Climate Change, Conflict and Peace in International River Basins - A Theoretical Perspective*

Tobias Siegfried,[1*] Lucas Beck,[1]
Vally Koubi,[1] Thomas Bernauer[1]

[1]ETH Zurich, Center for International Studies, Zurich, Switzerland

*To whom correspondence should be addressed; E-mail: siegfried@hydrosolutions.ch

Recent research shows that one of the most significant risk for societal development pertains to water availability and that the greatest risks for unrest stemming from economic deprivation and the erosion of livelihoods is found in international river basins in poor and politically unstable parts of the world. While until now, historic linkages between water scarcity and conflict were weak at best, there is growing fear that environmental change will increasingly lead to an entanglement of conflict and resources dynamics in the future. Where resources are not jointly managed in a cooperative way and resources sharing mechanisms not legislated by sound international institutions and were significant impacts from environmental change are expected, these developments give rise to concern. To study environmental change and conflict interlinkages, we develop a formal hydro-climatological model for transboundary freshwater resources and theoretically investigate how climate change translates into potential for conflict and peace contingent

*Support from the Swiss Network for International Studies (SNIS) is acknowledged.

on configurations of power between riparians. The model accounts for how upstream countries exercise power by using water whereas downstream countries use power to obtain water. We show that equilibrium water allocation outcomes are biased towards the more powerful riparian, and that absolute upstream or downstream river basin dominance are limiting cases of our general model. Our model suggests that the basin-wide conflict potential is always more sensitive to changes in relative power between riparian states than to impacts from climatic changes.

1 Introduction

Global climate change is expected to be one of the most important challenges the international community will face in the near future. The evidence presented by scientists, in particular by the Intergovernmental Panel on Climate Change (Pachauri, 2007) and the Stern Review (Stern, 2007), demonstrates that climate change is indeed occurring, that human activity has clearly contributed to the phenomenon and that it will have far reaching repercussions on ecosystems and humans alike. Moreover, climate change will very likely exacerbate the scarcity of important resources such as freshwater, create mass population dislocations (migration) due to desertification and rising sea-levels, and is expected to ultimately fuel violent intrastate and/or interstate conflict.

The IPCC 3rd and 4th Assessment Reports (Solomon *et al.*, 2007; McCarthy, 2001) as well as a recent study by the German Advisory Council on Global Change (Schubert *et al.*, 2007), for example, explicitly state a possible link between climate change and violent conflict. These studies mostly refer to potential *water wars* and conflicts induced by environmental migrants. For example, the IPCC 3rd Assessment Report states that *negative trends in water availability have the potential to induce conflict between different users* (McCarthy, 2001). At the same time, high-ranking policy-makers have, on many occasions, also warned that water scarcity may contribute to armed conflict. In 2001, Kofi Annan warned that 'fierce competition for fresh water may well become a source of conflict and wars in the future'. And the current secretary general Ban Ki-Moon has for example argued that the ongoing Darfur crisis 'grew at least in part from desertification, ecological degradation, and a scarcity of resources, foremost among them water' (on that topic, see also e.g. Siegfried *et al.*, 2007).

Ever since Thomas Malthus published his *Essay on the Principle of Population* (Malthus, 1958), a group of scholars, referred to as neo-Malthusians, has claimed that environmental degradation can cause violent conflict at the sub-national level and between states (Homer-Dixon and Blitt, 1998; Percival and Homer-Dixon, 1998; Homer-Dixon, 2001; Baechler *et al.*, 1996). Homer-Dixon and Blitt (1998) sees 'environmental scarcity' arising in three ways: demand-induced scarcity driven mainly by population growth; supply-induced scarcity resulting from the depletion or degradation of a resource; and structural scarcity resulting from a skewed distribution of the resource. Other scholars, commonly referred to as Cornucopians or resource optimists, do not share this pessimistic view. They acknowledge that environmental degradation may negatively affect human wellbeing. But they argue that humans can adapt to resource scarcity by using market mechanisms (e.g. pricing), technological innovation, institutions for resource allocation, or any combination thereof (Lomborg, 2002; Simon, 1989). In the same vein, Cornucopians criticize neo-Malthusian arguments as overly deterministic and ignorant of economic and socio-political factors (Gleditsch, 1998; Matthew, 2000; Soysa, 2002; Barnett and Adger, 2007; Salehyan, 2008). Resource optimists argue that resource scarcity is just one of several key factors in the overall relationship between environmental changes and conflict and that cooperation between resource users is also a distinct possibility for mitigating and/or adapting to resource scarcity.

Although several resources such as oil, diamonds, minerals, etc. have been seen as sufficiently important to fight for, freshwater has received most of the attention in scholarship research. Several studies have sought to test the hypothesized Malthusian relationship between water scarcity and interstate conflict. Gleick (1993a) provides historical examples where water scarcity appears to be one of several factors that contribute to armed conflict. Hauge and Ellingsen (2001) also find that freshwater availability has a positive and significant impact on both intra and interstate conflict, with more significant impacts on intrastate conflicts.

Another strand of research examines whether sharing an international river increases the probability of interstate conflict. The main explanation why sharing a river might increase the probability of interstate conflict is that upstream-downstream situations might create conflicts related to resource scarcity Gleditsch *et al.* (2006a). Similarly, Butts (1997) contends that 'water conflict is more likely when rivers are shared by multiple users and downstream users are vulnerable to decisions made by upstream states'. Systematic empirical analyses suggests that transboundary waters are associated at least with low-level conflicts, if not with full-scale *water wars* (Toset *et al.*, 2000; Gleditsch *et al.*, 2006a; Hensel and Brochmann, 2007; Hensel *et al.*, 2006; Brochmann and Hensel, 2009; Dinar, 2009). Toset *et al.* (2000) and Gleditsch *et al.* (2006a) find evidence, that countries which share a river face a higher probability of engaging in armed conflict. Hensel *et al.* (2006) and Brochmann and Hensel (2009) using data from the 'Issue Correlates of War Project'[1] report that water scarcity and asymmetry of capabilities in a country dyad aggravate conflict and reduce the probability of successful negotiations, whereas freshwater treaties are conducive to resolving river claims

In contrast to the above mentioned studies, Dinar *et al.* (2007), Wolf (2002) and Yoffe *et al.* (2003) report that states tend to cooperate rather than fight over their shared water resources, and most international water conflicts are not full-scale wars, but rather diplomatic conflicts. Finally, several authors have used data from the Transboundary Freshwater Disputes Database (TEDD)[2] project to identify basins at risk, i.e. international river basins likely to experience political stress in the near future Wolf *et al.* (2003a, 2005). They conclude that the likelihood and intensity of disputes rises when population density is high, income is low, overall relations between countries are unfriendly, there are politically active minority groups, large dams or other water development projects are planned, and there are limited or no freshwater treaties.

Although the water wars hypothesis lacks conclusive evidence it will be premature to conclude that conflicts over freshwater are irrelevant. Moreover since serious non-militarized international disputes over water issues exist and may well increase in frequency in future, par-

[1] Correlates of War, COW, see `http://www.correlatesofwar.org/`

[2] available at `http://www.transboundarywaters.orst.edu/database/`

ticularly in economically and politically unstable areas with significant climate change impacts and pronounced population growth, more research is needed to establish interlinkages between climatic change and impacts and how these translate into the potential for conflict.

Here, we discuss these linkages in the context of internationally-shared surface water resources from a theoretical perspective. By means of the modeling framework presented here, our intent is to shed light on conflict dynamics under climate forcing in conjunction with power disparities between upstream and downstream countries. Our theoretical framework captures essential components without being overly burdened with complexity. As we show below, this allows for crucial insight on climate-related conflict in the context of transboundary water and how its dynamics *may* unfold contingent on climate forcing and relative power in basins under study.

Modeling components include: a) a hydro-climatological model that determines the space-time availability of water in a transboundary basin that is shared by two *economic* players, one in the upstream and one in the downstream, and that is subject to climatic change, b) a utilitarian model which translates consumptive and non-consumptive water use into utility which the players are maximizing, given constraints and c) a representation of the interactive decision situation in the presence of unequal power. The model is presented in Section 2.

