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Anik Bhaduri
Utpal Manna
Edward Barbier
Jens Liebe

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Cooperation in transboundary water sharing under climate change

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Center for Development Research
Walter-Flex-Strasse 3
D – 53113 Bonn
Germany
Phone: +49-228-73-1861
Fax: +49-228-73-1869
E-Mail: zef@uni-bonn.de
http://www.zef.de

The authors:
Anik Bhaduri, Center for Development Research (ZEF), University of Bonn, Germany.
(contact: abhaduri@uni-bonn.de)
Utpal Manna, School of Mathematics, Indian Institute of Science Education and Research, Thriuvananthapuram, India
(contact: manna.utpal@iisertvm.ac.in).
Edward Barbier, Department of Economics and Finance, University of Wyoming, USA
(contact: ebarbier@uwyo.edu)
Jens Liebe, Center for Development Research (ZEF) University of Bonn, Germany.
(contact: jliebe@uni-bonn.de)

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ABSTRACT

As multiple countries share a river, the likelihood of a water resource conflict from climate change could be higher between countries. In this paper, we demonstrate how countries can cooperate in transboundary water sharing in a sustainable way, given the impacts of climate change. We illustrate the case of water sharing of the Volta River between the upstream and downstream country, Burkina Faso and Ghana respectively, where the latter country faces a tradeoff of water use between agriculture in the north and production of hydro energy in the south. In the framework of a stochastic Stackelberg differential game, we have shown how the issue of water sharing could be linked to hydropower export that can make water sharing between the countries sustaining in the event of 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 distribution are stable even with increasing variances of water flow.

KURZFASSUNG

Wenn mehrere Staaten sich einen Fluss teilen, könnte die Wahrscheinlichkeit eines Konfliktes um vorhandene Wasserressourcen zwischen Nachbarländern durch den Klimawandel steigen. In dieser Arbeit demonstrieren wir, wie Staaten trotz der Auswirkungen des Klimawandels nachhaltig durch länderübergreifende gemeinsame Wassernutzung kooperieren können. Wir illustrieren den Fall der gemeinsamen Wassernutzung im Fluss Volta zwischen dem stromaufwärts gelegenen Burkina Faso und dem stromabwärts gelegenen Ghana, das vor der Aufgabe steht, zwischen der landwirtschaftlichen Nutzung des Wassers im Norden und der Produktion von Hydroenergie im Süden des Landes abzuwägen. Im Rahmen eines stochastischen Stackelbergschen Differentialspiels zeigen wir, dass auch bei Klimawandel der Aspekt der gemeinsamen Wassernutzung mit dem Export von Energie nachhaltig verbunden werden kann. Unsere Ergebnisse deuten darauf hin, dass Ghana bei einer Kooperation die Möglichkeit haben wird, seine bisher weitgehend eingeschränkte Wassernutzung für die Landwirtschaft zu erhöhen. Zudem bleiben die langfristigen Gleichgewichtslösungen auch dann stabil, wenn die Verfügbarkeit von Wasser stark variiert.

1. Introduction

There is broad agreement that global climate change may have substantial impacts on water resources [2, 10]. Possible impacts include accelerated hydrological cycle, alteration in the precipitation rate, and the magnitude and timing of runoff. The intensity and frequency of floods and droughts are also expected to change. In such possible climate change conditions, unreliable rainfall with changes in its spatial and temporal distribution may jeopardize rainfed agriculture and the farmers may respond by increasing the demand for irrigation water [17]. However, with climate change altering the location and timing of water availability, the decision to reallocate more water for irrigation and other vital uses becomes much more complex with host of competing users. The Stern report on the economics of climate change has suggested that climate-induced scarcities of food and water can potentially lead to or exacerbate deadly conflict [20]. The likelihood of water resource dispute and conflict stemming from climate change is even higher in a transboundary setting. As multiple countries share a river, the competition over available water resources will be acute among countries facing a climate change, and meeting the freshwater demand for agriculture and other vital uses could be one of the impending challenge for policy makers.

In past, water planners struggled with the problem of estimating water demand with supply uncertainties. Also, majority of current water sharing allocation arrangements do not take into account the hydrological variability of river flow [13]. Climate change challenges existing water resource management practices by adding further uncertainties. This will be an especially troubling issue for transboundary water sharing agreements [19]. Unless new approaches to water management are developed that take into account these new uncertainties, future conflict over water resource are certain to increase [18].

The following paper is concerned with the allocation of river water in a transboundary setting, and attempts to capture the influence of climate change on its water allocation. The paper illustrates the case of Volta River Basin in Sub-Saharan Africa, which is one of the poorest regions in the world, and where water and food security could be seriously undermined by climate change (see Figure 1 for map).

