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CLIMATE CHANGE AND COOPERATION IN TRANSBOUNDARY WATER SHARING: AN APPLICATION OF STOCHASTIC STACKELBERG DIFFERENTIAL GAMES IN VOLTA RIVER BASIN

ANIK BHADURI*
Center for Development Research (ZEF), University of Bonn,
Walter Flex Strasse 3, Bonn 53113, Germany
E-mail: abhaduri@uni-bonn.de

UTPAL MANNA
School of Mathematics, Indian Institute of Science Education and Research (IISER), CET Campus, Thiruvananthapuram 695016, Kerala, India
Thiruvananthapuram, India
E-mail: manna.utpal@iisertvm.ac.in

EDWARD BARBIER
Department of Economics and Finance, University of Wyoming,
Laramie 82071, WY
E-mail: ebarbier@uwyo.edu

JENS LIEBE
Center for Development Research (ZEF), University of Bonn, Walter Flex Strasse 3, Bonn 53113, Germany
E-mail: jliebe@uni-bonn.de

ABSTRACT. As multiple countries share a river, the likelihood of conflicts over distributing water resources increases, particularly under the effects of climate change. In this paper, we demonstrate how countries can cooperate in sustainable transboundary water sharing under such conditions. We examine the case of water distribution in the Volta Basin of West Africa between the upstream country, Burkina Faso, and the downstream country, Ghana. The latter faces an additional tradeoff between the production of hydropower in the south, close to the outlet of the basin, and agricultural water use

*Corresponding author. Anik Bhaduri, Center for Development Research (ZEF), University of Bonn, Walter Flex Strasse 3, Bonn 53113, Germany, e-mail: abhaduri@uni-bonn.de.
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in the reservoir's catchment area in the north. In the framework of a stochastic Stackelberg differential game, we show how sustainable water-sharing agreements can be achieved by linking transboundary flows to hydropower exports. Our results indicate that, through cooperation, Ghana will have an opportunity to increase its water abstraction for agriculture, which has remained largely restricted. We also find that the equilibrium strategies for the long-run distribution are stable even with increasing variances of water flow.

KEY WORDS: Transboundary, cooperation, climate change, Volta River Basin.

1. Introduction. The Stern report on the economics of climate change suggested that climate-induced scarcities of food and water can potentially lead to or exacerbate deadly conflicts (Stern (2007)). The likelihood of disputes and conflicts over water resources due to climate change effects is even higher in a transboundary setting. As multiple countries share a river, the competition over the available water resources will be acute under climate change, and meeting freshwater demand for agriculture and other vital uses becomes one of the impending challenges for policy makers.

In the past, water planners struggled with the problem of estimating water demand with supply uncertainties. Also, the majority of current water-sharing arrangements do not take into account the variability of river flow (Giodarno and Wolf (2003)). Climate change challenges existing water resource management practices by adding further uncertainties (IPCC (2007), Vorosmarty (2002)). This becomes a troubling issue, particularly for transboundary water-sharing agreements (Stephen and Kundell (2008)). Unless new approaches to water management are developed that take into account these new uncertainties, future conflict over water resource are likely to increase (Gleick (1992)).

Several studies have analyzed the impact of water scarcity on cooperation in water sharing, of which some take into account deterministic water flows and analyze the factors that influence stability of treaties and motivate negotiations (Ambec and Sprumont (2002), Beard and McDonald (2007), Ambec and Ehlers (2008), Janmatt and Ruijs (2007)). Other studies go beyond static measures of water availability. Dinar [2009] shows that, under increased variability of water supply, a cooperative approach in the form of risk sharing may be preferred over an individual solution (Dinar (2009)). In such circumstances, strategic alliance becomes the basis for a cooperative arrangement to address the impact of climate change on the stability of water-sharing treaties. Using empirical data, Dinar et al. [2010] demonstrate a bell-shaped relationship between water supply variations and treaty cooperation (Dinar et al. (2010)). Ansink and Ruijs [2008] also demonstrate that a decrease in mean flow of a river reduces the stability of an agreement, while an increase in variance may have both positive and negative effects on treaty stability.

The following paper captures the influence of stochastic water resource on transboundary water allocation following a dynamic noncooperative game theoretic approach. Employing a stochastic Stackelberg differential game, we show how issue linkage can facilitate cooperation between countries, even in the case of climate change. We illustrate the model with the case of water sharing of the Volta River in West Africa, between the upstream country, Burkina Faso, and the downstream country, Ghana. The "*issue linkage to water sharing*" in this case concerns the trade of hydropower electricity generated from Ghana to Burkina Faso.

The Volta River Basin is one of the major basins in West Africa, and drains an area of 407,000 km^2 into the Gulf of Guinea. It is shared by six riparian countries, Burkina Faso, Ghana, Togo, Benin, Ivory Coast, and Mali, and spans subhumid to semi-arid climate regions. The basin is characterized by steep North–South gradients, with annual precipitation ranging from greater than 2000 mm in the South to less than 500 mm in the North, while potential evaporation rates show an inverse gradient from 1500 mm in the South to 2500 mm in the North. To meet the water demand of their economies, the Volta Basin countries largely depend on freshwater availability (Van de Giesen et al. (2001)). Burkina Faso and Ghana comprise nearly 90% of the area of the Volta Basin and stand in a distinct upstream–downstream formation. The upstream country, Burkina Faso, is dependent on freshwater to meet primarily its agricultural water demand, while for the downstream country, Ghana, hydropower generation is the main water user (see Figure 1). Most of the hydropower in Ghana is generated at Akosombo Dam, which forms Lake Volta, one of the largest man-made lakes in the world. Unlike in most other river basins, the dam is located close to the outlet of the basin, such that almost the entire basin makes up the

FIGURE 1. The volta basin.

catchment area of the dam. In such a case, water usage for hydropower can be termed consumptive, as any water use in upstream of the dam can affect hydropower production. Such a feature makes this case study very unique, as it allows competition to take place between agriculture and hydropower water usage.

Currently, the water withdrawal rate to meet agricultural, domestic, and industrial water demand is much lower in Ghana (1.73%) than in

Burkina Faso (6.15%). Ghana perceives that higher water abstraction for agricultural use upstream of Akosombo Dam reduces water inflow into Lake Volta, and thereby may affect hydroelectric generation. This could be one of the reasons that led Ghana to restrict its water abstraction for other purposes in the upstream areas.

However, the Government of Ghana has projected that, due to population growth, agricultural water demand will increase several fold in the next two decades Ministry of Water, and Housing Govt. of Ghana (1998). The higher uncertainty in water availability due to climate change is likely to further increase the demand for irrigation (Bhaduri, Nicostrato, and Jens (2008)).[1]

Meeting higher demand for irrigation in response to climate change is even more challenging for policy makers, as higher water abstraction in the upper parts of the Basin may increase the scarcity value of the water reserve in Lake Volta. However, both Burkina Faso and Ghana agree that sharing the water of the Volta Basin will likely be a key issue in coming years, especially if climate change leads to significantly lower rainfall and runoff (Oli and Crawford (2008)). Both countries, in principle, have agreed to cooperate given the potential risk of conflict. The manner of cooperation is still in the planning process (Youkhan, Lautze, and Barry (2006)). Several attempts to initiate a negotiated agreement between Ghana and Burkina Faso have already been made. In one such attempt, Ghana offered Burkina Faso electricity in order to prevent the latter country from unilateral diversion of water. In this paper, we investigate if the issue of water sharing can be linked to hydropower export as the basis for attaining sustained cooperation in water distribution of the Volta River.

We first model the allocation of stochastic water resources between Ghana and Burkina Faso in a noncooperative framework, where the upstream country, Burkina Faso, chooses how much water it diverts unilaterally to maximize its own welfare. The downstream country Ghana acts as a "follower," whose water availability depends on the flow of water diverted by Burkina Faso. We next construct a stochastic differential Stackelberg leader–follower game setting, where Ghana offers a discounted price for electricity exports to Burkina Faso in exchange for more transboundary water flow. Finally, we compare both the cooperative and noncooperative outcomes in a possible climate change scenario.

There is a substantial body of literature on stochastic water resource management. Fisher and Rubio [1997] have studied the determination of optimal water storage capacity in a region, taking into account the uncertainties of inflow into the reservoirs, and found that the reservoir capacity building will become more costly with climate change (Fisher and Rubio (1997)). Other analyses are mainly concerned with the impact of stochastic surface water flows on the value of additional surface reservoir or groundwater stocks (Tsur and Graham-Tomasi (1991), Knapp and Olson (1995)). Only a few studies exist on the influence of stochastic water resource management on transboundary water sharing. The unique contribution of this paper is to investigate uncertainty in water resource management in a transboundary water-sharing problem, and to evaluate the scope and sustainability for a potential cooperative agreement between countries.

Following Fisher and Rubio [1997], we assume that water resources evolve through time and follow a geometric Brownian motion. However, the characteristics of Brownian motion in terms of variance are different in both countries, based on the assumption that the effects of climate change are regionally different. The steady state conditions of the corresponding stochastic problem are then derived with respect to the water abstraction rates. We evaluate how these steady state conditions are modified by changes in the variance of the water resource. In this fashion, we are able to determine how the water abstraction of the riparian countries will change in the long run, taking into account the greater variability of water availability caused by climate change.