Our model presumes that equilibrium allocation outcomes are resulting from a joint optimization process of all stakeholders in a given watershed. It formalizes how allocative decisions (external effects) from upstream allocations, i.e. either diminished runoff or a change in the seasonality in runoff or both, migrate downstream in flow direction and how these effects can lead to adverse impacts in the downstream, through impairing economic performance in freshwater-dependent sectors there. Proportional to these impacts on the downstream economy, it suggests the emergence of a corresponding level of dissatisfaction. This downstream *conflict potential* poses a certain threat from the upstream's perspective in situations where the downstream is

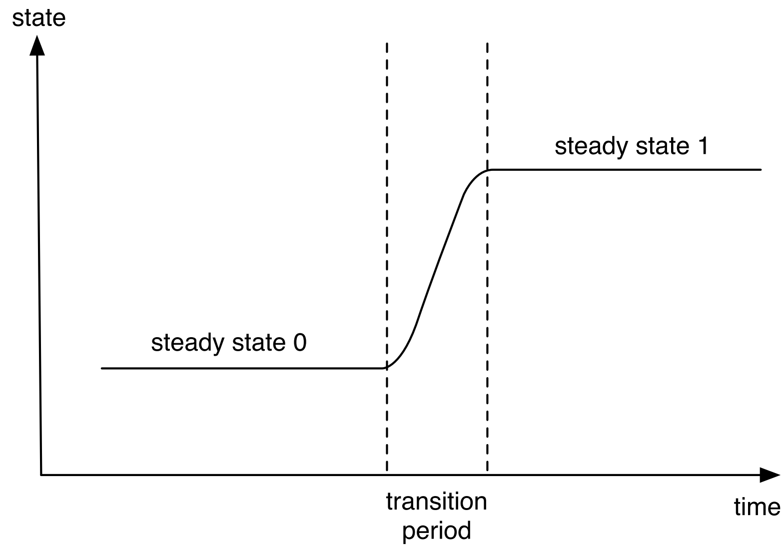

Figure 1: Sample transition of a hydro-political system experiencing a shift from a state 0 to a new state 1 as a response to external (climate) and/or internal (relative power distribution) forcings.

able to project its power upstream, given economic, political and/or militaristic capabilities.

We presume that in any real-world decision-making context, upstream always factors these potential impacts from elevated and unilaterally biased levels of conflict into her allocation decisions. Consequently, upstream adjusts its water allocation so that its marginal loss of benefit equals a marginal reduction of the adverse impacts in the downstream. New optimal equilibrium allocation outcomes thus emerge as tradeoff solutions in function not only of the distribution of available runoff but also in function of the relative distribution of power within the watershed.

Based on our formalization of the collective decision-making problem in the transboundary basin, notions of the *conflict potential* and *peace* are then developed. In Section 3, we apply our model to a case where we investigate a shift in hydro-climatological conditions due to climatic change (external forcing) and/or the shift in the distribution of relative power in a basin (internal forcing) by means of a steady state framework where it is assumed that the hydro-political allocation system moves from steady state 0 to a new steady state 1 due to these forcings (see

Figure 1). This also allows us to assess systems sensitivities relative to these forcings. Finally, Section 4 concludes.

2 Model

2.1 Climate Change Impacts on Hydrology

Under the assumption that non-evapotranspirative losses are small, total average basin-wide water availability $r = r_u + r_d$ is determined by total basin-wide precipitation $p = p_u + p_d$ net of evapotranspirative fluxes $ET = ET_u + ET_p$, i.e.

$$r = p - ET \tag{1}$$

The subscripts are sub-basin identifiers that denote the upstream $(\cdot)_u$ and downstream $(\cdot)_d$ players, respectively. The respective relations also hold for upstream and downstream domains. We refer to r_u and r_d as internally renewable water resources (IRWR) from the individual countries perspective (see also Food and Agricultural Organization, 2003).

Consumptive water uses are denoted correspondingly by $q_{u,c}$ and $q_{d,c}$ and entail evapotranspirative fluxes over natural ecosystems as well as agricultural lands. Non-consumptive uses are $q_{u,n}$ and $q_{d,n}$ and describe in-stream fluxes, either from baseflow, direct runoff or from reservoir releases or a mixture thereof. For the downstream, $q_{u,n}$ is the externally renewable water resource component (ERWR) whereas for the upstream, ERWR is by definition nil. Figure 2 shows a stylized representation of the transboundary basin water balance with the relevant fluxes and storage.

The long-term water balances for the upstream and downstream is given by

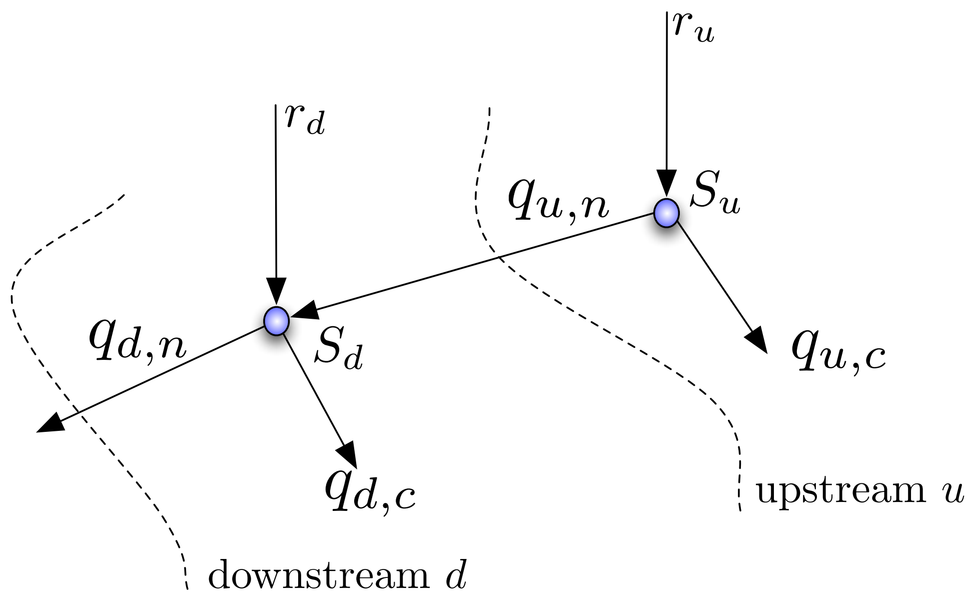

Figure 2: Stylized representation of a typical upstream / downstream configuration in a transboundary river basin. The dotted lines indicate political domain boundaries, such as national territories. Available runoff is indicated by r_i, storage S_i is depicted by blue nodes and allocative fluxes are denoted with $q_{i,c}$ and $q_{i,n}$ respectively.

$$0 = r_u - q_{u,c} - q_{u,n} \tag{2}$$

$$0 = r_d + q_{u,n} - q_{d,c} - q_{d,n} \tag{3}$$

As is readily visible from the above equations, all allocation decisions in the upstream influence water availability in the downstream. Increases / decreases in $q_{u,c}$ in the upstream decrease / increase total water availability in the downstream through changes in the transboundary flow, i.e. $q_{u,n}$[3].

For the downstream, an interesting figure is how IRWR compares to ERWR as it allows to

[3]In a fully intertemporal model specification, Equations 2 and 3 would be $dS_u/dt = r_u - q_{u,c} - q_{u,n}$ and $dS_d/dt = r_d + q_{u,n} - q_{d,c} - q_{d,n}$ respectively where dS_u/dt and dS_d/dt denote changes in storage in the upstrem and downstream. In this specification, $q_{u,n}$ can also be influenced by human activity, such as hydropower production and cause significant changes in the seasonality of the transboundary flow with resulting impacts in the downstream. Hence, strictly speaking, both $q_{u,c}$ and $q_{u,n}$ are externalities in an economic sense for the downstream users (Griffin, 2006).

assess to which extent the downstream receives water from external sources, given particular basin configurations, and thus depends on it (Food and Agricultural Organization, 2003). For this purpose, we define the downstream's dependency ratio as

$$\delta_d = \frac{\text{IRWR}}{\text{IRWR} + \text{ERWR}} = \frac{q_{u,n}}{r_d + q_{u,n}} \tag{4}$$

Climate change can alter net water availability in individual subcatchments and the overall watershed through differential changes in precipitation and/or evapotranspirative fluxes (Arnell, 2004). To study these, we depart from Equation 1 and follow Wigley and Jones (1985) by defining the present-day runoff ratio w of a watershed basin by

$$w = \frac{r^0}{p^0} \tag{5}$$

Hence, for a watershed, we get $ET^0 = (1 - w)p^0$ where p^0 and ET^0 are current mean precipitation and evapotranspiration values. Let us now assume that the relative changes in precipitation and evapotranspiration under a climate change scenario can be expressed with $\pi = p^1/p^0$ and $\epsilon = ET^1/ET^0$. Here, p^1 and ET^1 describe future mean precipitation and evapotranspiration values for the climate change scenario under consideration. The change in runoff under such climate change scenario relative to today, i.e. r^1/r^0, can then be easily derived. Using the above relationships and the definition of the present day runoff ratio in Equation 5, we get

$$\frac{r_1}{r_0} = \frac{p^1 - ET^1}{p^0 - ET^0} = \frac{\pi - (1 - w)\epsilon}{w} \tag{6}$$

In many semi-arid to arid large-scale watersheds, the majority of runoff is generated in the elevated upstream part of the total catchment whereas the downstream is only contributing marginally to the generation of runoff. For example, in the case of the Aral Sea catchment and its two main rivers, more than 70 percent of the total runoff is generated in the mountainous terrain of upstream Kyrgyzstan and Tajikistan (Pereira-Cardenal *et al.*, 2011). Under these circumstances, using a basin-wide runoff ratio may fail to adequately represent the conditions in the hydrologically active part of the basin and potential climate impacts there (Wigley and Jones, 1985).

