principle, $v_\varphi$is the unique fixed point of the following contraction mapping:

$$v_\varphi(a_t, \varepsilon_{Dt}) = \underset{D}{Max} \{\eta z_D(a_t) + \varepsilon_{Dt} + \rho \sum f_\delta(a_{t+1}|a_t, D) \int v_\varphi(a_{t+1,}\varepsilon_{Dt+1}) g_\sigma(d\varepsilon_{Dt+1})\}$$

The optimal decision rule $D^*_{\varphi t}(a_t, \varepsilon_{Dt})$ can be represented as the argmax in D of the term in brackets in the equation above.

In order to describe the econometric model, we integrate the value function over the unobservables, thus defining the integrated value function,

$$V_\varphi(a_t) = \int v_\varphi(a_t, \varepsilon_{Dt}) g_\sigma(d\varepsilon_{Dt})$$

Thus the Bellman equation can be expressed as,

$$V_\varphi(a_t) = \int \underset{D}{Max} \{\eta z_D(a_t) + \varepsilon_{Dt} + \rho \sum_{a_{t+1}} f_\delta(a_{t+1}|a_t, D) V_\varphi(a_{t+1})\} g_\sigma(d\varepsilon_{Dt}) \text{ ...(i)}$$

The right hand side of the above equation is a contraction mapping in the integrated value function and hence $V_\varphi$is the unique fixed point of this mapping.

The integrated optimal decision rules, or conditional choice probabilities (CCPs) can be defined as,

$P^D_\varphi(a_t) = \int I\{D^*_\varphi(a_t, \varepsilon_{Dt}) = D\} g_\sigma(d\varepsilon_{Dt}) = Pr(D_t = D|a_t; \varphi)$

Since the unobservables are extreme value distributed, the CCPs take the following form:

$$P^D_\varphi(a_t) = \frac{exp\{z_D(a_t)\frac{\eta}{\sigma} + \frac{\rho}{\sigma} \sum_{a_{t+1}} f_\delta(a_{t+1}|a_t, D) V_\varphi(a_{t+1})\}}{\sum_{j=1}^{J} exp\{z_j(a_t)\frac{\eta}{\sigma} + \frac{\rho}{\sigma} \sum f_\delta(a_{t+1}|a_t, l) V_\varphi(a_{t+1})\}} \text{ ....(ii)}$$

The econometric model is described by equations (i) and (ii). The solution of the Bellman equation (i), for any vector of structural parameters φ, gives the vector of ptimal values V_φ. Given these values it is possible to obtain the choice probabilities using equation (ii). The conditional risk of the treaty disintegrating in this case is the conditional choice probabilities corresponding to $D = 0$. Hotz and Miller (1993) illustrate a two stage procedure that provides consistent and asymptotically normal estimates of the structural parameters of the dynamic programming problem.

4 Basin Description:

For the purpose of our study we consider two major transboundary river basins –the Zambezi and the Mekong, primarily because being located within the tropics, it is likely that they are among the ones most susceptible to climate fluctuations. Other reasons include, the heavy dependence of the socio-economic activities of the basin countries on the shared river basins. Moreover existing treaties between the riparians, lend us the opportunity to analyze the impact of extreme flow on disputes between the riparians for the two basins. Also the natural flow assumption is intact over a large cross-section of the basin and hence makes it possible to use the BWI (Basist Wetness Index) to obtain predicted flow probabilities. The Zambezi and the Mekong due to their diverse hydrological patterns, and other basin characteristics, like income distribution and population density within the riparians, make them representative of most of the existing international basins. Further both Zambezi and Mekong are listed by the Basins at Risk (BAR) project of the Transboundary Freshwater Dispute Database, Oregon State University as the "hot spots" where the riparian countries are currently negotiating conflicts and also have a potential for continued conflict. These basins consist of some of the lowest income countries (per capita GDP less than $765) as per WRI 1998. They also comprise of some of the most conflictive pairs of countries like Cambodia and Vietnam (-5.26)[5], Laos and Vietnam (-4.17)[6], Mozambique and Vietnam (-3.13)[7] [the maximum BAR scale index being -7 or formal declaration of war].