In the Volta River Basin, the upstream and the downstream countries Burkina Faso and Ghana respectively, comprise nearly 90 percent of the the $400,000 km^2$ Volta Basin area, and is dependent on the freshwater availability to a great extent in meeting the water demand of the economy [4]. However the pattern of water demand in these two countries follows different trajectories (see Figure 2). The upstream country, Burkina Faso, is dependent on freshwater

FIGURE 1. The Volta Basin

from the Volta River to meet primarily its agricultural water demand; while in the downstream Ghana, the main water use is for hydropower generation. Most of the hydropower in Ghana is generated from Lake Volta (Akosombo Dam, located at the mouth of the River Volta). Unlike in other river basins, as the Dam is located at the very tail of the river, water usage for hydropower is consumptive in such case. It makes this case study very unique, as it allows competition to take place between agriculture and hydropower water usage.

Currently, water withdrawal rate to meet agricultural, domestic and industrial water demand in Ghana is much lower (1.73 per cent) compare to that in Burkina Faso (6.15 per cent). Ghana perceives that higher water abstraction for agriculture in upstream can reduce water inflow in

Irrigation potential	'000 ha
Burkina Faso	142
Ghana	346

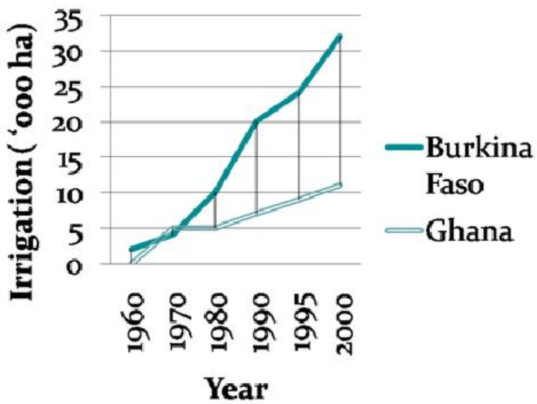

FIGURE 2. Irrigation Development in Burkina Faso and Ghana

Lake Volta, and thereby affect hydro-electric generation. This could be one of the reasons that has induced Ghana to restrict its water abstraction for other purposes in its upstream.

However, the Government of Ghana has projected that with higher population, the agricultural water demand will increase several fold in the next two decades [15]. Moreover, higher uncertainly in water availability from climate change can also increase the demand for irrigation significantly [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 to changes in climate variables. The study predicted that annual mean temperature could increase by 1.2 to 1.3 degree Celsius during the next thirty years in the Volta River Basin. A change in precipitation is expected with a mean increase of 5 per cent 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 [11].

Meeting higher demand for irrigation in the face of climate change is even more challenging for the policy makers in the Basin, as higher water abstraction in the upstream may increase the scarcity value of reserve water in Lake Volta. 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, the conflict between the two countries exacerbated 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 in the 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 [14]. Burkina Faso, however, denied such Ghana's claim and cited low rainfall and natural variability of water flow as the main causes for the reduction in river flow. The pertinent question is whether higher water abstraction in the upstream Burkina Faso can lead to lower water availability in Lake Volta, where hydropower is generated for Ghana with the help of Akosombo Dam. Van de Giesen *et.al* (2001) claim that irrigation development activities can create an impact in water availability in the downstream; though, it is difficult to capture such influence [4]. The amount of irrigable area in Burkina Faso is much higher than that of Ghana, estimated at 160000*ha* [8]. The amount of water that could be used for irrigation in Burkina Faso is approximated to be around 10 percent of the water inflow to downstream Lake Volta. In the recent past, Burkina Faso had already built two large dams and some 1500 small dams in the upper basin of the Volta river [14]. Moreover, Burkina Faso has plans of building three more large dams on the tributaries of the Volta within its territory for water supply to its capital, Ouagadougou. While these trends seem to support the claims that Burkina Faso's investments in water infrastructures could be the main cause of water deficit in the lower Volta, there are also opposite views suggesting that Burkina Faso has little to do with the reduced flow in Ghana [12, 14].

However, both the counties agree that the sharing of water between Burkina Faso and Ghana will likely be a key issue in coming years, especially if climate change leads to significantly lower rainfall and run-off [16]. Both countries, in principle, have agreed to cooperate given the potential risk of conflict, and the manner of cooperation is still in the planning process [7].

There were several attempts to initiate a self-enforcing cooperative agreement between Ghana and Burkina Faso. One such attempt was made when Ghana offered Burkina Faso with energy in order to prevent the country from unilateral diversion of water. In this paper, we investigate if the issue of water sharing could be linked to hydropower export that can make water sharing between the countries sustaining in the event of climate change.

In this paper, the key issue we raise is whether the countries could gain from such cooperation. However the scope of cooperation largely depends on whether Burkina Faso action can influence the water inflow to Lake Volta. Bhaduri *et.al*(2008) suggest that at the present condition, the probability of water stock falling below the critical level is around 1 percent [1]. However, if both countries' water abstraction rates increase in future, then the probability increases sharply. Under such circumstances, there is an opportunity for Ghana to cooperate. Our paper extends the analytical work of Bhaduri *et.al*(2008) by evaluating the scope of cooperation in the light of climate change.

The second pertinent issue is whether such kind of cooperation is sustainable in case of climate change. Climate change can increase marginal benefit of water usage from irrigation, and might motivate the upstream country, Burkina Faso to deviate from cooperation, even though Ghana may gain from more from cooperation as future uncertainties in water supply may increase the opportunity cost of storing water in Lake Volta. This paper evaluate such effect of uncertainties on sustainability of cooperation between the two countries.