We can account for this by defining upstream and downstream specific climate impact ratios for precipitation and evapotranspiration together with corresponding runoff ratios. The total upstream and downstream runoff under a climate change scenario thus becomes

$$r_i^1 = \frac{\pi_i - (1 - w_i)\epsilon_i}{w_i} r_i^0 \tag{7}$$

with $i \in \{u, d\}$ and where $r_i^0 = r_i$ in Equations 2 and 3 for up- and downstream correspondingly. This formulation will allow us to study differential climate impacts on allocation and conflict, e.g. a further drying in the downstream and precipitation increases in the upstream.

As we will see below, the ratio between downstream and upstream runoff is an important figure in determining optimal allocation outcomes and, with that, conflict. Hence, we define for the current ratio $\rho^0 = r_d^0 / r_u^0$ and $\rho^1 = r_d^1 / r_u^1$ for the runoff ratio under the climate change scenario $p^0 \to p^1$ and $ET^0 \to ET^1$. With Equation 7 and the simplifying assumption of a uniform rainfall-runoff ratio w (see Equation 5) throughout the basin, we can establish a linear relationship between ρ^0 and ρ^1, i.e.

$$\rho^1 = \alpha \cdot \rho^0, \text{ where } \alpha = \frac{\pi_d - w^* \epsilon_d}{\pi_u - w^* \epsilon_u} \tag{8}$$

and $w^* = 1 - w$. α can be regarded as a sensitivity parameter of how runoff is impacted by climate change in particular basins. For the balance of runoff generation to shift towards the downstream ($\alpha \geq 1$), we need $\pi_d - \pi_u \geq w^* (\epsilon_d - \epsilon_u)$. Similarly, for $\alpha \leq 1$, $\pi_d - \pi_u \leq w^* (\epsilon_d - \epsilon_u)$.

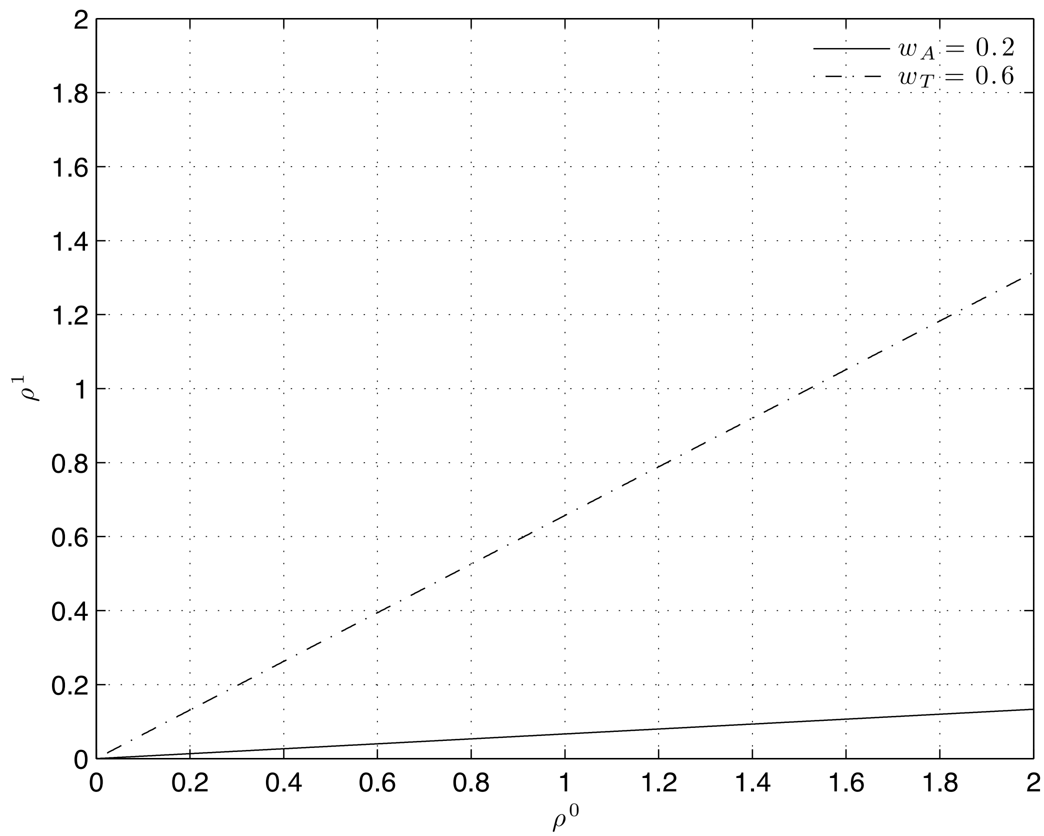

Figure 3: The figure shows a continuum of various runoff ratio regimes for two sample river basins, one in a semi-arid climate (runoff coefficient of $w_A = 0.2$) and one in a temperate climate with $w_T = 0.6$ and shows how they will be impacted by a climate regime shift $p^0 \to p^1$ and $ET^0 \to ET^1$. Chosen parameter values are: $\pi_u = 1.1$, $\pi_d = 0.9$, $\epsilon_u = 1$ and $\epsilon_d = 1.1$.

As is shown in Figure 3, we can easily calculate the change in relative availability of runoff under climate change scenarios. For a sample semi-arid and a temperate basin, the figure shows impacts from a 10% upstream increase and 10% downstream decrease in precipitation as well as a 10 % increase in ET there. Thus, for the semi-arid Syr Darya basin in Central Asia, we have $\rho^0 = 0.3/0.7 = 0.43$ and thus get a dramatic shift in the ratio of net runoff generation with $\rho^1 = 0.28$. Similarly, for a temperate basin with uniform net water balances, i.e. $\rho^0 = 1$, we get $\rho^1 = 0.66$. In other words, a 10% increase of upstream precipitation will translate into a relative (relative to downstream) increase of 34% in runoff generation there, given the corresponding drying in the downstream.

2.2 Water Allocation and Power Asymmetry

By following standard approaches in utilitarian welfare theory, players' utilities U_i are understood as cardinal measures to be used in the context of utilitarian welfare evaluations (Griffin, 2006). Hence, we assume that a) economic utility is derived from consumptive (i.e. water for irrigation, industry, domestic water use, etc.) as well as non-consumptive water use (i.e. hydropower production, in-stream utility for wetlands, etc.); b) the stakeholders prefer more over less water and c) factor productivity is diminishing throughout the relevant range of water requirements or availability.

Traditionally, the collective action problem has been formulated as

$$U_u = g_u(q_u) \tag{9}$$

$$U_d = g_d(q_d, q_u) \tag{10}$$

where the g_i are individual payoff (or utility) functions for each agent i and the $q_i = \{q_{i,c}, q_{i,n}\}$ denote the set of decision variables [4]. Each players well defined objective is then

[4] Again, in a fully intertemporal specification, a generalized objective function can be expressed as $g_i =$

to maximize her utility, given physical, economic and institutional constraints that may influence her pre-bargaining positions and the feasible set of allocation outcomes.

A number of generic regimes have usually been differentiated in basins, either cooperative or non-cooperative, which determine the nature of optimal equilibrium allocation outcomes. For the two-player case for example, two non-cooperative situations can be distinguished, i.e. the upstream dominated basin (UDB) and the downstream dominated basin (DDB), both of which are conceptually different from a fully cooperative situation, where the basin players are trying to jointly allocate water so as to attain a basin-wide optimal utility level (BWO)[5].