[5]terms in parantheses represent BAR scale index which captures the presence of overall hostile relations between dyads sharing a basin. BAR scale ≤ -1 is reflective of the most conflictive pairs of countries based on historical events from 1948-1994. A BAR scale of -5 would imply existence of small scale military acts, while a scale of ≤ -7 would be reflective of a formal declaration of war between the country dyads [yoffe et. al. (2003)].

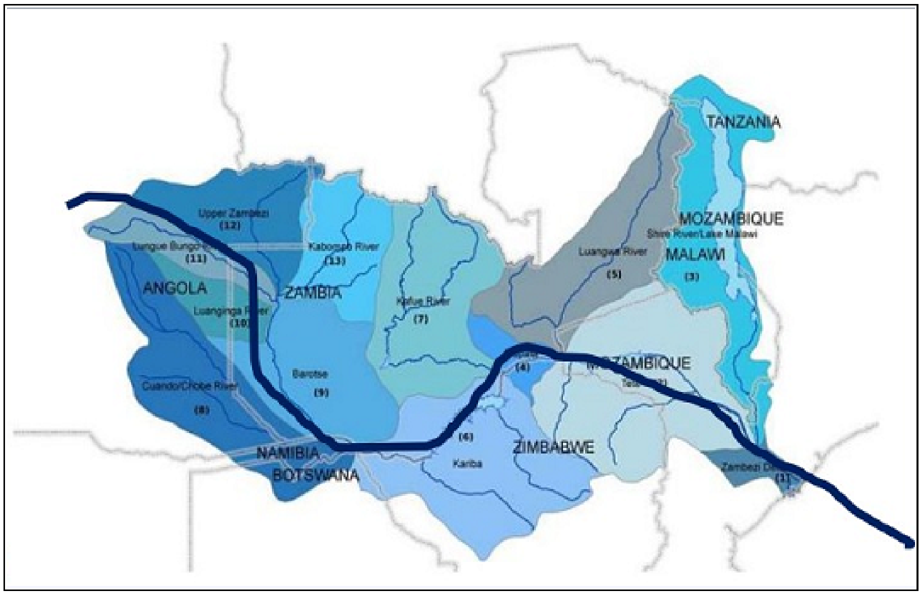
[6]BAR scale of -4 reflects political/military hostile actions

[7]BAR scale of -3 represents diplomatic/economic hostile actions.

4.1 *Description of the Zambezi Basin:*

The Zambezi is the fourth largest river in Africa after the Congo, Nile and the Niger and it is the largest river in Africa flowing into the Indian Ocean. The catchment area covers 1.37 million square km. and is shared by eight countries – Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe, as seen in Figure 1.

Figure 1: Map of the Zambezi Basin.