Such a framework, although relying on a specific case of water sharing in the Volta River Basin, is potentially relevant to many other river basins where international cooperation on river basin management may play a role, particularly under climate change. Our results indicate that during cooperation, Ghana will have an opportunity to increase its water abstraction for agriculture, which has remained largely restricted. We also find that the equilibrium strategies in the long-run steady state are stable even with increasing variance in water flow.

In the following section, we first outline the model of water sharing between Burkina Faso and Ghana in the case of noncooperation over water sharing. Next, we formulate a differential game of cooperation and evaluate the outcome with respect to climate change; and finally the conclusion section summarizes the main findings and results of the paper.

2. Water sharing between Burkina Faso and Ghana. For many years, the Volta Basin had been one of the few transboundary water basins in Africa that had no formal agreement in place for cross-border cooperation and management (Oli and Crawford (2008)). The following describes water allocation between Ghana and Burkina Faso in such a case, without any cooperation in water sharing. We explore how uncertainty in water supply affects the water abstraction rates of the countries, and explore the underlying conditions that may influence decisions on water allocations.

Burkina Faso has the upper riparian right to unilaterally divert water, while Ghana's freshwater availability partially depends on the water usage in the upstream country. We denote the countries by superscripts, where B denotes Burkina Faso and G stands for Ghana. W^B is the annual total renewable water resource available in Burkina Faso. In the model, we assume that water flow is stochastic and uncertainty in the flow of water can be attributed to climate change. The total renewable fresh water resources in the upstream country, W^B, evolve through time according to a geometric Brownian motion:[2]

$$dW^B = \sigma^B W^B dz_t^B, \tag{1}$$

where z_t^B is a standard Wiener process and $\sigma^B W^B$ is the variance rate in the water flow in Burkina Faso.[3] Here, σ^B can be considered as a volatility of water flow in Burkina Faso.

Let the total per capita freshwater utilization in each country i ($i = B$, G) be denoted by w^i. Considering the rate of water utilization of country i as α^i, the total per capita freshwater utilization in the upstream country, Burkina Faso, can be exhibited in mathematical form as

$$w^B = \alpha^B W^B. \tag{2}$$

The water availability in Ghana depends on water consumption in the upstream, W^B, and runoff, R.[5] The runoff of Ghana, denoted by R, is also stochastic in the model and follows Geometric Brownian motion,

$$dR = \sigma^R R dz_t^R, \tag{3}$$

where z_t^R is a standard Wiener process. In the following, we suppress the dependency on t and write the Wiener processes as z^B and z^R. The water availability in Ghana can be represented as

$$W^G = (1 - \alpha^B) W^B + R. \tag{4}$$

The water withdrawal in Ghana, w^G, can be expressed as

$$w^G = \alpha^G \left[\left(1 - \alpha^B \right) W^B + R \right]. \tag{5}$$

The stock of water in Lake Volta, where hydropower is produced, is denoted by S, and is a function of the stochastic water resources and the control variables (α^G, α^B).

The state equation can be represented as

$$dS = (1 - \alpha^G) \big[(1 - \alpha^B) W^B + R \big] dt - O dt, \tag{6}$$

where $S(0) = S_0$ is an initial condition.

Here, O denotes the outflow and evaporation of water from Lake Volta. We also assume that water reserves exceed a minimum (critical) level, $\bar{S}$. If the water reserves are above the critical level, there is no scarcity of water in Lake Volta. However, if the constraint is binding, then the scarcity value of water will be positive.[6] Consider the benefit of water consumption of countries as $V^i(w^i)$ for $i = B, G$, where w^i is the water utilization in agriculture. The benefit function is assumed to be strictly concave for all possible values of w^i. The cost function of withdrawing water from the river and distribution is $C^i(\alpha^i) = C(w^i / W^i)$, which is assumed to be increasing and convex for all values of α^i, $i = B, G$. We consider that as water becomes increasingly scarce in the economy, the government would exploit water through appropriating and purchasing a greater share of aggregate economic output, in terms of dams, pumping stations, supply infrastructure, etc. (Barbier

(2000)). Given the high cost of building infrastructure and expanding supplies, this will lead to a higher marginal cost of water.

Apart from agricultural water use, Ghana receives benefits from storing water at Lake Volta. We denote $H^G(S)$ as the net consumer surplus or economic benefit from hydropower generation. Based on the above considerations, the net benefit of both countries can be written as

$$NB^B = V^B(w^B) - C^B(\alpha^B) \text{ for Burkina Faso}$$

and

$$NB^G = V^G(w^G) + H^G(S) - C^G(\alpha^G) \text{ for Ghana.}$$

The above state, flow, and control variables can be redefined as follows. Let $(\Omega, \mathcal{F}, \mathcal{F}_t, P)$ be a complete filtered probability space, and z^B, z^R are independent standard Wiener processes with trace class covariances. The state of the game at each instant $t \in [0, \infty)$ is described by $S(\,\cdot\,) \in \Omega \times X \times [0,\ T]$, where $X \subset \mathbb{R}^+$ is called the state space, and $0 < T < \infty$. Let $U(S(t))$ be the control set where all the feasible values of α^B and α^G lie at time t, and for a fixed $\omega \in \Omega$, i.e., α^B, α^G: $\Omega \times X \times [0,\ T] \mapsto U \subset [0,\ 1]$. One can similarly define the flow variables W^B and R on $\Omega \times Y \times [0,\ T]$, where Y is the union of the sets that describe the realization of the water resources and runoff in Burkina Faso and Ghana, respectively. The payoff functions $J^i \in \mathbb{R}^+, i = B, G$, are nonrandom and are assumed to be continuously differentiable in all the variables.

2.1. Burkina Faso's problem. In the absence of any agreement, Burkina Faso chooses the economically potential rate of water utilization that maximizes its own net benefit . Burkina Faso's maximization problem is as follows:

$$J^B = E\left[\max_{\alpha^B} \int_t^{\infty} e^{-r\tau} NB^B \, d\tau\right], \tag{7}$$

subject to the equation

$$dW^B = \sigma^B W^B dz^B.$$

The Hamilton-Jacobi-Bellman (HJB) equation for this problem can be written as

$$rJ^B = \max_{\alpha^B} \left\{ NB^B + \frac{1}{dt} E\left[dJ^B \right] \right\}. \tag{8}$$

Note that, since W^B is a stochastic process, Itô's formula on J^B yields

$$dJ^B = J^B_{W^B} dW^B + \frac{1}{2} J^B_{W^B W^B} (dW^B)^2,$$

which, with the help of equation (1), reduces to

$$dJ^B = \sigma^B W^B J^B_{W^B} dz^B + \frac{1}{2} (\sigma^B)^2 (W^B)^2 J^B_{W^B W^B} dt.$$

Now applying the differential operator $(1/dt)E$ on the above expression and considering the mean of the Wiener processes, $E[dz^B] = 0$, the HJB equation (8) can be written as

$$rJ^B = \max_{\alpha^B} \left\{ B^B(w^B) - C^B(\alpha^B) + \frac{1}{2} (\sigma^B)^2 (W^B)^2 J^B_{W^B W^B} \right\}. \tag{9}$$

Differentiating with respect to α^B, we obtain the first-order optimality condition,

$$V^B_{\alpha^B} = C^B_{\alpha^B} \text{ or } W^B V^B_{w^B} = C^B_{\alpha^B}. \tag{10}$$

The solution of the above equation will lead to the optimal α^B, denoted by $\alpha^{B^*} = \alpha^{B^*}(W^B)$. The solution is determined at a point where the marginal benefit of water withdrawal is equal to its marginal cost. It indicates that the optimal water abstraction rate α^B is subject to uncertainty in the water flow. We evaluate the conditions under which Burkina Faso will change its water abstraction rate with an increase in water supply variance. Our results, provided in Appendix A, suggest that if the upstream country, Burkina Faso, has a convex marginal benefit function of water, then it will increase its water abstraction with rising variance of water supply. However, the rate of increase in water abstraction will be lower if the country has a concave marginal benefit function.

2.2. Ghana's problem. As a downstream country, Ghana's water consumption depends on the inflow from Burkina Faso and the runoff generated within the country's share of the Volta Basin. Based on the given availability of water, Ghana maximizes its net benefit:

$$J^G = E\left[\max_{\alpha^G} \int_t^{\infty} e^{-r\tau} NB^G d\tau\right], \tag{11}$$

subject to the water constraint (5), state equation (6), and the stochastic equations (1) and (3). We also consider the constraint that water reserves,S should exceed the minimum level,$barS$ at Lake Volta to produce hydropower.

The corresponding HJB equation is as follows:

$$rJ^G = \max_{\alpha^G} \left\{ NB^G + \frac{1}{dt} E\big[dJ^G\big] + \lambda(S - \bar{S}) \right\}, \tag{12}$$

where the parameter λ represents the scarcity value of water.