The UDB and DDB are thus the two cases related to extremes in property rights interpretation that can be found in international law on water resources. The doctrine of *unlimited territorial sovereignty* (UDB) states that any country has absolute decision authority over the resources on its territory whereas the doctrine of *unlimited territorial integrity* (DDB) states that cross-border flow cannot be altered in any way Barrett *et al.* (1994). These different doctrines clearly imply differences in the perception of property rights and thus pre-bargaining positions of the individual players.

For UDB, the riverine topology determines the optimization sequence where downstream optimal use is entirely conditional on non-cooperative optimal upstream allocation. Hence, the players solve the following optimization problem along the flow direction,

$$q_u^*(\text{UDB}) = \underset{q_u}{\text{argmax}}\ \mathbb{E}[g_u] \tag{11}$$

$$q_d^*(\text{UDB}) = \underset{q_d}{\text{argmax}}\ \mathbb{E}[g_d|(q_u^*)] \tag{12}$$

subject to constraints, where $\mathbb{E}\,[]$ is the expectation operator and q_u^* as well as q_d^* denote op-

$\sum_{t=0}^{T} \Delta_i(t) f_i(q_{i,c}(t), q_{i,n}(t)) + \Delta_i(T+1) f_i(q_{i,c}(T+1), q_{i,n}(T+1))$ (on that topic, see also Labadie and ASCE, 2004). $f_i(q_{i,c}(T+1), q_{i,n}(T+1))$ are estimated current benefits beyond the optimization time horizon T and $\Delta_i(t)$ is a discount factor.

[5]The BWO model is explained in greater detail in Appendix 5.1

timal allocation strategies in the upstream and downstream, respectively. $g_d|(q_u^*)$ indicates that the downstream optimal allocation is fully conditional on optimal upstream allocation decisions.

Conversely, for DDB, absolute downstream dominance would translate into the situation where upstream modifications of the runoff regime, that could translate into either reduced downstream flows or changes in the seasonality in the runoff or both, are not permitted. Hence, under the assumption of property rights being derived from the doctrine of unlimited territorial integrity, the optimal consumptive upstream allocation is $q_{u,c}^* = 0$ and $q_{u,n}^* = r_u$ (no in-stream alterations, under which the seasonality of naturally occurring runoff, are permitted), the optimization problem for the downstream can be written as

$$q_d^*(\text{DDB}) = \underset{q_d}{\text{argmax}}\ \mathbb{E}[g_d|(r_u)] \tag{13}$$

subject to constraints, where $q_{u,n}$ is simply the naturally occurring transboundary flow[6].

The important question now becomes how bargaining outcomes can get biased towards downstream or upstream as a function of the relative distribution of power between the riparians. In other words, how do asymmetries in the distribution of military, economic and political power influence bargaining outcomes in international river basins?

What we have established so far is that the upstream agent impacts the downstream actor either through flow reductions (consumptive use) and/or increases (reservoir releases) or through a change in runoff timing or both. These unidirectional flow externalities impacting the downstream are accounted for in the specification of the collective bargaining problem in Equations 9 and 10. Now, we posit that depending on a) the relative distribution of power and b) the size of welfare impacts in the downstream, the latter *may* decide to interfere with upstream activities by means of a projection of power so as to influence allocation outcomes towards more beneficiary

[6]Note, even though the upstream is a *passive* player its utility level is not necessarily nil, it can still derive utility, e.g. from hydropower production in run–by–the–river plants.

outcomes for herself. The important point here is that this *potential* threat is perceived in the upstream which itself induces a change in its allocation behavior.

If the downstream is much more powerful than the upstream, we expect allocation outcomes that are close to DDB situations. Contrary to that, in the case where the downstream has no potential leverage over upstream activity at all since the latter is not just water rich but also the dominion in the basin (i.e. the downstream has much less power relatively speaking), we expect outcomes to close to or equal to the UDB case.

Given such an understanding of the collective nature of basin-wide decision-making in an environment of asymmetric flow externalities as well as the presence of an asymmetric configuration of power, the adequate representation of this kind of strategic interaction is that of a normal form cooperative game which assumes that each agent is pursuing her individual goal by rationally optimizing her payoff as a function of the other riparians' optimizing behavior.

In the following hydro-political conflict model, we assume that a) the dissatisfaction level in the downstream (due to upstream allocation) is proportional to negative welfare impacts there and that b) the upstream is perceiving this impact as a potential for inter-state intervention, depending on the relative configuration of power in the basin. For this purpose, we define an impact factor $\Im$ with

$$\Im(q_d, q_u) = \left(1 - \frac{h(q_d, q_u)}{h^*}\right)^\gamma \tag{14}$$

where

$$h(q_d, q_u) = g_d(q_d^*(\text{DDB})) - g_d(q_d, q_u) \tag{15}$$

$$h^* = g_d(q_d^*(\text{DDB})) - g_d(q_d^*(\text{UDB})) \tag{16}$$

In words, h^* is the *additional* attainable benefit for the downstream actor under a DDB situation relative to a UDB situation. Similarly, h is the benefit for the downstream actor under a DDB setting relative to an *actual*, observed situation of basin-wide allocation q_d and q_u.

The exponent γ can be regarded as a measure for power asymmetry between riparians or coalitions thereof, where low values reflect tolerance / little power to intervene (γ small) and intolerance / economic-political basin dominance (γ large) of downstream versus unilateral upstream action. γ can be scaled according to the ratio of the individual downstream's and upstream's capabilities for intervention, which are themselves determined by factors such as population size, GDP, military capabilities, etc.. As discussed later, the Composite Index of National Capability (CINC) is a convenient measure in this context (COW, 2005).

$\Im(q_d, q_u)$ thus embodies the notion of how much the upstream is impacting the downstream economic performance, via actual consumptive allocation and alterations of transboundary in-stream flows, relative to what the downstream could have gained under hypothetical, sole basin dominance (DDB). Note, since by definition $0 \leq \frac{h(q_d,q_u)}{h^*} \leq 1$, it follows that $\Im(q_d, q_u) \in [0, 1]$.

Based on this specification of the impact factor above, we are now in the position to redefine the bargaining model specified in Equations 9 and 10 as

$$U_u = \Im(q_d, q_u) g_u(q_u) \tag{17}$$

$$U_d = g_d(q_d, q_u) \tag{18}$$

Equilibrium allocation strategies in such a hydro-political conflict model (HCM) are then

$$\{q_u^*(\text{HCM}), q_d^*(\text{HCM})\} = \underset{q_u, q_d}{\text{argmax}}\ \mathbb{E}[\Im(q_d, q_u) g_u + g_d] \tag{19}$$

Note the similarity of the above model to the cooperative BWO model as presented in Equation 32.

2.3 Conflict Potential and Peace

Let us now turn our attention towards conflict and investigate a) the basin-wide conflict potential of equilibrium allocation outcomes and b) implications for peace. We posit that the potential for conflict is just one measure of total dissatisfaction. What matters though from the perspective of a probability of interstate conflict is not just the total *loading* of the system in the sense how much combined dissatisfaction (conflict) there is but also how it is distributed, relatively speaking, and how it aligns with the distribution of power between the riparian states.

According to the *Hegemonic Stability* and *Power Transition Theories* (Snidal, 1985; Kugler and Organski, 1989), states are interested in maximizing their control over the rules and customs that govern their interactions so that they can define the status quo according to their interests. If the rules of their interaction are selected by the dominant state and enforced by that state, this would implies that the dominant state has the power maintain the status quo and correspond to the two cases where either γ is small or large.

However, dissatisfaction with the status quo can become a major source of tension when there is no clear power asymmetry ($\gamma \approx 1$), e.g. in the case where the dissatisfied state grows strong enough to challenge the authority of the dominant state/hegemon and a potential war between the riparian states could aim at changing the rules of the game. Consequently, peace is likely to persist when there is a preponderance of power among states in any given upstream-downstream setting.

With this in mind, we define a basin-wide conflict potential as

$$c = c_u + c_d \tag{20}$$

with

$$c_u = \frac{U_u(\text{UDB}) - U_u(\text{HCM})}{U_u(\text{UDB})} \tag{21}$$

$$c_d = \frac{U_d(\text{DDB}) - U_d(\text{HCM})}{U_d(\text{DDB})} \tag{22}$$

Hence, the conflict potential c is understood as total dissatisfaction which can be framed in formal terms as the sum of individual utility losses for upstream and downstream relative to their corresponding utility levels, $U_u(\text{UDB})$ and $U_d(\text{DDB})$ under UDB and DDB hydro-hegemony, and scaled by $U_u(\text{UDB})$ and $U_d(\text{DDB})$ respectively.