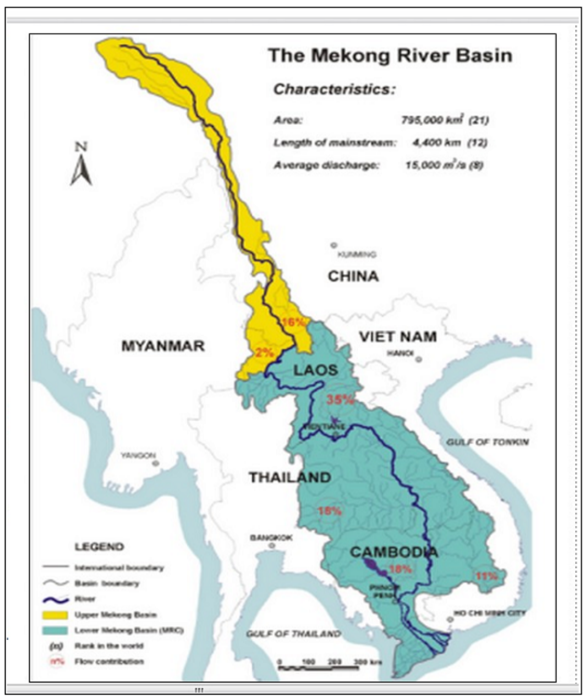
Source : Beck and Bernauer 2010

The economic conditions of the riparian countries are quite dissimilar and vary from an annual per capita GDP of about $122 in Zimbabwe to more than $7000 in Botswana. Angola, Botswana and Namibia have strong current account surpluses mainly because of their oil and diamond resources. The ZRB is characterized by extreme climatic fluctuations and as such the river and its tributaries are subject to cycle of floods and droughts that claim lives and cause grave economic losses, thus severely impeding socio-economic development in the basin.

4.2 *Description of the Mekong Basin:*

As illustrated in Figure 2, the Mekong River located in Southeast Asia is estimated to be the 10th largest river in the world, in terms of its total length (4909km) and mean annual flow (MRC 2005). Overall six countries – China, Myanmar, Thailand, Laos, Cambodia and Vietnam fall partly within its basin. Due to variations in the monsoon rain, the basin is subject to water fluctuations both intra-annually as well as annually.

Figure 2: Map of the Mekong River Basin



Source: Vietnam National Mekong committee 2009

The Mekong River Basin is currently facing rapid changes in terms of its population and urbanization rates and economic development.Yet at the same time disparities are growing both between and within the countries, and water and related resources are under increasing pressure. While the on-going water development projects like the construction of large hydropower dams are considered important for the countries' development, the likely negative impacts borne by river-dependent ecosystems where the livelihoods of millions of people are largely dependent on the river water, are estimated to be huge

(IUCN et al. 2007a; MRCS/WUP-FIN 2007a; MRC 2006a). Though several impact have been undertaken in the basin, their estimates vary widely (Kummu & Sarkkula 2008). There is a significant dearth of knowledge about the cumulative impacts of the different developmental plans on different parts of the basin.

5 Empirical Strategy:

We initially assume that the river is being shared by two countries, country 1 and country 2, each with two production sectors (agriculture and industry) and two subsectors (i.e. two types of crops). We also assume that country 1 is the upstream country with limited storage capacity. Figure 3 illustrates the node diagram of this river. Releases from the reservoir in a given period, are a proportion of the water stored in the reservoir in that period. The volume of water at the source is Q_0while Q_c represents the volumes of water flowing into each subsequent node$c$, . The diversions from the river, D1 and D2 reprepresent the water delivered to country 1 for productive purposes, while R1 and R2 are the return flows from each country respectively.

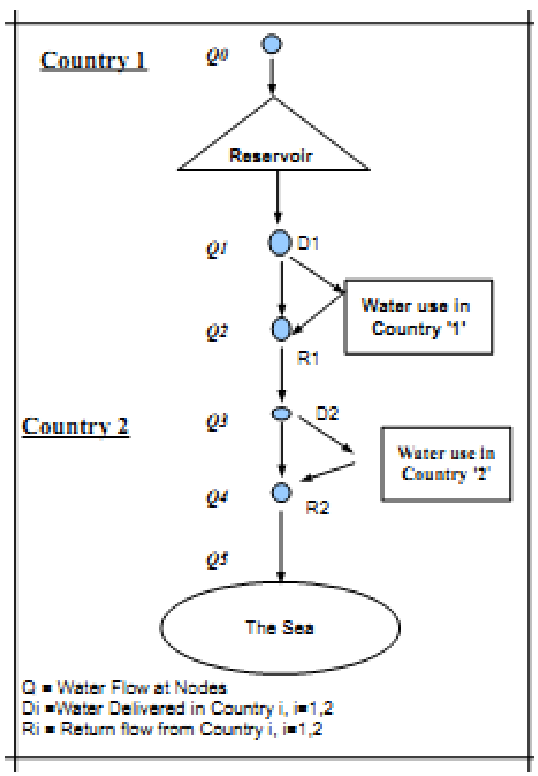


Figure 3: A simplified Node Diagram

The individual utility functions for each country are $U^1(\pi^1; r)$ and $U^1(\pi^1; r)$ respectively,