From Appendix B, we know that that above HJB equation can be written as

$$\begin{aligned} rJ^G = \max_{\alpha^G} \Big\{ & B^G\left(w^G\right) + H^G\left(S\right) - C^G\left(\alpha^G\right) \\ & + \left[\left(1-\alpha^G\right)\left[\left(1-\alpha^B\right)\bar{W}^B + \bar{R}\right] - O\right] J^G_S \\ & + \frac{(\sigma^B)^2}{2} E\left[(W^B)^2\right] J^G{}_{W^B W^B} + \frac{(\sigma^R)^2}{2} E\left[R^2\right] J^G{}_{RR} + \lambda\left(S - \bar{S}\right)\Big\}. \end{aligned} \tag{13}$$

Differentiating with respect to α^G we obtain the optimality condition,

$$B^G{}_{\alpha^G} - C^G{}_{\alpha^G} = [(1-\alpha^B)\bar{W}^B + \bar{R}] J^G_S.$$

Thus,

$$J^G_S = \frac{1}{K}\left[B^G{}_{\alpha^G} - C^G{}_{\alpha^G}\right], \tag{14}$$

where

$$K = \left(1 - \alpha^B\right) \bar{W}^B + \bar{R}.$$

The above first-order condition says that at the margin, water is equally valuable for agricultural consumption and for water reserve accumulation in Lake Volta for hydropower generation. The right-hand side of the equation (14) represents the marginal benefit of water consumption, while the left-hand side, J_S^G, denotes the marginal value of water for storage. It indicates that the price used to value increments of water reserves in Lake Volta is equal to the net marginal benefit of water consumption. Now, for notational simplicity, we denote $J_S^G = A^G(\alpha^G, \alpha^B)$. Differentiating equation (13) with respect to the state variable S for the optimal values of the control variables α^G and α^B, one finds

$$rJ_S^G = H_S^G + \frac{1}{dt}E\left[dJ_S^G\right] + \lambda. \tag{15}$$

Substituting J_S^G as $A^G(\alpha^G, \alpha^B)$ and after rearranging, we obtain,

$$rA^G - H_S^G - \lambda = \frac{1}{dt}E\left[dA^G\right]. \tag{16}$$

From Appendix C, we obtain

$$\begin{aligned} rA^G - H_S^G - \lambda = {} & A^G{}_{\alpha^G} \frac{1}{dt}E\left[d\alpha^G\right] \\ & + \frac{1}{2}A^G{}_{\alpha^G\alpha^G}\left[(\sigma^B)^2(W^B)^2\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + (\sigma^R)^2R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]. \end{aligned}$$

As in the long-run steady state distribution, the following conditions, $\frac{1}{dt}E\left[dS\right] = \frac{1}{dt}E\left[d\alpha^G\right] = 0$, must be satisfied, we have

$$\begin{aligned} \lambda = {} & rA^G - H_S^G - \frac{1}{2}A^G{}_{\alpha^G\alpha^G} \\ & \times \left[(\sigma^B)^2(W^B)^2\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + (\sigma^R)^2R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]. \end{aligned} \tag{17}$$

The above equation (17) establishes another optimality condition. It indicates that the shadow price of the constraint, or the scarcity value of water in Lake Volta, λ, is equal to the difference between the marginal benefit of water consumption $[rA^G]$ and its opportunity cost. The latter includes the benefits forgone for hydropower generation from higher water abstraction in the upstream $[H_S^G]$ and also incorporates a term related to the instantaneous variance rate, $\left[\frac{1}{2}A^G{}_{\alpha^G\alpha^G}\left[(\sigma^B)^2(W^B)^2\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + (\sigma^R)^2R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]\right]$. The sign of the latter term depends on the convexity of the net marginal benefit from water consumption.

The key issue that emerges here is how Ghana will act in the case of extreme climate change events. Such behavior will depend on how Ghana's optimal water abstraction rate α^G is affected by climate change. Two possible outcomes may occur. First, as a result of an extreme event (such as a drought) in both countries, Ghana may decrease its own water abstraction in areas upstream of Lake Volta to keep the stock of water above the critical level, so that hydropower generation is not affected. But this will certainly affect the benefit, V^G, from the water abstraction for agriculture and other uses in upstream Ghana. Second, as an alternative response to the extreme event (e.g., drought), Ghana may increase its water abstraction to maximize its benefit V^G from upstream water used for agriculture. Under such circumstances, only a fraction of Ghana's demand for energy will be generated from hydropower, and the rest must be generated with gas turbines or be bought from other countries.

From (17), it is evident that the nature of the marginal benefit function plays an important role in evaluating the sign of $\frac{d\alpha^G}{d\sigma^{B^2}}$ and $\frac{d\alpha^G}{d\sigma^{R^2}}$; and thus determining which action Ghana will take in response to the uncertainty in water flow caused by climate change. From results in Appendix D, we found that if the marginal benefit function is concave $[A^G > 0, A^G{}_{\alpha^G} < 0, A^G{}_{\alpha^G\alpha^G} > 0]$, then $\frac{d\alpha^G}{d(\sigma^B)^2} < 0$ and $\frac{d\alpha^G}{d(\sigma^R)^2} < 0$ for low extreme events where $\frac{dS}{d(\sigma^B)^2} < 0$.

The above results suggests that if the marginal benefit of water consumption is convex, then the effect of increasing water consumption on the country's welfare is limited, and Ghana will decrease its upstream water abstraction to ensure sufficient water flows to Lake Volta during a drought or other extreme climate event. If the marginal benefit of water consumption is concave, then the opposite outcome occurs. In this case, Ghana's welfare will increase from higher water consumption, and this may lead Ghana to increase its water abstraction for agriculture.

It is also pertinent to understand how Ghana may respond to Burkina Faso's action of higher water abstraction under uncertainty. We evaluate the reaction function of Ghana and also to understand the effect of α^G with changes in α^B. We found (see Appendix E) that Ghana will decrease its water abstraction with increase in the water diversion by Burkina Faso. Moreover, with an increase in uncertainty (i.e., with increases in variances), the value of $\frac{d\alpha^G}{d\alpha^B}$ will become increasingly negative.

3. Water and hydropower sharing between Burkina Faso and Ghana. In this section, we model the water allocation between Ghana and Burkina Faso in a cooperative setting, where Ghana offers a discounted price for hydropower exports to the upstream country, Burkina Faso, in exchange for greater transboundary water flow. We utilize a differential Stackelberg leader–follower game to determine the optimal share of water between Ghana and Burkina Faso. The conditions for stability in water sharing are explored with respect to increasing variance in water flow due to climate change.

In the model, Burkina Faso represents the leader and moves first, *a priori* knowing that the follower country, Ghana, observes its actions and moves accordingly. We employ the standard backward-induction approach to solving the Stackelberg leader–follower game. First, we find the solution to the follower's problem of maximizing a payoff function. Then, using the follower's reaction function, the leader's objective function is maximized.[7] We assume that the respective countries use Markovian perfect strategies. These strategies are decision rules that dictate optimal action of the respective players, conditional on the current values of the water stock $S(t)$, that summarize the latest available information of the dynamic system. The Markovian perfect strategies determine a subgame perfect equilibrium for every possible value of $S(t)$, and the strategy defines an equilibrium set of decisions dependent on previous actions.

We denote Burkina Faso's benefit or net consumer surplus from electricity imported from Ghana as $H^B(S, \alpha^B)$. The benefit is a function of the water stock in Lake Volta, S, as higher stock will reduce the price of power at which Ghana is exporting to Burkina Faso. This allows Burkina Faso to gain from higher S. However, the benefit, H^B, also depends on Burkina Faso's action of restricting water abstraction. If Burkina Faso increases its water abstraction, then Ghana will increase the price of electricity exports, and it will reduce the net consumer surplus of Burkina Faso. The economic benefit that Burkia Faso obtains from power, $H^B(S, \alpha^B)$, is thus a function of both the stock of water and its own rate of water abstraction. Hence, $\frac{\partial H^B}{\partial S} > 0$ and $\frac{\partial H^B}{\partial \alpha^B} < 0$.[8] The size of H^B, the total consumer surplus derived by Burkina Faso from the hydropower it receives from Ghana, can also be represented as a measure of the degree of cooperation between the countries. If H^B is large, then Burkina Faso will take into account more of the benefits gained from cooperating with Ghana. If H^B tends to zero, then the result is the original noncooperative situation as modeled in Section 2.