3 Model Application

3.1 Equilibrium Steady-State Strategies

Analytical solutions of optimal steady-state equilibrium allocation strategies $q^*_{i,n}$ and $q^*_{i,c}$ for upstream and downstream can be derived for the above specified HCM model while assuming a CES-type utility function (Arrow *et al.*, 1961). Hence, agent utilities are given by

$$g_i = \phi_i(a_i \cdot q_{i,c}^{s_i} + (1 - a_i) \cdot q_{i,n}^{s_i})^{\frac{1}{s_i}} \tag{23}$$

The subscript i is again the upstream and downstream agent identifier respectively, ϕ_i denotes the individual basin players' factor productivities, a_i and $1 - a_i$ are share parameters or weights that determine to what extent consumptive and non-consumptive use contributes to overall utility. If for the substitution parameter s it holds that $s_i < 1$, the utility function is concave with decreasing returns to scale. For ease of exposition, we presume that consumptive and non-consumptive use contributes equally to factor productivity, i.e. $a_i = 1/2$[7]. Also, we choose

[7] Note that general solutions for a_i can easily be derived. Results under this more general specification however are lengthy algebraic expressions. If real-world problems are investigated, share parameters can be calibrated to actual country situations.

a quadratic production function specification with diminishing returns to scale and a satiation point by assuming $s_i = 1/2$ which is standard in water resources economics (Griffin, 2006).

By solving the optimization problem in Equation 19, HCM equilibrium allocation solutions get

$$q^*_{u,c} = \frac{r_u\left(1+\gamma-\sqrt{\gamma(2+\gamma)}\right)}{2(1+\gamma)} \quad , \quad q^*_{u,n} = \frac{r_u\left(1+\gamma+\sqrt{\gamma(2+\gamma)}\right)}{2(1+\gamma)} \tag{24}$$

$$q^*_{d,c} = \frac{r_u}{4}\left(2\rho+1+\frac{\sqrt{\gamma(2+\gamma)}}{1+\gamma}\right) \quad , \quad q^*_{d,n} = \frac{r_u}{4}\left(2\rho+1+\frac{\sqrt{\gamma(2+\gamma)}}{1+\gamma}\right) \tag{25}$$

where ρ is again the ratio of runoff generate in the downstream versus the one generated in the upstream[8].

It is interesting to note that optimal strategies in the UDB and DDB cases depend on hydro-climatological factors only, i.e. r_u and r_d (Equations 28-31 in Appendix A). This is the standard result for the cases where allocation outcomes are solely determined by basin dominance of the corresponding hydro-hegemon. For the HCM model, the UDB and DDB solutions can be recovered if we let $\lim_{\gamma \to 0} q^*_{i,c}(\gamma)$ and $\lim_{\gamma \to 0} q^*_{i,n}(\gamma)$ for the upstream dominated case and $\lim_{\gamma \to \infty} q^*_{i,c}(\gamma)$ as well as $\lim_{\gamma \to \infty} q^*_{i,n}(\gamma)$ for the downstream dominated case correspondingly.

This is an important point because it means that the hydro-political conflict model presented here generalizes the extreme corner solutions of absolute basin dominance under the two opposing doctrines of unlimited territorial sovereignty on the one hand and unlimited territorial integrity on the other. At the same time, it allows for a more nuanced representation of actual hydro-political conflict situations in watersheds.

It is instructive to study prototypical surface water resources sharing conflicts with the hydro-political model specified above. For this purpose, we discuss three canonical cases, i.e.

[8]Note, HCM model solutions depend on solutions from the UDB and DDB models. These are reported in Appendix A, Equations 28 - 34), including those from the benchmark cooperative BWO model as specified in Equation 32 below.

Case 1: hydrological and economic symmetry, Case 2: upstream wet, low economic productivity and weak, downstream dry and economically productive as well as powerful and Case 3: upstream wet and economically strong as well as powerful, downstream dry and subservient to upstream interests.

Case 1 describes situations where precipitation net evapotranspiration is relatively equally distributed within the basin. Such basins are most often found in mid-latitude, temperate regions on the planet or in regions where topography-driven precipitation is not the dominant runoff generating process. Examples of large transboundary rivers include the the River Rhine, the Zambezi River Basin, the Mississippi River, etc.. In our Case 1 model, we furthermore assume uniform economic productivity as well as a $\gamma = 1$, i.e. a uniform power distribution (Table 1 lists canonical model parameter values). Results for the three canonical river basin cases for individual regimes are shown in Figure 4.

Cases 2 and 3 describe canonical cases of river basins in semi-arid to arid regions where upstream generates a majority of the basin-wide runoff. Conversely to Case 2, where we assume that the lesser developed as well as weak riparian is in the upstream, we presume the opposite economic and political configuration in Case 3, where productivity and power is aligned with hydrology. Real-world examples for Case 2 include the Amu and Syr Darya in Central Asia as well as the Nile River Basin in north-eastern Africa. Euphrates and Tigris rivers, the Rio Grande River and the Mekong River can be considered to belong to Case 3 (Gleick, 1993b; Wolf *et al.*, 2003b; Yoffe *et al.*, 2003; Gleditsch *et al.*, 2006b).

This is clearly only a first step towards a full application of the modeling framework presented in Section 2. Nevertheless, it allows for important insight regarding equilibrium allocation outcomes as a function of hydro-climatology and relative power and also allows to quantify allocation inefficiencies as they arise from power asymmetries in a basin.

Location	Parameters	Case 1	Case 2	Case 3
Upstream	r_u	1	3	3
	Φ_u	1	1	3
Downstream	r_d	1	1	1
	Φ_d	1	3	1
Basin-wide	ρ	1	0.33	0.33
	γ	1	3	0.33

Table 1: List of parameter values utilized for the canonical cases. As can be readily verified, in Case 2 for example, upstream generates 75 percent of total basin runoff on its territory. While the chosen parameter values are hypothetical, they nevertheless depict typical real-world cases.

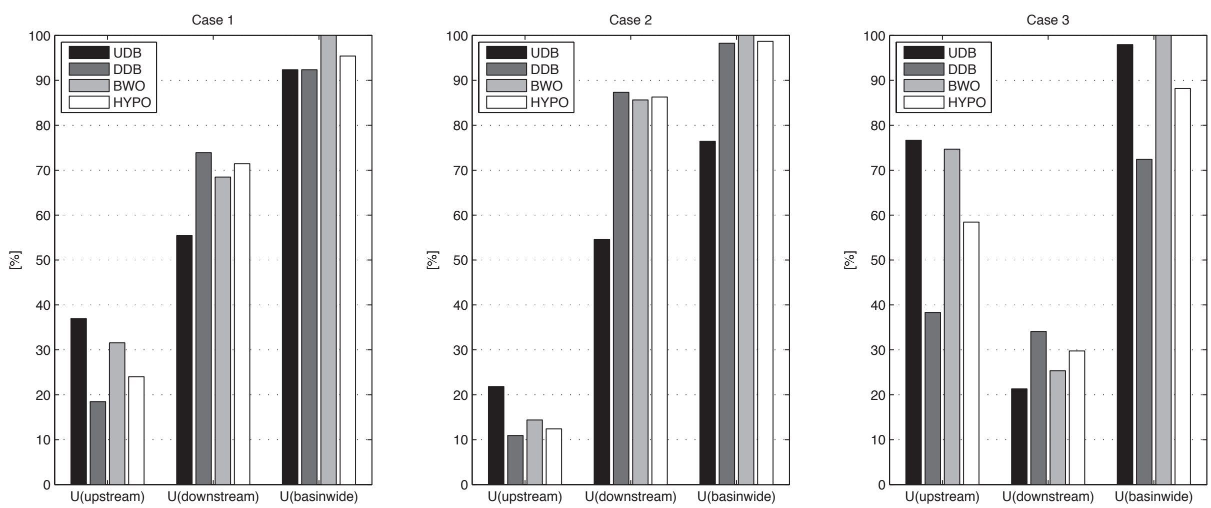

Figure 4: Optimization outcomes for three canonical river basins under different regimes. The vertical axes show relative productivities (percentages) for upstream and downstream as well as the total basin. All results are scaled by the corresponding benchmark BWO basin-wide utility. The individual optimization results from the four river basin regimes are grouped according to upstream, downstream and basin-wide outcomes.