Optimal allocations are determined by the social planner by solving the Bellman's equation,

$$J(Q_{c,t}) = \underset{A_{1it}, A_{2it}}{Max} \; G[\bar{U}_t, E_t[J(Q_{c,t+1})]]$$

where $Q_{c,t}$ is the volume of water flowing into node c at period t

The countries face several constraints as follows. The land constraint is given by,

$$\sum_k L_{nks} \leq \bar{L}_n \qquad \forall s, t$$

Water Constraint M_{ns} is the excess demand for water $(w - A)$ in farm n

$$\sum_k L_{nks} \cdot w_{nks} - M_{ns} \leq \bar{L}_n \cdot A_s$$

Non negativity constraints are,

$$L_{nks,} \, w_{nks} \geq 0$$

$L_{nks}$and w_{nks} represent the land and water used respectively in farm n for crop k at state s

Water balance equations for every reservoir is,

$$S_j = Q_{in,j} - Q_{out,j} - Evap_j$$

S_j is the storage at reservoir j

$Q_{in,j}$is the inflow to reservoir j

$Q_{out,j}$ is the release from reservoir j

$Evap_j$ is the loss from reservoir from seepage or evaporation

Water balance for nodes representing confluence of rivers

$$Q_{out,c} = Q_{in,c} + Q_{source,c}$$

$Q_{source,c}$is the source of water for node c

The return flow from water users,

$$Q_{out,c} = Ret_c \times \sum_{nk} Q_{del,c}$$

Ret_c is the return flow coefficient for node c and $0 < Ret_c < 1$

$Q_{del,c}$ is the water diverting to the different sectors from node c

The net benefit from power generation is,

$$\pi_{sE} = E \cdot (P_E - C_E)$$

E is the hydel power produced given by,

$$E = 2730 \times e_j \cdot Q_{out,j} \cdot H_j$$

H_j is the effective hydraulic head on plant j and is a constant

$e_j$is the effeciency of plant j

$Q_{out,j}$ is the release from reservoir j

P_E and $C_E$are the price and cost of electricity respectively

The net benefit from agriculture or irrigation is:

$$\pi_{sI} = \sum_{k} L_k(Y_k \cdot P_k - C_k)$$

Where L_k is the harvested area for crop k

P_k and $C_k$are the crop price and the fixed cost crop for k

$Y_k$is the crop yield function and is assumed to take the form as below following Dinar and Letey (1996)

$$Y = Y_{max}[b_0 + b_1(w/ET_{max}) + b_2 \cdot ln(w/ET_{max})]$$

Y is the crop yield per unit of land

$Y_{max}$is the maximum attainable yield

$b_0, b_1, b_2$are the regression coefficients

w is the water applied

ET_{max} is the maximum evapo-transpiration

Following Babcock et al. (1993), a constant absolute risk aversion CARA utility function is assumed, as it is a reasonable approximation of rational producer behaviour. Thus the utility function is of the form,

$$U(\pi) = 1 - exp(-\phi\pi)$$

$\phi$is the constant of absolute risk aversion.

According to Babcock et. al. (1993), $\phi = 0.01996$ indicates moderate risk aversion.

The advantage of preferences being CARA is that the certainty equivalent returns (CER) can be obtained by inverting the utility function. For expected utility EU_i , the certainty equivalent return is,

$$CER_i = -ln(1 - EU_i)/\phi$$

For two information levels I and $I^{'}$, the willingness to pay (WTP) in order to switch from information level I to $I^{'}$ given CER for that level of information is:

$$WTP = CER_{I'} - CER_I$$

6 Data Sources:

The required data and their sources are as follows:

(i) Data on natural run-offs would be collected from the Global Runoff Data Center (GRDC).