As part of the agreement, Burkina Faso cooperates with Ghana to increase the level of water in Lake Volta by reducing or restricting its water abstraction. Suppose Burkina Faso, the leader, announces to the follower, Ghana, a policy rule that it will use throughout the game. Let this policy rule be denoted by $\alpha^B(t) = \phi^B(S(t))$. Ghana, taking this policy rule as given, seeks to maximize its payoff. In principle, this yields the follower's reaction function of the form $\alpha^G(t) = \phi^G(S(t), \phi^B(\,\cdot\,))$. The leader (Burkina Faso) knowing this reaction function, then chooses the possible rules $\phi^B(\,\cdot\,)$ that maximizes its objective function. However, since $\phi^B(\,\cdot\,)$ can be any function, it is not clear how such an optimal rule can be obtained in practice Engelbert et al. (2000). One of the ways to solve this problem is to restrict the space of functions from which Burkina Faso can choose its strategy $\phi^B(\,\cdot\,)$. We consider $\phi^B(\,\cdot\,)$ as a quadratic function of the state variable, with the stock of water as a possible restriction. We denote the policy rule as

$$\alpha^B = \phi^B(\cdot) = aS^2 + b, \tag{18}$$

where a and b are control parameters and independent of time.[9]

3.1. Ghana's problem. Given a response function of Burkina Faso as in (18), Ghana will maximize its net benefit as follows:

$$J^G = E\left[\max_{\alpha^G} \int_t^{\infty} e^{-r\tau} NB^G d\tau\right], \tag{19}$$

where the net benefit function is given by[10]

$$NB^G = V^G\left(w^G\right) + H^G\left(S\right) - C^G\left(\alpha^G\right),$$

and subject to the state equation (6) and other constraints given in equations (1), (3), (5), and (18). Here, we also assume that water reserves (S) exceed the critical level ($\bar{S}$), i.e., $S \geq \bar{S}$.

We can write the HJB equation corresponding to the above problem as:

$$rJ^G = \max_{\alpha^G}\left\{NB^G + \frac{1}{dt}E\left[dJ^G\right] + \lambda(S - \bar{S})\right\}, \tag{20}$$

where the parameter λ represents the scarcity value of water in Lake Volta.

Since $J^G = J^G(S,\ W^B,\ R)$, applying Itô's formula on J^G using the equations (2), (3), and (6), one can obtain an equation similar to (13),

$$\begin{aligned} rJ^G = \max_{\alpha^G}\Bigg\{ & V^G(w^G) + H^G(S) - C^G(\alpha^G) \\ & + \left[(1-\alpha^G)[(1 - aS^2 - b)\bar{W}^B + \bar{R}] - O\right] J^G_S \\ & + \frac{{\sigma^B}^2}{2} E\left[{W^B}^2\right] J^G_{W^B W^B} + \frac{{\sigma^R}^2}{2} E[R^2] J^G_{RR} + \lambda(S - \bar{S})\Bigg\}. \end{aligned} \tag{21}$$

Let us denote

$$K(a, b, S) = (1 - aS^2 - b)\bar{W}^B + \bar{R}.$$

Then differentiating the equation (21) with respect to α^G, we can obtain the optimality condition,

$$V^G{}_{\alpha^G} - C^G{}_{\alpha^G} = K(a, b, S) J^G_S. \tag{22}$$

We denote

$$J^G_S = A^G(\alpha^G, a, b, S) = \frac{B^G{}_{\alpha^G} - C^G{}_{\alpha^G}}{K(a, b, S)}.$$

Now differentiating equation (21) with respect to the state variable S for the optimal values of the control variable α^G, we obtain

$$rA^G = H^G_S + \frac{1}{dt} E\big[dA^G(\alpha^G, a, b, S)\big] + \lambda.$$

After setting the long-run steady state distribution conditions (i.e., $\frac{1}{dt}E\big[dS\big] = \frac{1}{dt}E\big[d\alpha^G\big] = 0$) as in the previous section of Ghana's problem, we obtain the following expression:

$$\begin{aligned} \lambda = rA^G - H^G_S - \frac{1}{2} A^G(\alpha^G, a, b, S)_{\alpha^G \alpha^G} \\ \times \left[\sigma^{B\,2} W^{B\,2} \left(\frac{\partial \alpha^G}{\partial W^B} \right)^2 + \sigma^{R\,2} R^2 \left(\frac{\partial \alpha^G}{\partial R} \right)^2 \right]. \end{aligned} \tag{23}$$

The above equation leads us to derive the optimal Markov strategy for Ghana and to evaluate its optimal response to the changes in Burkina Faso's water abstraction rate. In order to find the optimal response function, we need to understand the effect of α^G with changes in a and b.

Proposition 1. *During cooperation, Ghana will have an opportunity to increase water abstraction for agriculture. If Burkina Faso increases its water abstraction during this period, then Ghana will reduce its water abstraction initially due to the higher level of cooperation. However, after a certain point, the change in Ghana's marginal benefit of water consumption in agriculture is greater than* *the change in its marginal benefit of water stock in Lake Volta. In such a situation, Ghana will increase its water abstraction to prevent Burkina Faso to gain from further increasing water diversion under the agreement.*

Proof. We totally differentiate equation (23) with respect to S, α^G, a, b, rearrange the terms and assume in the long-run steady state equilibrium $d\lambda = 0$, so we obtain

$$\frac{d\alpha^G}{da} = \frac{1}{rA^G{}_{\alpha^G}} \left[-rA^G{}_S + H^G_{SS} + A^G{}_{\alpha^G \alpha^G} \left[(\sigma^B)^2 (W^B)^2 \frac{\partial \alpha^G}{\partial W^B} \frac{\partial^2 \alpha^G}{\partial S \partial W^B} + {\sigma^R}^2 R^2 \frac{\partial \alpha^G}{\partial R} \frac{\partial^2 \alpha^G}{\partial S \partial R} \right] \right] \frac{dS}{da} - \frac{A^G{}_b}{A^G{}_{\alpha^G}} \frac{db}{da} - \frac{A^G{}_a}{A^G{}_{\alpha^G}}. \tag{24}$$

We assume that the parameters a and b are mutually independent so that $\frac{db}{da}$ is zero. As before, we also assume that the marginal benefit function A^G is convex with respect to α^G, $\frac{\partial^2 \alpha^G}{\partial S \partial W^B} < 0$ and $\frac{\partial^2 \alpha^G}{\partial S \partial R} < 0$. We find that for $a > 0$, the sign of $\frac{dS}{da} < 0$ and $A^G{}_a > 0$.

Then the following results hold:

if

$$rA^G{}_a < \left[-rA^G{}_S + H^G_{SS} + A^G{}_{\alpha^G \alpha^G} \left[{\sigma^B}^2 {W^B}^2 \frac{\partial \alpha^G}{\partial W^B} \frac{\partial^2 \alpha^G}{\partial S \partial W^B} + {\sigma^R}^2 R^2 \frac{\partial \alpha^G}{\partial R} \frac{\partial^2 \alpha^G}{\partial S \partial R} \right] \right] \frac{dS}{da}, \tag{25}$$

then

$$\frac{d\alpha^G}{da} < 0.$$

If a decrease in Burkina Faso's water abstraction rate reduces the marginal benefit of water consumption in agriculture for Ghana less than that of hydropower production (from increase in the water stock in Lake Volta), then Ghana will increase its water abstraction. However, if the inequality sign of the condition (25) is reversed, then the change in marginal benefit of water consumption in agriculture will be more

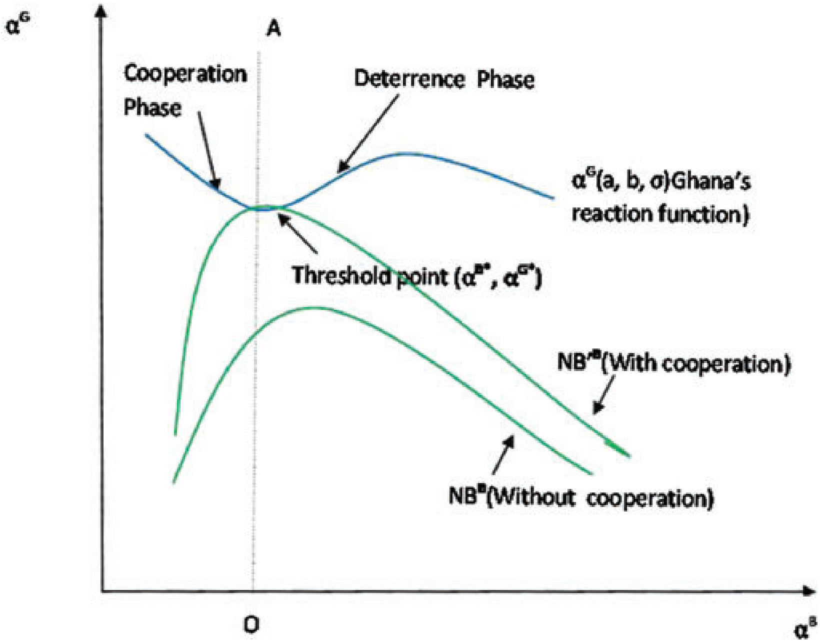

FIGURE 2. Response function of Ghana and Burkina Faso's net benefit function.

than the change in marginal benefit of water stock at Lake Volta, and we obtain

$$\frac{d\alpha^G}{da} > 0.$$

It implies that in such a situation, Ghana will increase its water abstraction as Burkina Faso diverts more water. If we differentiate both sides of (24) with respect to a, we observe that $\frac{d^2\alpha^G}{da^2} > 0$ for low values of a and $\frac{d^2\alpha^G}{da^2} < 0$ for high values of a.[11] The relationship between α^G and a is convex for low values of a and concave for high values of a. The above result is illustrated in Figure 2 . It implies that for a high level of cooperation, Ghana will have an opportunity to increase water abstraction. However, if Burkina Faso increases its water abstraction during this period, Ghana will reduce its water abstraction initially, due to higher level of cooperation, to ensure that a sufficient amount of water flows to Lake Volta. However, at some threshold point, the change in Ghana's marginal benefit of water consumption in agriculture is greater than the change in marginal benefit of water stock at Lake Volta. In such a situation, Ghana will increase its water abstraction to deter Burkina Faso from increasing its water diversion. Otherwise, if Ghana decreases its water abstraction in such a case, then Burkina Faso can increase its water diversion and still enjoy the benefits of hydropower from a higher stock of water. This phase can be labeled as a deterrence phase, and it will continue until the marginal benefits of Ghana from increasing its water abstraction with higher water diversion by Burkina Faso is equal to its opportunity cost. After the deterrence phase, Ghana will reduce its water abstraction again to allow water to flow to Lake Volta.