3.2 Conflict and Peace

Let us now turn our attention to the conflict potential. By using the definition given in Equation 20 together with equations 24–25 and Equations 28–31 in Appendix A we get

$$c(\gamma, \rho) = \frac{1 - \sqrt{\gamma(2+\gamma)} + \gamma(2+\rho)}{2(1+\gamma)(1+\rho)} \tag{26}$$

where $\rho = r_d/r_u$ is again the ratio of upstream versus downstream precipitation. In a very intriguing way, we see thus the conflict potential c emerging as a function of two kinds of asymmetries, the asymmetry in power γ on the one hand and the asymmetry of the distribution of precipitation ρ on the other[9]. Hence our notation $c = c(\gamma, \rho)$. Note, $\lim_{\gamma \to 0} c(\gamma, \rho) = 1/(2 + 2\rho)$ and $\lim_{\gamma \to \infty} c(\gamma, \rho) = 1/2$. This means that under total downstream dominance DDB (i.e. $\gamma = \infty$), the conflict basin-wide conflict potential is equal to the relative utility loss in the upstream due to the inability to consumptively utilize any amount of water there (see also Equation 30 and compare with Equation 28, both in Appendix A). Conversely, the conflict potential in the limiting case of absolute upstream dominance UDB is a function of the relative runoff contributions ρ over the individual downstream and upstream domains. If all the runoff is generated in the downstream, i.e. $\rho = \infty$, conflict vanishes ($c(0, \infty) = 0$)) naturally since upstream has not access to any means of production and since there is no potential for a transboundary flow reduction anyway. If runoff is aligned with absolute basin dominance, i.e. $c(0, 0) = 1/2$ where the maximum conflict potential in the basin emerges from the adverse impacts in the downstream.

It is convenient to express the conflict potential of a given basin and allocation structure in percentages of the maximum *potential* conflict. We denote this relative conflict potential with c^*. Figure 5 shows c^* for four distributions of runoff ρ in function of the distribution of power γ. The grey-shaded area in Figure 5 indicates the domain $\gamma \in [0.8, 1.2]$ where there is no clear

[9] One might wonder why economic factor productivities do not enter this expression. It should be remembered though that γ is also a measure of total productivity, among other things, and thus incorporates economic considerations.

power asymmetry or, in other words, an absence of stability[10]. Within the domain of unstable configurations, the conflict potential increases for all power ratios γ in relation to the relative amount of precipitation generated in the upstream. This would be indication of high conflict potential in cases where a mountainous humid upstream territory produces the majority of the runoff and where there is no clear hegemon among the riparian states. Using country-specific CINC factors averaged over the years 1990–2000 from the COW database to calculate basin-specific γ-values, we see that prominent real-world examples of rivers where ρ is small ($\rho \leq 1$) , i.e. Indus ($\rho = 0.4$, $\gamma = 0.2$), Syr Darya ($\rho = 0.33$, $\gamma = 7.55$) and Amu Darya ($\rho = 0.25$, $\gamma = 7.5$), Euphrates and Tigris ($\rho = 0.57$, $\gamma = 0.28$), the Blue Nile river ($\rho = 0.015$, $\gamma = 2.73$) and Rio Grande ($\rho = 1$, $\gamma = 0.10$), are not located within the domain range for instability[11].

The corresponding data of these river basins is plotted in Figure 5. As can be easily seen by inspecting this Figure, our model suggests for example that the conflict potential is highest (approx. 90 % of the maximum conflict potential) in the case of the two Central Asian rivers, i.e. the Amu Darya and the Syr Darya. At the same time, the power asymmetry is pronounced in both cases suggesting hegemonic stability as the rivers locations in the conflict – power asymmetry space is far removed from the critical region of instability (grey shaded).

3.3 Climate Change Impacts

For a specific climate change scenario $p^0 \rightarrow p^1$ and $ET^0 \rightarrow ET^1$ and by using Equations 8 and 26, impacts on the conflict potential in function of the basin-specific climate change sensitivity α can be expressed as

[10] Note that the domain range for instability under the absence of a preponderance of power has been arbitrarily chosen.

[11] Hydrological data sources: Indus River, http://www.eoearth.org/article/Water_profile_of_Pakistan; Euphrates-Tigris basin, http://www.balwois.com/balwois/administration/full_paper/ffp-462.pdf, Table 4; Rio Grande, http://www.crwr.utexas.edu/gis/gishyd98/library/wbtexas/sect5.htm and http://en.wikipedia.org/wiki/Rio_Grande.

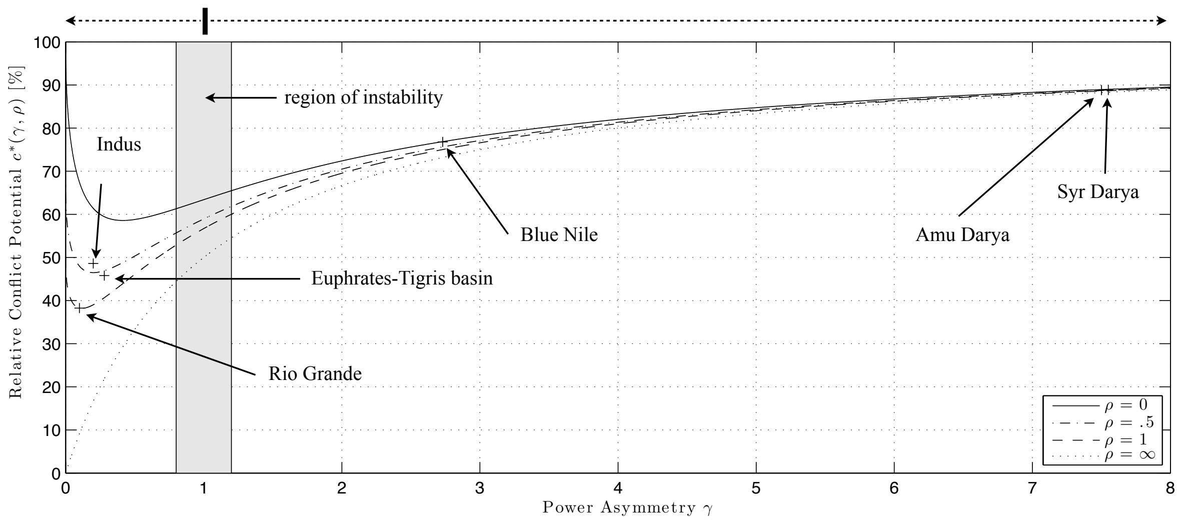

Figure 5: $c^*(\gamma, \rho)$ dependence on γ for various relative runoff contribution ratios are shown. $\rho = 0$ and $\rho = \infty$ are limiting cases and indicate that all runoff is generated in the upstream and downstream respectively due to (fictitious) hyper-arid conditions in the adjacent domains within a basin. Real-world data for six large-scale transboundary river basins is additionally shown. The two horizontal arrows at the top of the figure point into the direction of increasing hegemonic stability.

$$c^1 = c(\gamma, \rho^1) = c(\gamma, \alpha\rho^0) \tag{27}$$

Let us illustrate the model by again investigate the climate change scenario introduced in Figure 3 where we compared impacts from a climatic change scenario ($\pi_u = 1.1$, $\pi_d = 0.9$, $\epsilon_u = 1$) in a semi-arid basin with those in a temperate basin. Utilizing Equation 8, we can calculate the individual α and plug these into Equation 27. Like this, the sensitivity of particular rivers in function of climate change can easily be assessed.