(ii) Facts about different units and sectors of water utilization would be obtained from the AQUASTAT and the CROPWAT datasets of the United Nations Food and Agricultural Organization database. Meridian Global Dam Database and CARMA (2009) provides information on dams and hydel power stations. Also World's Water Report (2010) has countrywide information on dams.

(iii) Predicted climate change scenarios for 5 basins are tabulated by Palmer et al. (2008).

(iv) Probability of extreme flows are obtained from Dinar et al. (draft, unpublished) for the two basins. (Probability distributions shown in Figure 3 and Figure 4 in Appendix)

(v) Drought and flood damages are documented in the EM-DAT dataset by the Centre for Research on the Epidemiology of Disasters (CRED) and the University of Colorado Natural Disaster Centre.

(vi) Information on existing treaties and past disputes categorized on the basis of the issue of dispute between riparians are well documented by the Transboundary Freshwater Dispute Database (TFDD).

7 Expected Results:

The theoretical framework and empirical strategy has to be developed further before developing and running the model to obtain the results. Future extensions would entail extending the model to incorporate a game theoretic analysis of the co-operative behaviour between the riparians. However at this stage, it can be expected that the disaster risk would, among other factors, depend on the kind of governance and local institutions within a country, since these factors could curb increases in vulnerability even in the face of increasing exposure. Further, it can be expected that the probability of disintegration of a treaty, given a specific level of disaster risk, would depend on differences in risk aversions, power asymmetries, asymmetries in the levels of development and the existence of international institutions. Also the extent to which a country needs to rely on shared rivers is driven to a great extent by how much freshwater a country can draw from other sources to meet its water demands. If water scarcity turns out to be an issue, there is likely to be a clash in interest between the nations and many studies predict that this would place the riparians into a conflictual zero-sum mindset (e.g. Cooley 1984; Klare 2001; Lonergan 2001). An upstream downstream relation between treaty signatories could turn out to be particularly problematic since it could allow the upstream state to impose negative externalities on the downstream state (Mitchell and Keilbach 2001; Stinnett and Tir 2009). It would be interesting to perform a comparative analysis of the equilibrium strategy with and without the presence of trade relations, since trade relationships can act as signals of countries' trustworthiness and create environments in which cooperation can flourish and costs of conflict are increased (Gartzke, Li, and Boehmer 2001).

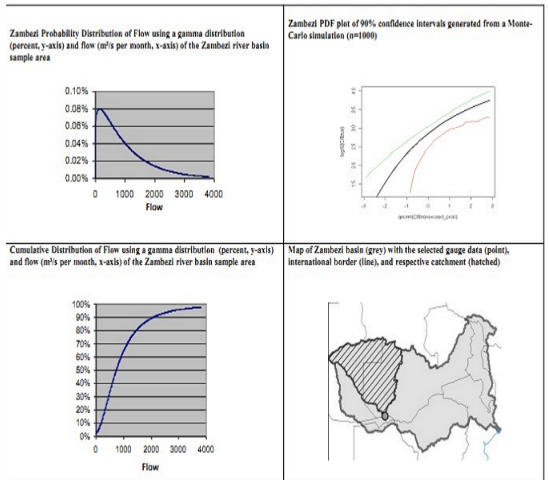
8 Summary:

To summarize, this paper develops a theoretical framework in order to assess the economic risk from extreme flows and the also risk of a treaty breaking down due to such extreme flows. This framework is then applied to two basins - Zambezi and Mekong. The theoretical framework starts with the inclusion of uncertainty into the decision making process through the expected utility framework in a single country, static framework without the presence of water markets (Section 3.1.1), which is subsequently introduced (in section 3.1.2.) in order to compare the analyses under market as well as non-market conditions. Section 3.1.3 demonstrates the problem of the social planner with recursive preferences, that determines the optimal allocations of water to each country and to each sector within the country such that social welfare is maximized. Once the allocations are determined for each level of water flow, the corresponding values of social welfare can be found. Using the distribution of flows obtained from Blankespoor et. al. (2011) it is possible to generate the probability distribution of social welfare for the two basins. This distribution is then used for the assessment of economic risk for the basin under extreme flow conditions. The flow distribution from Blankespoor et. al. (2011) also enables us to derive the probability of low flows or drought like conditions as well as that of high flows or flood like conditions. Combining these probability values with the conditional risk obtained from section 3.1.4, we can derive the risk to treaty for the two basins under study. The flow probabilities and the conditional choice probabilities also renders it possible to undergo a game theoretic analysis of the equilibrium strategy of the riparians and examine the stability of an existing treaty.