We get similar results for the relationship between α^G and b. A similar condition (replacing the derivatives with respect to a by b in inequality (25)) is also required to show that $\frac{d\alpha^G}{db}$ is negative and positive for low and high values of b, respectively.

3.2. Burkina Faso's problem. Assuming that the downstream country Ghana plays the above Markovian strategy, $\phi^G(S(t), a(t), b(t))$, the upstream country, Burkina Faso, chooses the optimal water abstraction rate under cooperation by solving the following maximization problem:

$$J^B = E\left[\max_{a,b} \int_t^{\infty} e^{-r\tau} NB^B \, d\tau\right], \tag{26}$$

where the net benefit function of Burkina Faso is given by

$$NB^B = V^B(w^B) + H^B(S, \alpha^B) - C^B(\alpha^B),$$

and subject to the state equation (6), and given other equations (1), (3), (5), (6), and (18). Here, α^G is obtained from the optimality condition (22). The HJB equation for the above formulated problem can be written as:

$$
\begin{aligned}
rJ^B &= \max_{a,b}\Big\{V^B\left(w^B\right) + H^B\left(S,\alpha^B\right) - C^B\left(\alpha^B\right) \\
&\quad + \left[\left(1-\alpha^G\right)\left[\left(1-aS^2-b\right)\bar{W}^B + \bar{R}\right] - O\right] J^B_S \\
&\quad + \frac{{\sigma^B}^2}{2} E\left[{W^B}^2\right] {J^B}_{W^B W^B} + \frac{{\sigma^R}^2}{2} E\left[R^2\right] {J^B}_{RR}\Big\}.
\end{aligned} \tag{27}
$$

As before, we denote

$$K(a,b,S) = \left(1-aS^2-b\right)\bar{W}^B + \bar{R}.$$

Then differentiating the equation (22) with respect to a and b, we obtain the optimality conditions,

$$V^B_a - {C^B}_a + {H^B}_a - K(a,b,S)\frac{\partial \alpha^G}{\partial a} J^B_S - (1-\alpha^G)S^2\bar{W}^B J^B_S = 0, \tag{28}$$

$${V^B}_b - {C^B}_b + {H^B}_b - K(a,b,S)\frac{\partial \alpha^G}{\partial b} J^B_S - (1-\alpha^G)\bar{W}^B J^B_S = 0. \tag{29}$$

From the above two equations, one obtains

$$
\begin{aligned}
J^B_S &= \frac{{V^B}_b - {C^B}_b + {H^B}_b}{K\dfrac{\partial \alpha^G}{\partial b} + (1-\alpha^G)\bar{W}^B} = \frac{{V^B}_a - {C^B}_a + {H^B}_a}{K\dfrac{\partial \alpha^G}{\partial a} + (1-\alpha^G)S^2\bar{W}^B},: \\
&= A^B(\alpha^G, a, b, S).
\end{aligned} \tag{30}
$$

The above equation indicates that, during cooperation, the value of a marginal increase in the water stock in Lake Volta for Burkina Faso is equal to its opportunity cost in terms of upstream agricultural benefits forgone.

Now differentiating equation (27) with respect to the state variable S for the optimal values of the control variables α^G, a, and b,

$$rA^B = H_S^B + \frac{1}{dt}E\left[dA^B\right].$$

Finally, after assuming in the long-run steady state conditions (i.e., $\frac{1}{dt}E\left[dS\right] = \frac{1}{dt}E\left[da\right] = \frac{1}{dt}E\left[db\right] = 0$), we obtain the following expression:

$$\begin{aligned} rA^B = H_S^B &+ \frac{1}{2}A^B{}_{aa}\left[\sigma^{B^2}W^{B^2}\left(\frac{\partial a}{\partial W^B}\right)^2 + \sigma^{R^2}R^2\left(\frac{\partial a}{\partial R}\right)^2\right] \\ &+ \frac{1}{2}A^B{}_{bb}\left[\sigma^{B^2}W^{B^2}\left(\frac{\partial b}{\partial W^B}\right)^2 + \sigma^{R^2}R^2\left(\frac{\partial b}{\partial R}\right)^2\right]. \end{aligned} \tag{31}$$

The above equation says that in the long-run steady state, the marginal cost of reducing water abstraction in terms of agricultural benefits forgone is equal to the sum of the marginal benefits that Burkina Faso may gain in hydropower from higher level of stock due to cooperation and a term related to the instantaneous variance rate, $\left[\frac{1}{2}A^B{}_{aa}\left[\sigma^{B^2}W^{B^2}\left(\frac{\partial a}{\partial W^B}\right)^2 + \sigma^{R^2}R^2\left(\frac{\partial a}{\partial R}\right)^2\right] + \frac{1}{2}A^B{}_{bb}\left[\sigma^{B^2}W^{B^2}\left(\frac{\partial b}{\partial W^B}\right)^2 + \sigma^{R^2}R^2\left(\frac{\partial b}{\partial R}\right)^2\right]\right]$. The sign of the latter term depends on the convexity of net marginal benefit from cooperation.

Note that the optimal a^* and b^* can be achieved from the optimality conditions (28) and (29). We now characterize the stability of above solution given the optimal strategy of Ghana. We judge the stability of the solution with respect to higher variance in water flow caused by climate change.

As the optimal α^{B^*} depends on optimal values of a^* and b^*, then for $\alpha^{B^*} = \alpha^B(a^*,\, b^*)$, we get

$$\frac{d\alpha^B}{d\sigma^{B^2}} = \frac{d\alpha^B}{da}\frac{da}{d\sigma^{B^2}} + \frac{d\alpha^B}{db}\frac{db}{d\sigma^{B^2}} = S^2\frac{da}{d\sigma^{B^2}} + \frac{db}{d\sigma^{B^2}}.$$

Using the above equation and combining them with the results from Appendix F, we can now deduce the effect of optimal water abstraction of Burkina Faso α^B with changes in variances σ^B and σ^R. During drought (i.e., when $\frac{dS}{dk} < 0, k = {\sigma^B}^2, {\sigma^R}^2$), $\frac{d\alpha^B}{dk} > 0$ for $\frac{d\alpha^G}{di} << 0, (i = a, b)$ (i.e., for low values of a^* and b^*). But $\frac{d\alpha^B}{dk} < 0$ for $\frac{d\alpha^G}{di} > 0, (i = a, b)$ (i.e., for high values of a^* and b^*). It suggests that if the marginal benefit function of water withdrawal for Burkina Faso is convex, the optimal water abstraction rate for Burkina Faso will decrease (increase) with the increase in variances at higher (lower level) of water abstraction, respectively. This result holds true for extreme climate events such as droughts.

Given the Markovian strategy of Ghana and optimal level of water abstraction, we can deduce the optimal level of water abstraction in Ghana. We determine the effect of changes in water supply on optimal water abstraction of Ghana, α^G. As shown in Appendix G, an optimal value for the water abstraction rate of Ghana exists, which will decrease in extreme climate events (droughts). However, the rate of decline will be smaller with a lower water abstraction rate by Burkina Faso.

These results guarantee stability of the cooperative outcome even under increasing variance of water flow, as the countries will find that any deviation from cooperation costly even under climate change. However, this result also depends heavily on the existence of an appropriate institutional arrangement, which can facilitate such energy–water issue linkage and sustain cooperation among the two countries in the long run.[12]

4. Summary and conclusion. This paper explores whether countries can cooperate in a sustainable way to share water, taking into account the uncertainty posed by climate change. Climate change increases the variability in water flow and might exacerbate conflicts among countries sharing transboundary water resources. We illustrate the problem with the case of water sharing of the Volta River between the upstream country, Burkina Faso, and the downstream country, Ghana, where Ghana faces a tradeoff of water use between agriculture in the north and production of hydropower at the outlet of the Basin in the south. In the past, increasing demand for water coupled with higher uncertainty in the water flow has been a potential source of water conflict between Ghana and Burkina Faso. In 1998, a conflict arose between the two countries when low water levels in the dam resulted in the reduction of the hydropower generating capacity by half and caused major energy crisis in Ghana. Ghana accused Burkina Faso of constructing dams upstream as reservoirs for irrigation water; and thus, the latter country's higher water consumption was suspected of being the main cause of reduced water levels at the Akosombo Dam (Madiodio (2005)).