Additionally, we can utilize Equation 27 to easily quantify the sensitivity of a basin's conflict potential over a range of potential climate change scenarios α. Results are shown in Figure 6. Note that the shape of the individual lines corresponding to different γ values shows the conflict potential's sensitivity to the climate change parameter α. One of the key results here is that

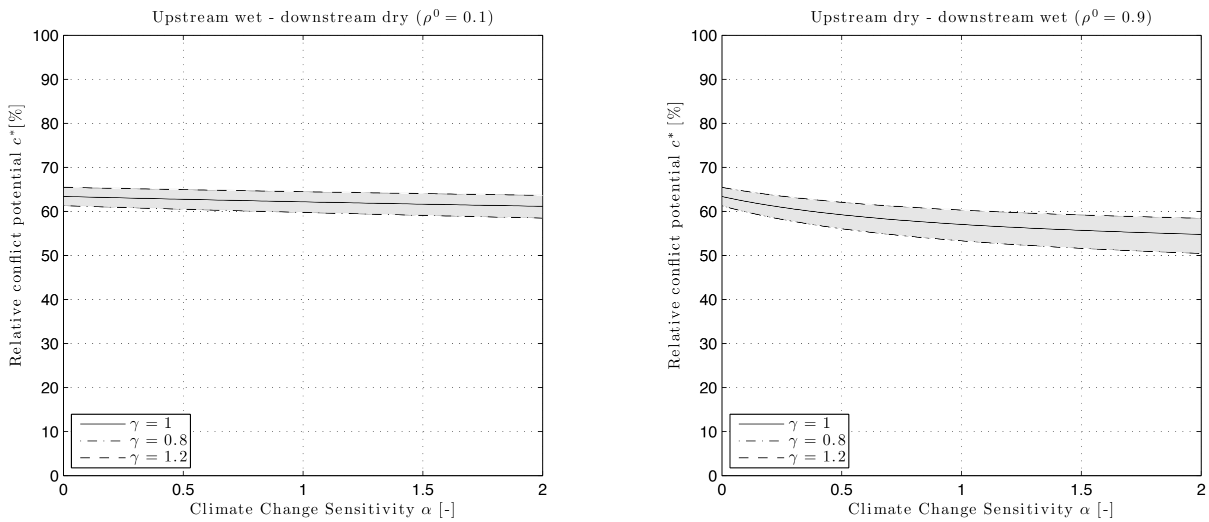

Figure 6: $c(\gamma, \alpha, \rho^0)$ as a function of the climate sensitivity α is shown for 2 prototypical basins and unstable γ configurations. The region of instability is again shaded grey (compare also with Figure 5 above). The increase in the grey area's spread proportional to α suggests higher sensitivity of conflict to the distribution of power when there is more water to fight over.

there is very little sensitivity of the relative conflict potential c^* to α, even over significant ranges of α. Conversely, the vertical spread of the grey shaded area shows sensitivity of the conflict potential for a given α relative to changes in γ. Even from visual inspection, it is easily visible that the relative conflict potential is always more sensitive to changes in the power configurations between riparian states than to climatic changes[12].

Figure 6 also suggests that a) the relative conflict potential is always higher in a semi-arid basin (left Panel) when compared to the temperate basin (right Panel), albeit only very slightly and b) the conflict potential's sensitivity to an increase in α is always negative. In other words, greater water availability in a basin due to climate change implies a decrease in the conflict potential.

The hydro-political model (HCM) presented here thus imply that impacts from shifts in the relative distribution of power between riparians (socio-economic changes) will always outweigh

[12]This result can be confirmed by calculating $\left(\partial c(\gamma, \alpha\rho^0)/\partial\gamma\right)$ / $\left(\partial c(\gamma, \alpha\rho^0)/\partial\alpha\right)$.

climate impacts. Our theoretical model results thus confirm recent global-scale empirical modeling studies which found that changes in socio-economic configurations in basins, including increasing population numbers, are more important drivers of global change than greenhouse warming impacts (e.g. see Vorosmarty *et al.*, 2000).

4 Conclusions

In this paper, we have developed a theoretical model of hydro-political conflict (HCM) and subsequently investigated climate impacts. Our point of departure was the observation that allocative decisions based on economic criteria *always* take place within a basin-wide collective decision-making space, even in non-cooperative regimes. The presence of a potentially powerful downstream that can excerpt a threat towards the upstream state, contingent on her ability to project power, implicitly leads the upstream to adjust her allocation decisions so that downstream externalities are less pronounced as compared to the case where upstream were the only basin player. Power, in this sense, can bias allocation outcomes towards the more potent riparian state in a general setting of interactive decision-making. This is comparable to the fictitious case where a set of cooperative basin agents would allocate freshwater according to efficiency criteria and water consequently flow to the riparian state which has the highest economic productivity, only that in the presence of unequal power and a non-cooperative setting, water gets biased towards the hydro-hegemon.

Our definition of a conflict potential in a river basin relies on the notion of individual riparian dissatisfaction which is a measure of individual disutility for each agent emerging from the presence of the other. Summed up, total dissatisfaction measured relatively to upstream and downstream hegemonic systems respectively, is then the total relative utility loss. Interestingly, with this definition, the HCM conflict potential is a function of hydrological upstream / downstream asymmetry and the distribution of power between the riparian states only which is intuitively appealing.

We analyze 6 real-world basins (Blue Nile, Indus, Amu Darya, Syr Darya, Euphrates-Tigris and Rio Grande) with regard to their conflict potential and find that while some of these rivers have an extraordinarily high conflict potential, they are also characterized by a preponderance of power. These basins with near or clear hegemonic power situations and despite the presence of a large conflict potential are expected to be stable in the sense that riparians have little inclination to go to war over access and distribution of freshwater resources. At the same time, in situations where there is a less clear power setting, we identify a region of instability and posit that river basins are at risk if they fall within that domain while at the same time being characterized by extreme asymmetry between individual internally renewable water resources. None of the real-world river basins investigated here fall anywhere near that region of instability.

Climate change impacts on steady-state equilibrium allocation outcomes have been investigated with the HCM model and quantified. We show that expected climate change impacts on conflict in international river basins are limited due to the relative insensitivity of conflict to environmental change. On the contrary, conflict sensitivity to a change in the configuration of power is always larger and increasing when there is more water to have a fight over.

This work should serve as a theoretical foundation for a large-N case study that investigates allocation outcomes under different hydro-climatological and power configuration at a global scale. Our steady-state model has minimal data requirement, hence it easily amends itself to be empirically tested. The six real-world basin cases that we discussed above are a first step towards this direction. Individual case studies with a fully intertemporal model specification should equally become future research targets. A good entry point would be the Amu Darya and Syr Darya in Central Asia where the authors have previously developed hydrological and economic models of the shared river basins there and studied in great detail climate change impacts on hydrology (Siegfried and Bernauer, 2007; Bernauer and Siegfried, 2008; Siegfried *et al.*, 2010; Pereira-Cardenal *et al.*, 2011).

Furthermore, model sensitivity to the particular specification of economic utility has to be carefully assessed. A more general model specification, for example with regard to consumptive and non-consumptive sectoral share parameters, should be developed and results compared with the present model so as to assess the validity of the current results.

Until then, we can be excited about the model presented here because the results are intuitive and meaningful. However, the litmus test, as to whether or not collective decision making processes in allocation decisions in international river basins in fact follow our reasoning here, is still outstanding.

5 Appendices

5.1 Appendix A

UDB model solutions (see Equations 11 - 12):

$$q^*_{u,c} = r_u/2 \quad , \quad q^*_{u,n} = r_u/2 \tag{28}$$

$$q^*_{d,c} = \frac{r_u}{4}(1+2\rho) \quad , \quad q^*_{d,n} = \frac{r_u}{4}(1+2\rho) \tag{29}$$

Note, $\rho = r_d/r_u$. DDB model solutions (see Equation 13):

$$q^*_{u,c} = 0 \quad , \quad q^*_{u,n} = r_u \tag{30}$$

$$q^*_{d,c} = \frac{r_u}{2}(1+\rho) \quad , \quad q^*_{d,n} = \frac{r_u}{2}(1+\rho) \tag{31}$$

In a situation where both riparians would set their allocation targets in a way so as to maximize joint utility (BWO) and hence completely internalize the externalities that arise from the the hydrological connectedness in the basin, equilibrium outcomes can also be determined easily. These outcomes provide a natural efficiency benchmark against which alternative, non–cooperative allocation regimes can be ranked. The BWO optimization problem thus is

$$\{q^*_u(\text{BWO}), q^*_d(\text{BWO})\} = \underset{q_u, q_d}{\text{argmax}}\ \mathbb{E}[g_u + g_d] \tag{32}$$

subject to a set of constraints. As we will show later, the characteristics of a prisoners dilemma are also present in shared river basins, i.e. the non-cooperative equilibria UDB and DDB are inefficient and enforcing the efficient outcome BWO requires cooperation (Hardin, 1968; Ostrom, 1990).