Climate change involves uncertainties in an overwhelming number of dimensions including, but not limited to transboundary water management. This paper shows that our analysis, explicitly incorporating uncertainty which plays a dominant role in any economic decision making process, provides valuable insights into welfare distribution of the riparians under status quo vis-a-vis that under co-operation and the comparison of welfare losses from extreme flows under the status quo vis-a-vis that under various levels of co-operation between the riparians. Our study also emphasises the importance of institutions particularly water markets and general trade agreements in fostering a co-operative environment between riparians. The deleterious effects of water scarcity on international security could be alleviated through well formulated agreements which define the rights and obligations of each nation, sets rules for sustainable joint use of a river basin along with the existence of proper institutions that focus on monitoring and law enforcement and has well-designed mechanisms to deal with disputes before they could arise. Several empirical studies bear the claim that states willingly agree to bear the cost of institutions when they feel the need for it. Tir and Ackerman (2009); showed that scarcity prompted countries to form treaties and also to include more institutional features to it. It is expected that the sobering estimates of the economic risks associated with disasters and the corresponding probability distribution of the breakdown of a treaty and its long-term consequences, would hopefully prompt planners to expedite the process of making provisions for such adverse circumstances, design ways to sustain co-operation in order to mitigate hazards and their potential to disrupt global peace.

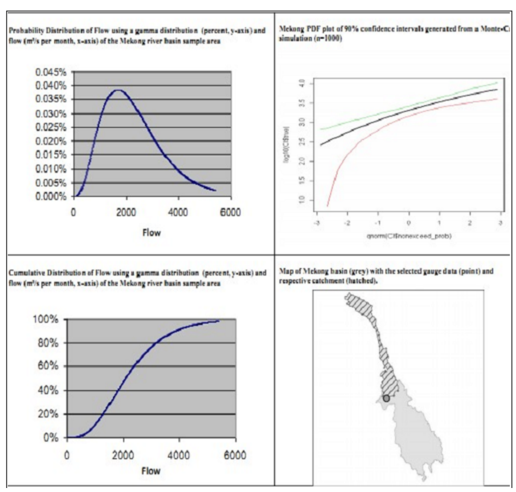
Appendix:

Figure 3:



(Source: Dinar et. al., Draft Unpublished)

Figure 4



(Source: Dinar et. al., Draft Unpublished)

List of Important Notations:

y: aggregate output

$q(A)$:production function

c: per unit cost of investment in x units of infrastructure

$g(A \mid x)$: conditional density of x

m: presence of a market

U_t^1, U_t^2 : national welfare functions

$W_t = G[\bar{U}_t, E_t(W_{t+1})] = [(1-\beta) \cdot \bar{U}_t + \beta \cdot E_t(W_{t+1}^r)^{\alpha/r}]^{1/\alpha} \qquad 0 \neq \alpha \leq 1, \quad 0 < \beta < 1$: Social Welfare at period t

where β is the subjective discount factor,

$\gamma = \frac{1}{1-\alpha}$ is the constant elasticity of intertemporal substitution

and r reflects the risk aversion.

The optimal value function $J(Q_{c,t})$ is defined as optimal welfare over the horizon as a function of the state variable which is water flows or the volume of water available at each node c.

RP : Arrow-Prat risk premium which measures the willingness to pay to fix income at its mean level

$\lambda(x)$: premium that represents the country's willingness to resolve the uncertainty regarding A for a given level of x.