However, both the countries have tried to form an institutional arrangement that can prevent such conflict. In one such instance, Ghana offered electricity to Burkina Faso to prevent the latter country from unilaterally diverting water. Using a stochastic Stackelberg differential game, we have examined whether such a cooperative arrangement is feasible by determining optimal water allocation of the countries and comparing the outcome to the results of a noncooperative game. We find that cooperation will give Ghana an opportunity to increase water abstraction for agriculture without losing water at Lake Volta. If Burkina Faso increases its water diversion, then Ghana will reduce its water abstraction initially due to a higher level of cooperation. However, after a certain point, Ghana will increase its water abstraction to prevent Burkina Faso to gain from increasing water diversion under the agreement. We also find that the equilibrium distribution strategies in the long run are stable even with increasing variances of water flow. The summary and comparison of the results are presented in form of a Table in Appendix H.

ENDNOTES

1. A regional analysis on the impact of climate change on the Volta Basin, conducted by Kunstmann and Jung [2005], shows a high variability of river runoff due to changes in climate variables. The study predicts that annual mean temperature could increase by 1.2 − 1.3 Celsius during the next 30 years in the Volta Basin. A change in precipitation is expected with a mean increase of 5 and a strong decrease in rainfall in April, which is connected to a delay in the onset of the rainy season. Increased duration of the dry season and delay of the rainy season could influence the demand for irrigated water (Kunstmann and Jung (2005)).

2. W^B is a log-normally distributed random variable and is always positive. The mean $E[W^B] = \bar{W}^B$ is equal to its initial value, say, W_0^B, and the variance is ${W_0^B}^2(e^{{\sigma^B}^2 t} - 1)$, which increases rapidly with increase in σ^B. Moreover, equation (A4) has a unique analytical solution, $W^B(t) = W_0^B \exp\left(-({\sigma^B}^2 t)/2 + \sigma^B z_t^B\right)$.

3. From a hydrological perspective, the contribution of drift component in the total change of water flow is negligible. Hence, we have excluded the deterministic drift component. For further reference, see Fisher and Rubio [1997].

4. In the Volta River Basin, irrigated water is used mainly during the dry seasons. As we are not considering supplemental irrigation, higher rainfall may not reduce the demand of irrigated water during the dry season.

5. The runoff R can be defined as $R = P - ET \pm \triangle S$, where P is the precipitation, ET is evapotranspiration in the nonirrigated areas, and S is the storage of water in groundwater aquifer and soil moisture.

6. O has two components, O_1 and O_2. Let O_1 denote the outflow of water which is a control parameter of S, since outflow from the lake depends on the water stock in the lake, and it is controlled in such a way that the stock of water stays above the critical level . Let O_2 be the amount of evaporated water from Lake Volta, which depends on the surface area of the lake and on the climate. There might be an extreme situation (e.g., drought over a period of years) where the inflow of water to the lake is almost zero, and O_2 is a fairly large quantity over a period of time. Then, even if O_1 is minimized, $\frac{dS}{dt}$ can be negative. In other words, during extreme situation S can fall below $\bar{S}$. For the sake of simplicity in our model we have assumed that O is a given limiting parameter.

7. In a standard Stackelberg game, the follower maximizes its objective function given an arbitrary level of leader's choice variable. However, in a differential Stackelberg game the follower's objective function is maximized given a policy rule of the leader, where the control variable of the leader is a function of the state variable.

8. Since we are looking at the Markovian Stackelberg strategies, leader's current strategy is dependent on its own past strategies and also that of rival. So, the benefit from hydropower import H^B for Burkina Faso is dependent not only on stock S but also on its own action α^B.

9. The policy rule also reflects Burkina Faso's preferences in substituting α^B for S at the margin in terms of the consumer surplus generated by hydropower (which is a true measure of a welfare change in hydropower if income effects are negligible). Due to nonlinearities of such preference, we have assumed the policy rule to be quadratic.

10. As a follower, Ghana is observing Burkina Faso's move and accordingly adjusting the discount price for electricity exports, and hence Ghana's hydropower function H^G depends only on the stock of water, S.

11. It refers to the part of Ghana's reaction function in the left (right) part of the line OA in Figure 2 for low (high) values of a.

12. Burkina Faso's benefit from hydropower is considered to be a function of stock of water instead of some fixed benefit (such as fixed side payments). This institutional arrangement has influenced the stability of the outcome.

13. The magnitude of the third term is larger than that of the second one due to the presence of $(w^B)^2$ in $\left(\frac{\partial \alpha^B}{\partial W^B}\right)^2$.

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Appendix A

Considering $\alpha^{B\star} = \alpha^{B\star}(W^B)$ along the optimal path and using Itô's Lemma and substituting (1), we obtain

(A1)
$$\frac{d^2\alpha^B}{dtd(\sigma^B)^2} = \frac{1}{2}(W^B)^2\frac{\partial^2\alpha^B}{\partial(W^B)^2}.$$

From the above equation, it is obvious that the slope of $\frac{d^2\alpha^B}{dtd(\sigma^B)^2}$ depends on how the marginal abstraction rate of water changes with further changes in water supply, $\frac{\partial^2\alpha^B}{\partial {W^B}^2}$. To derive $\frac{\partial^2\alpha^B}{\partial(W^B)^2}$, we differentiate equation (10) with respect to W^B, and after rearranging, we obtain

$$V^B_{\ w^B} + \alpha^B W^B V^B_{\ w^B w^B} = C^B_{\ \alpha^B\alpha^B}\frac{\partial\alpha^B}{\partial W^B},$$

which gives

(A2)
$$\frac{\partial\alpha^B}{\partial W^B} = \frac{V^B_{\ w^B} + \alpha^B W^B V^B_{\ w^B w^B}}{C^B_{\ \alpha^B\alpha^B}}.$$

Similarly, differentiating again, we find

(A3)
$$\frac{\partial^2\alpha^B}{\partial {W^B}^2} = \frac{2\alpha^B V^B_{\ w^B w^B} + (\alpha^B)^2 W^B V^B_{\ w^B w^B w^B} - C^B_{\ \alpha^B\alpha^B\alpha^B}\left(\frac{\partial\alpha^B}{\partial W^B}\right)^2}{(C^B_{\ \alpha^B\alpha^B})^2}.$$

As the benefit and the cost function are concave with respect to water consumption ($V^B_{\ w^B w^B} < 0, C^B_{\ \alpha^B\alpha^B\alpha^B} < 0$), and the second term of the numerator of the expression (A2) dominates the first term due to the presence of large W^B, we obtain $\frac{\partial \alpha^B}{\partial W^B} < 0$.

For the second expression (A3), we can determine the positive sign of $\frac{\partial^2 \alpha^B}{\partial (W^B)^2}$. It suggests that further decline in water supply will strengthen the relationship between α^B and W^B, and Burkina Faso will react strongly to a decline in water supply by further increasing the water abstraction. On the basis of this finding, we obtain $\frac{d^2 \alpha^B}{dtd(\sigma^B)^2} > 0$ after substituting $\frac{\partial^2 \alpha^B}{\partial (W^B)^2} > 0$ in (A1).

The result suggests that when the variance of water flow increases, Burkina Faso will increase its water abstraction over time. However, if marginal benefit function is concave (i.e., $V^B{}_{w^B w^B w^B} < 0$), then the increase in consumption of water will have a lower impact on the welfare than the case where marginal benefit is convex (i.e., $V^B{}_{w^B w^B w^B} > 0$). In such case, as the third term still dominates the second term in the numerator of (A3), Burkina Faso will still increase its water abstraction with higher variance but at a lower rate.[13]

Appendix B

From (12), we obtain the HJB equation as

$$rJ^G = \max_{\alpha^G} \left\{ NB^G + \frac{1}{dt} E\left[dJ^G\right] + \lambda(S - \bar{S}) \right\}.$$

Since $J^G = J^G(S, W^B, R)$, using Itô's formula we obtain,

$$dJ^G = J^G_S dS + J^G{}_{W^B} dW^B + J^G{}_R dR + \frac{1}{2} J^G{}_{W^B W^B} (dW^B)^2 + \frac{1}{2} J^G{}_{RR} (dR)^2 + J^G{}_{W^B R} d[W^B, R].$$

Substituting for dS, dW^B, and dR from equations (1) to (3) and assuming that W^B and R are uncorrelated, we have

$$dJ^G = \big[(1-\alpha^G)[(1-\alpha^B)W^B + R] - O\big] J^G_S\, dt + \sigma^B W^B J^G{}_{W^B}\, dz^B$$
$$+ \sigma^R R J^G{}_R\, dz^R + \frac{1}{2}(\sigma^B)^2 (W^B)^2 J^G{}_{W^B W^B}\, dt + \frac{1}{2}(\sigma^R)^2 R^2 J^G{}_{RR}\, dt.$$