Using the utility specification provided in Equation 23, solutions to the benchmark BWO model (see Equation 32) are

$$q^*_{u,c} = \frac{r_u}{2}\left(1-\omega\right) \quad , \quad q^*_{u,n} = \frac{r_u}{2}\left(1+\omega\right) \tag{33}$$

$$q^*_{d,c} = \frac{r_u}{4}\left(2\rho+1+\omega\right) \quad , \quad q^*_{d,n} = \frac{r_u}{4}\left(2\rho+1+\omega\right) \tag{34}$$

Interestingly, in the case of BWO, upstream and downstream factor productivities enter optimal allocation solutions via a weighting factor ω, where

$$\omega = \frac{\Phi_d}{\sqrt{\Phi_d^2+\Phi_u^2}} \tag{35}$$

In other words, water here simply flows to the highest use value and not to the more powerful riparian. By letting $\lim_{\Phi_u \to 0} \omega = 0$ and $\lim_{\Phi_u \to 0} \omega = 1$, the non-cooperative corner solutions UDB and DDB are recovered

References and Notes

Arnell, N. (2004). Climate change and global water resources: Sres emissions and socio-economic scenarios. *Global Environmental Change*, **14**(1), 31–52.

Arrow, K., Chenery, H., Minhas, B., and Solow, R. (1961). Capital-labor substitution and economic efficiency. *The Review of Economics and Statistics*, **43**(3), 225–250.

Baechler, G., Boege, V., Libiszewski, S., and Spillman, K. (1996). Environmental Degradation as a Cause of War: Ecological Conflicts in the Thrid World and Peaceful Ways of Resolving Them. *Chur and Zuerich: Rueegger*.

Barnett, J. and Adger, W. (2007). Climate change, human security and violent conflict. *Political Geography*, **26**(6), 639–655.

Barrett, S., for Social, C., and on the Global Environment, E. R. (1994). *Conflict and cooperation in managing international water resources*. The World Bank, Policy Research Dept., Public Economics Division.

Bernauer, T. and Siegfried, T. (2008). Compliance and performance in international water agreements: The case of the naryn/syr darya basin. *Global Governance: A Review of Multilateralism and International Organizations*, **14**(4), 479–501.

Brochmann, M. and Hensel, P. (2009). Peaceful management of international river claims. *International Negotiation*, **14**(2), 393–418.

Butts, K. (1997). The strategic importance of water. *Parameters*, **27**(1), 65–83.

COW (2005). Correlates of War Project – National Material Capabilities Data Documentation. Technical report, Paul Diehl, Dept. of Political Science, Illinoy.

Dinar, A., Dinar, S., and McCaffrey, S. (2007). *Bridges over water: understanding transboundary water conflict, negotiation and cooperation*. World Scientific Pub Co Inc.

Dinar, S. (2009). Scarcity and cooperation along international rivers. *Global Environmental Politics*, **9**(1), 109–135.

Food and Agricultural Organization (2003). Review of World Water Resources by Country. Technical Report 23, Food and Agricultural Organization, Rome.

Gleditsch, N. (1998). Armed conflict and the environment: A critique of the literature. *Journal of Peace research*, **35**(3), 381.

Gleditsch, N., Furlong, K., Hegre, H., Lacina, B., and Owen, T. (2006a). Conflicts over shared rivers: Resource scarcity or fuzzy boundaries? *Political Geography*, **25**(4), 361–382.

Gleditsch, N. P., Furlong, K., Hegre, H., Lacina, B., and Owen, T. (2006b). Conflicts over Shared Rivers: Resource Scarcity or Fuzzy Boundaries? *Political Geography*, **25**, 361–382.

Gleick, P. (1993a). Water and conflict: Fresh water resources and international security. *International security*, **18**(1), 79–112.

Gleick, P. H. (1993b). Water and Conflict: Fresh Water Resources and International Security. *International Security*, **18 (1)**, 79–112.

Griffin, R. (2006). *Water Resource Economics, Analysis of Scarcity, Policies and Projects*. MIT Press.

Hardin, G. (1968). The tradegy of the commons. *Science*, **162**(3859), 1243–1248.

Hauge, W. and Ellingsen, T. (2001). *Causal Pathways to Peace*. Westview Press.

Hensel, P. and Brochmann, M. (2007). Armed conflict over international rivers: The onset and militarization of river claims. In *48th ISA Annual Convention, Chicago*.

Hensel, P., McLaughlin Mitchell, S., Sowers, I., and Thomas, E. (2006). Conflict management of riparian disputes. *Political Geography*, **25**(4), 383–411.

Homer-Dixon, T. (2001). *Environment, scarcity, and violence*. Princeton Univ Pr.

Homer-Dixon, T. and Blitt, J. (1998). *Ecoviolence: Links among environment, population and security*. Rowman & Littlefield Pub Inc.

Kugler, J. and Organski, A. (1989). The power transition: A retrospective and prospective evaluation. *Handbook of war studies*, pages 171–194.

Labadie, J. and ASCE, M. (2004). Optimal operation of multi-reservoir systems: state-of-the-art review. *Management*, **130**(2).

Lomborg, B. (2002). The skeptical environmentalist: measuring the real state of the world. *Austral Ecology*, **27**, 238–240.

Malthus, T. (1958). *An essay on population*. Dent.

Matthew, R. (2000). Environment and security in an international context: critiquing a pilot study from nato's committee on the challenges of modern society. *Environmental Change and Security Project Report*, (6), 95.

McCarthy, J. (2001). *Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge Univ Pr.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge Univ Pr.

Pachauri, R. (2007). *Climate Change 2007: Synthesis Report*. IPCC Secretariat, 7 bis Avenue de la Paix C. P. 2300 Geneva 2 CH- 1211 Switzerland,.

Percival, V. and Homer-Dixon, T. (1998). Environmental scarcity and violent conflict: The case of south africa. *Journal of Peace Research*, **35**(3), 279.

Pereira-Cardenal, S., Riegels, N., Berry, P., Smith, R., Yakovlev, A., Siegfried, T., and Bauer-Gottwein, P. (2011). Real-time remote sensing driven river basin modeling using radar altimetry. *Hydrol. Earth Syst. Sci*, **15**, 241–254.

Salehyan, I. (2008). From climate change to conflict? no consensus yet. *Journal of Peace Research*, **45**(3), 315.

Schubert, R., Schellnhuber, H., Buchmann, N., Epiney, A., Grießhammer, R., Kulessa, M., Messner, D., Rahmstorf, S., and Schmidt, J. (2007). Climate change as a security risk. *WBGU Flagship Report. Earthscan, London*.

Siegfried, T. and Bernauer, T. (2007). Estimating the performance of international regulatory regimes: Methodology and empirical application to international water management in the naryn/syr darya basin. *Water Resources Research*, **43**(11), W11406.

Siegfried, T., Beck, L., and Pizarro, G. (2007). Options for Water Resources Management in Darfur. Technical report, UNDP.

Siegfried, T., Bernauer, T., Guiennet, R., Sellars, S., Robertson, A., Mankin, J., and Bauer-Gottwein, P. (2010). Will climate change exacerbate or mitigate water stress in central asia? In *AGU Fall Meeting Abstracts*, volume 1, page 1250.

Simon, J. (1989). Lebensraum. *Journal of Conflict Resolution*, **33**(1), 164.

Snidal, D. (1985). The limits of hegemonic stability theory. *International Organization*, **39**(04), 579–614.

Solomon, S. *et al.* (2007). *Climate change 2007: the physical science basis*. Cambridge University Press Cambridge.

Soysa, I. (2002). Ecoviolence: shrinking pie, or honey pot? *Global Environmental Politics*, **2**(4), 1–34.

Stern, N. (2007). *The economics of climate change: the Stern review*. Cambridge Univ Pr.

Toset, H., Gleditsch, N., and Hegre, H. (2000). Shared rivers and interstate conflict* 1. *Political Geography*, **19**(8), 971–996.

Vorosmarty, C., Green, P., Salisbury, J., and Lammers, R. (2000). Global water resources: vulnerability from climate change and population growth. *Science*, **289**(5477), 284.

Wigley, T. and Jones, P. (1985). Influences of precipitation changes and direct co2 effects on streamflow.

Wolf, A. (2002). *Conflict prevention and resolution in water systems*. Edward Elgar Publishing.

Wolf, A., Yoffe, S., and Giordano, M. (2003a). International waters: Identifying basins at risk. *Water policy*, **5**(1), 29–60.

Wolf, A., Kramer, A., Carius, A., and Dabelko, G. (2005). Managing water conflict and cooperation. *State of the World 2005: Redefining Global Security*, pages 80–99.

Wolf, A. T., Yoffe, S. B., and Giordano, M. (2003b). International waters: identifying basins at risk. *Water Policy*, **5**, 29–60.

Yoffe, S., Wolf, A. T., and Giordano, M. (2003). Conflict and Cooperation over International Freshwater Resources: Indicators of Basins at Risk. *Journal of the American Water Resources Association*, pages 1109–1126.