π_{sE} is the net benefit derived from energy production at state s

π_{sI} is the net benefit derived from irrigation at state s

θ and $1-\theta$ are the weights given by decision makers to hydro power production and irrigation respectively.

π_{ms} is the total profit in the presence of a water market at state s

P_{ms} is the price of water in the presence of water market at state s

$(w - A)$is the demand for water w in excess of the allotment A

$\pi'_E(w)$ is the marginal productivity of water in the energy production sector.

$\pi'_I(w)$ is the marginal productivity of water in the agricultural sector.

$E(\pi_m)$, $V(\pi_m)$ $M_3(\pi_m)$ are the mean, variance and skewness of the profit function respectively

$REDQ = -\{\frac{\partial U}{\partial V[\pi_m]}\}/\{\frac{\partial U}{\partial E[\pi_m]}\}$: Risk Evaluation Differential Coefficient

$MSQ = \{\frac{\partial U}{\partial M_3[\pi_m]}\}/\{\frac{\partial U}{\partial E[\pi_m]}\}$: Marginal Skewness Coefficient

$f_i(w_i - A_i)$:inverse demand function for sector i using w_i amount of water.

$B(D_t, A_t) = B(D_t, a_t, \varepsilon_{Dt}) = \eta z_t(a_t) + \varepsilon_{Dt}$ represents payoff at period t fromallocation $A_t$and the decision D_t

where η is a vector of structural parameters and $z_D(a_t)$ is a vector of functions of a_t

$$D = \left\{ \begin{array}{cc} 1 & cooperation \\ 0 & non-cooperation \end{array} \right\}$$

a_t and ε_{Dt} are the observable and unobservable components ofA_t

$\{\varepsilon_{Dt} : D_t \in (0, 1)\}$ is iid over the choice alternatives having an extreme value distribution with zero mean and dispersion σ.

where $g_\sigma$is the density of $\varepsilon_{Dt}$and $f_\delta$is the conditional choice transition probability at a_t, that depends on the vector of parameters δ .

$P(a_{t+1}, \varepsilon_{Dt+1}|a_t, \varepsilon_{Dt}, D_t) = g_\sigma(\varepsilon_{Dt+1}) \cdot f_\delta(a_{t+1}|a_t, D_t)$ is the Markov transition probability representing the belief about the uncertain state

$g_\sigma$is the density of ε_{Dt}

$f_\delta$is the conditional choice transition probability at a_t, that depends on the vector of parameters δ .

$\varphi = \{\eta, \sigma, \delta, \rho\}$vector of the structural parameters in the discrete choice dynamic model

$v_\varphi(a_t, \varepsilon_{Dt})$ be the value function

$V_\varphi(a_t) = \int v_\varphi(a_t, \varepsilon_{Dt}) g_\sigma(d\varepsilon_{Dt})$ is the redefined value function integrated over the unobservables

$Q_{c,t}$ is the volume of water flowing into node c at period t

M_{ns} is the excess demand for water $(w - A)$ in farm n

$L_{nks}$and w_{nks} represent the land and water used respectively in farm n for crop k at state s

S_j is the storage at reservoir j

$Q_{in,j}$is the inflow to reservoir j

$Q_{out,j}$ is the release from reservoir j

$Evap_j$ is the loss from reservoir from seepage or evaporation

$Q_{source,c}$is the source of water for node c

Ret_c is the return flow coefficient for node c and $0 < Ret_c < 1$

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P_E and $C_E$are the price and cost of electricity respectively

Where L_k is the harvested area for crop k

P_k and $C_k$are the crop price and the fixed cost crop for k

$Y_k$is the crop yield function

Y is the crop yield per unit of land

$Y_{max}$is the maximum attainable yield

$b_0, b_1, b_2$are the regression coefficients in the crop yield function

ET_{max} is the maximum evapo-transpiration

$\phi$is the constant of absolute risk aversion.

(CER) the certainty equivalent returns

(WTP) the willingness to pay in order to switch from information level I to I' given CER for that level of information.

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