Now applying the differential operator $(1/dt)E$ on the above expression and considering the mean of the Wiener processes $E[dz^B] = 0$, we can write,

$$\frac{1}{dt} E\big[dJ^G\big] = \big[(1-\alpha^G)[(1-\alpha^B)\bar{W}^B + \bar{R}] - O\big] J^G_S$$
$$+ \frac{(\sigma^B)^2}{2} E\big[{W^B}^2\big] J^G{}_{W^B W^B} + \frac{(\sigma^R)^2}{2} E\big[R^2\big] J^G{}_{RR}.$$

Then the HJB equation yields

$$rJ^G = \max_{\alpha^G} \Bigg\{ V^G(w^G) + H^G(S) - C^G(\alpha^G)$$
$$+ \big[(1-\alpha^G)[(1-\alpha^B)\bar{W}^B + \bar{R}] - O\big] J^G_S$$
$$+ \frac{(\sigma^B)^2}{2} E\left[(W^B)^2\right] J^G{}_{W^B W^B} + \frac{(\sigma^R)^2}{2} E\left[R^2\right] J^G{}_{RR} + \lambda(S - \bar{S}) \Bigg\}. \tag{A4}$$

Appendix C

As $A^G = A^G(\alpha^G, \alpha^B)$, using Itô's formula

$$dA^G = A^G{}_{\alpha^G}\, d\alpha^G + \frac{1}{2} A^G{}_{\alpha^G \alpha^G} \left(d\alpha^G\right)^2. \tag{A5}$$

Since from the optimality condition, we notice that $\alpha^G = \alpha^G(S, W^B, R)$, using Itô's formula,

$$d\alpha^G = \frac{\partial \alpha^G}{\partial S} dS + \frac{\partial \alpha^G}{\partial W^B} dW^B + \frac{\partial \alpha^G}{\partial R} dR$$
$$+ \frac{1}{2} \frac{\partial^2 \alpha^G}{\partial {W^B}^2} (dW^B)^2 + \frac{1}{2} \frac{\partial^2 \alpha^G}{\partial R^2} (dR)^2.$$

Replacing dS, dW^B, and dR (1)–(3) and using the properties of Wiener processes, we have

$$(d\alpha^G)^2 = \left[(\sigma^B)^2(W^B)^2\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + (\sigma^R)^2R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]dt.$$

Thus from equation (A5), we obtain

$$\begin{aligned} dA^G = {} & A^G{}_{\alpha^G}\, d\alpha^G + \frac{1}{2}A^G{}_{\alpha^G\alpha^G}\left[(\sigma^B)^2(W^B)^2\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2\right. \\ & \left. + (\sigma^R)^2R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]dt. \end{aligned}$$

Using the differential operator $\frac{1}{dt}E$ on the both sides of the above expression and substituting $\frac{1}{dt}E\left[dA^G\right]$, we can rewrite equation (16) as

$$\begin{aligned} rA^G - H^G_S - \lambda = {} & A^G{}_{\alpha^G}\frac{1}{dt}E\left[d\alpha^G\right] \\ & + \frac{1}{2}A^G{}_{\alpha^G\alpha^G}\left[(\sigma^B)^2(W^B)^2\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2\right. \\ & \left. + (\sigma^R)^2R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]. \end{aligned}$$

Appendix D

Totally differentiating equation (17) with respect to S, α^G, σ^{B2}, σ^{R2} and considering no change in the scarcity value of water in Lake Volta $d\lambda = 0$, we obtain

(A6)

$$0 = \left[H^G_{SS} + A^G{}_{\alpha^G\alpha^G} \left[(\sigma^B)^2 (W^B)^2 \frac{\partial \alpha^G}{\partial W^B} \frac{\partial^2 \alpha^G}{\partial W^B \partial S} + (\sigma^R)^2 R^2 \frac{\partial \alpha^G}{\partial R} \frac{\partial^2 \alpha^G}{\partial R \partial S} \right] \right] dS + A^G{}_{\alpha^G\alpha^G} (W^B)^2 \left(\frac{\partial \alpha^G}{\partial W^B} \right)^2 d(\sigma^B)^2 + A^G{}_{\alpha^G\alpha^G} R^2 \left(\frac{\partial \alpha^G}{\partial R} \right)^2 d(\sigma^R)^2 - r A^G{}_{\alpha^G} \, d\alpha^G.$$

This yields

$$\begin{aligned} \frac{d\alpha^G}{d(\sigma^B)^2} = \frac{1}{rA^G{}_{\alpha^G}} & \left[H^G_{SS} + A^G{}_{\alpha^G\alpha^G} \left[(\sigma^B)^2 W^{B\,2} \frac{\partial \alpha^G}{\partial W^B} \frac{\partial^2 \alpha^G}{\partial W^B \partial S} + (\sigma^R)^2 R^2 \frac{\partial \alpha^G}{\partial R} \frac{\partial^2 \alpha^G}{\partial R \partial S} \right] \right] \frac{dS}{d(\sigma^B)^2} \\ & + \frac{1}{rA^G{}_{\alpha^G}} A^G{}_{\alpha^G\alpha^G} (W^B)^2 \left(\frac{\partial \alpha^G}{\partial W^B} \right)^2 \\ & + \frac{1}{rA^G{}_{\alpha^G}} A^G{}_{\alpha^G\alpha^G} R^2 \left(\frac{\partial \alpha^G}{\partial R} \right)^2 \frac{d(\sigma^R)^2}{d(\sigma^B)^2}. \end{aligned} \tag{A7}$$

From the above equation (A7), it is evident that the effect of variance on water abstraction rate of Ghana depends on several factors. First, it depends on the positive relationship between Ghana's water abstraction rate α^G and the flow variable in Burkina Faso, W^B. By the similar arguments, $\frac{\partial \alpha^G}{\partial R} > 0$. Second, we assume $\frac{\partial^2 \alpha^G}{\partial W^B \partial S} < 0$ as it signifies that a decrease (increase) in stock S of water in Lake Volta strengthens (weakens) the relationship between the water abstraction rate α^G with the flow variable W^B. Using similar logic, we can assume $\frac{\partial^2 \alpha^G}{\partial S \partial R} < 0$. Third, the variance of water flow in the upstream σ^B, and the variance of runoff in the downstream country $\sigma^R$are uncorrelated, or, $\frac{d(\sigma^R)^2}{d(\sigma^B)^2} = 0$ as we have assumed different Brownian motion for water in the two countries.

Then, under the above-mentioned assumptions, if the marginal benefit function is concave $[A^G > 0, A^G{}_{\alpha^G} < 0, A^G{}_{\alpha^G\alpha^G} > 0]$, then from (A7), we obtain the following results,

$$\frac{d\alpha^G}{d(\sigma^B)^2} < 0 \quad \text{for low extreme events where } \frac{dS}{d(\sigma^B)^2} < 0.$$

A similar result can also be derived from (A6) for $\frac{d\alpha^G}{d(\sigma^R)^2}$.

Taking the differentiation of $\frac{d\alpha^G}{d\alpha^B}$ with respect to $(\sigma^B)^2$ in (A9), we obtain

$$\text{(A8)} \qquad \frac{d^2\alpha^G}{d\alpha^B d(\sigma^B)^2} = \frac{A^G{}_{\alpha^G\alpha^G}}{rA^G{}_{\alpha^G}}(W^B)^2 \frac{\partial\alpha^G}{\partial W^B}\frac{\partial^2\alpha^G}{\partial S\partial W^B}\frac{dS}{d\alpha^B}.$$

As $\frac{\partial^2\alpha^G}{\partial S\partial W^B} < 0, A^G{}_{\alpha^G} < 0, A^G{}_{\alpha^G\alpha^G} > 0$ and $\frac{\partial\alpha^G}{\partial W^B} > 0$, we obtain $\frac{d^2\alpha^G}{d\alpha^B d(\sigma^B)^2} < 0$. It means that with increase in uncertainty (or with increase in variances), Ghana will decrease its water abstraction rate more for an increase in water abstraction rate of Burkina Faso.

Appendix E

Totally differentiating the equation (17) with respect to S, α^G, and α^B and rearranging the terms and assume in the long-run steady state equilibrium $d\lambda = 0$, we obtain

(A9)

$$\frac{d\alpha^G}{d\alpha^B} = \frac{1}{rA^G{}_{\alpha^G}}\left[H^G_{SS} + A^G{}_{\alpha^G\alpha^G}\left[(\sigma^B)^2(W^B)^2\frac{\partial\alpha^G}{\partial W^B}\frac{\partial^2\alpha^G}{\partial W^B\partial S} + (\sigma^R)^2R^2\frac{\partial\alpha^G}{\partial R}\frac{\partial^2\alpha^G}{\partial R\partial S}\right]\right]\frac{dS}{d\alpha^B} - \frac{A^G{}_{\alpha^B}}{A^G{}_{\alpha^G}}.$$

Let us assume that the marginal benefit function of water withdrawal for Ghana is convex $[A^G{}_{\alpha^G} < 0, A^G{}_{\alpha^G\alpha^G} > 0]$. We also find that ${A^G}_{\alpha^B} < 0$ if $({V^G}_{\alpha^G} - {C^G}_{\alpha^G})_{\alpha^B} < 0$, and $({V^G}_{\alpha^G} - {C^G}_{\alpha^G}) < \frac{K}{\bar{W}^B}|({V^G}_{\alpha^G} - {C^G}_{\alpha^G})_{\alpha^B}|$.

With further assumptions $\frac{\partial^2 \alpha^G}{\partial W^B \partial S} < 0$, $\frac{\partial^2 \alpha^G}{\partial R \partial S} < 0$, and $\frac{dS}{d\alpha^B} < 0$, we obtain from equation (A9), $\frac{d\alpha^G}{d\alpha^B} < 0$, which implies with increase in water abstraction in Burkina Faso, that Ghana will decrease its own water abstraction.

Appendix F

To find the effect of $a(>0)$ and $b(>0)$ with changes in σ^B and σ^R, we totally differentiate the above equation with respect to S, a, σ^B, and σ^R and rearrange the terms,

$$\text{(A10)} \qquad \frac{da}{d{\sigma^B}^2} = \frac{X_1 \dfrac{dS}{d{\sigma^B}^2} + X_2}{rA^B_a - H^B_{Sa}}, \qquad \frac{da}{d{\sigma^R}^2} = \frac{X_1 \dfrac{dS}{d{\sigma^R}^2} + X_3}{rA^B_a - H^B_{Sa}},$$

where

$$X_1 = \Bigg[-r{A^B}_S + H^B_{SS} + {A^B}_{aa}\left\{{\sigma^B}^2 {W^B}^2 \frac{\partial a}{\partial W^B}\frac{\partial^2 a}{\partial S \partial W^B} + {\sigma^R}^2 R^2 \frac{\partial a}{\partial R}\frac{\partial^2 a}{\partial S \partial R}\right\} + {A^B}_{bb}\left\{{\sigma^B}^2 {W^B}^2 \frac{\partial b}{\partial W^B}\frac{\partial^2 b}{\partial S \partial W^B} + {\sigma^R}^2 R^2 \frac{\partial b}{\partial R}\frac{\partial^2 b}{\partial S \partial R}\right\}\Bigg],$$

$$X_2 = \frac{1}{2}\left[{A^B}_{aa}{W^B}^2\left(\frac{\partial a}{\partial W^B}\right)^2 + {A^B}_{bb}{W^B}^2\left(\frac{\partial b}{\partial W^B}\right)^2\right],$$

$$X_3 = \frac{1}{2}\left[{A^B}_{aa}R^2\left(\frac{\partial a}{\partial R}\right)^2 + {A^B}_{bb}R^2\left(\frac{\partial b}{\partial R}\right)^2\right].$$

Let us assume that the marginal benefit function $(V^B - C^B + H^B)_{\alpha^B}$ of water withdrawal for Burkina Faso is convex. Moreover, as before we assume $\frac{\partial^2 i}{\partial S \partial j} < 0$ for $i = a$, b, and $j = W^B$, R. Then we find from (30), $A^B_S > 0, A^B_a < 0, A^B_{aa} > 0$, and $A^B_{bb} > 0$. Also $H^B_{SS} < 0, H^B_{Sa} < 0$, and thus we get $X_1 < 0$, $X_2 > 0$, and $X_3 > 0$. Given the Markovian strategy of Ghana of increasing its water abstraction for a decrease in water abstraction level of Burkina faso during cooperation, we observe that $rA^B_a - H^B_{Sa} > 0$. It suggests that for a lower level of water abstraction, further decrease in water abstraction will increase the opportunity cost in terms of forgone agricultural benefits more than the increase in marginal benefit from change in the stock of the water at Lake Volta. Under such conditions, $\frac{da}{d\sigma^{B^2}} > 0$ and Burkina Faso will increase its water abstraction with increase in variance of water flow during extreme drought conditions.

Again, at Burkina Faso's higher level of water abstraction, Ghana will respond by increasing its water abstraction, additional increase in water abstraction by Burkina Faso will decrease its marginal benefit of the stock of water at Lake Volta more than the increase in marginal benefit of water consumption in agriculture; and we get $rA^B_a - H^B_{Sa} < 0$. As a consequence, $\frac{da}{d\sigma^{B^2}} < 0$ and Burkina Faso will reduce its water abstraction with higher variance in drought.

Similarly, one can also find the effect of $b(>0)$ with changes in σ^B and σ^R, by totally differentiating the equation (31) with respect to S, b, σ^B, and σ^R and rearranging the terms to get,

$$\text{(A11)} \qquad \frac{db}{d\sigma^{B^2}} = \frac{X_1 \frac{dS}{d\sigma^{B^2}} + X_2}{rA^B_b - H^B_{Sb}}, \quad \frac{db}{d\sigma^{R^2}} = \frac{X_1 \frac{dS}{d\sigma^{R^2}} + X_3}{rA^B_b - H^B_{Sb}}.$$

Appendix G

Totally differentiating the equation (23) with respect to S, α^G, a, b, σ^{B2}, and σ^{R2}, we find

(A12)

$$\frac{d\alpha^G}{d\sigma^{B^2}} = \frac{X_4 \frac{dS}{d\sigma^{B^2}} - rA^G{}_a \frac{da}{d\sigma^{B^2}} - rA^G{}_b \frac{db}{d\sigma^{B^2}} + X_5 + X_6 \frac{d\sigma^{R^2}}{d\sigma^{B^2}}}{rA^G{}_{\alpha^G}},$$

where

$$X_4 = -rA^G{}_S + H^G_{SS} + A^G{}_{\alpha^G\alpha^G}\left[{\sigma^B}^2 {W^B}^2 \frac{\partial\alpha^G}{\partial W^B}\frac{\partial^2\alpha^G}{\partial S\partial W^B} + {\sigma^R}^2 R^2 \frac{\partial\alpha^G}{\partial R}\frac{\partial^2\alpha^G}{\partial S\partial R}\right],$$

$$X_5 = \frac{1}{2}A^G{}_{\alpha^G\alpha^G}\,{W^B}^2\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2,$$

$$X_6 = \frac{1}{2}A^G{}_{\alpha^G\alpha^G}\,R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2.$$

A similar expression can also be found for $\frac{d\alpha^G}{d{\sigma^R}^2}$. Suppose there is no effect on variance in the upstream country with changes in variance in the downstream country and vice versa, i.e., $\frac{d{\sigma^R}^2}{d{\sigma^B}^2} = 0$ and $\frac{d{\sigma^B}^2}{d{\sigma^R}^2} = 0$. Now with the assumption that the marginal benefit function of water withdrawal for Ghana is convex and $\frac{\partial^2\alpha^G}{\partial S\partial j} < 0$ for $j = W^B$, R, we have already shown that $X_4 < 0, X_5 > 0, A^G_a > 0, A^G_b > 0$, and $A^G_{\alpha^G} < 0$. Then from equation (A12) by using the results of Appendix F, we obtain the following , $\frac{d\alpha^G}{dk} < 0, (k = {\sigma^B}^2, {\sigma^R}^2)$, for any level of water abstraction of Burkina Faso during drought (when $\frac{dS}{dk} < 0$) irrespective of the sign of $\frac{di}{dk}(i = a, b)$. However, $\left|\frac{d\alpha^G}{dk}\right|$ is higher if $\frac{di}{dk} < 0$.

Appendix H

Without co-operation	With co-operation
Marginal benefit of Burkina Faso convex;	Marginal benefit of Burkina Faso convex;
$\sigma\uparrow\Rightarrow\alpha^B\uparrow$	$\frac{\partial^2\alpha^B}{\partial S\partial j} < 0$ for $j = W^B$, R.$\Rightarrow\alpha^{B^*}$ exists.
irrespective of low or high extreme events.	Low extreme: $\sigma\uparrow\Rightarrow\alpha^B\downarrow$ at higher level of water abstraction of Burkina Faso.
	$\sigma\uparrow\Rightarrow\alpha^G\downarrow$ at lower level of water abstraction of Burkina Faso,
	but with much lesser rate of decline.

Without co-operation	With co-operation
For a given σ: $\alpha^B\uparrow\Rightarrow\alpha^G\downarrow$.	For a given σ: in the co-op phase, $\alpha^B\uparrow\Rightarrow\alpha^G\downarrow$; after it crosses the threshold point (i.e., in the deterrence phase) $\alpha^B\uparrow\Rightarrow\alpha^G\uparrow$, to restrict Burkina Faso to gain from more abstraction.
$\left[\frac{d\alpha^G}{d\alpha^B}\right]_{\sigma_1} < \left[\frac{d\alpha^G}{d\alpha^B}\right]_{\sigma_2} < 0$, for $\sigma_1 > \sigma_2$.	In co-op phase: $\left[\frac{d\alpha^G}{d\alpha^B}\right]_{\sigma_1} < \left[\frac{d\alpha^G}{d\alpha^B}\right]_{\sigma_2} < 0, \sigma_1 > \sigma_2$ In deterrence phase: $0 < \left[\frac{d\alpha^G}{d\alpha^B}\right]_{\sigma_1} < \left[\frac{d\alpha^G}{d\alpha^B}\right]_{\sigma_2}$.

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