In this paper, first we model the allocation of stochastic water resource between Ghana and Burkina Faso in a non cooperative framework where the upstream country, Burkina Faso, chooses how much water to divert from the River to maximize it own's welfare. The downstream country Ghana acts as a "follower", whose water availability depends on the flow of water diverted by Burkina Faso.

Second, we formulate a stochastic differential Stackelberg leader-follower game in a setting where Ghana offers a discounted price for energy export to the upstream country, Burkina Faso, for more water in the downstream. The paper attempts to compares both the cooperative as well as non cooperative outcomes in a possible climate change scenario.

There are substantial literature on stochastic water resource management. Fisher *et.al*(1997) has studied the determination of optimal water storage capacity in a region taking into account the flow into water reserves as uncertain, and found that the reservoir capacity building will become more costly with climate change [3]. Other literatures are concerned mainly with impact of stochastic surface water flows on the value of additional surface reservoir or groundwater stocks [21, 9]. However there are few literatures on the influence of stochastic water resource on transboundary water sharing. This paper extends the work of Fisher *et.al*(1997) on two frontiers. The paper uniquely applies the framework of Fisher model on uncertainty in water resource management in a transboundary water sharing problem. Second, the paper applies a stochastic differential game to evaluate the scope and sustainability of cooperation possible between the countries in such transboundary setting.

Following Fisher*et.al*'s model, in this paper we assume that water resources evolve through time and follows Geometric Brownian motion. However the characteristics of the Brownian motion in terms of variance are different in both the countries, based on assumption of inter regional variable effect of climate change. We then derive the steady state conditions of the corresponding stochastic problem with respect to water abstraction rates. We evaluate how these steady state conditions will be modified by changes in the variance of the water resource. In such fashion, we are able to evaluate how riparian countries long run water abstraction will change for increase in variability caused by climate change. Also, if the countries cooperate in water sharing, then what will be the effect on cooperation from increased variance in water flow. Such a framework, although relying on the specific case of water sharing in the Volta River Basin, is potentially relevant to many other river basins in international cooperation on river basin management where climate change may play a role.

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 distribution are stable even with increasing variances of water flow.

The structure of the paper is as follows. In the next section, we outline the model of water sharing between the Burkina faso and Ghana in the case with noncooperation on water sharing. In the following section, we formulate a differential game of cooperation and evaluate the outcome with respect to climate change; and finally the conclusion summarizes the main findings and results of the paper.

2. Water Sharing Between Burkina Faso and Ghana

For years, Volta basin had been one of the few transboundary water basins in Africa without a formal agreement in place for cross-border cooperation and management [16]. This section of the paper is concerned with the allocation of Volta River water between Ghana and Burkina Faso in the case without any cooperation in water sharing. We explore how uncertainty in water supply will affect the water abstraction rates of the countries, and the underlying conditions that may influence such decisions.The upstream country, Burkina Faso has the upper riparian right to unilaterally divert water, while Ghana is a downstream country where the freshwater availability depends on the water usage of the upstream country. We denote the countries by superscript B, G, where B and G denote Burkina Faso and Ghana respectively. Let W^B be the annual total renewable fresh water resources in Burkina Faso. In the model, we assume that the water flow is stochastic. The uncertainty in the flow of water can be attributed to climate change. The total renewable fresh water resources in the upstream country, W^B, evolves through time according to a geometric Brownian Motion[1]:

$$\mathrm{d}W^B = \sigma^B W^B \mathrm{d}z_t^B, \tag{2.1}$$

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.[2] Here σ^B can be considered as a volatility of water flow in Burkina Faso.

Let the total per capita fresh water 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 upstream country Burkina Faso can be exhibited in the form of mathematical equation as

$$w^B = \alpha^B W^B. \tag{2.2}$$

The water availability in the downstream Ghana depends on the water consumption in the upstream, W^B, and rainfall, R, that the river picks up and added to its volume while flowing. The runoff denoted by R is also stochastic in the model and follows Geometric Brownian motion,[3]

$$\mathrm{d}R = \sigma^R R \mathrm{d}z_t^R, \tag{2.3}$$

where z_t^R is a standard Wiener process. Now on we will 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

$$W^G = (1-\alpha^B)W^B + R. \tag{2.4}$$

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

$$w^G = \alpha^G[(1-\alpha^B)W^B + R]. \tag{2.5}$$

[1] W^B is 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 variance is $W_0^{B2}(e^{\sigma^{B2}t} - 1)$, which increases rapidly with increase in σ^B. Moreover equation (2.1) has a unique analytical solution, $W^B(t) = W_0^B \exp(-(\sigma^{B^2} t)/2 + \sigma^B z_t^B)$.

[2] In the differential equation we have excluded the deterministic drift component. For further reference see Fisher and Rubio(1997) [3].

[3] Rainfall and other climatic conditions varies across the River Basin [16]. In the north, average precipitation varies from 500mm in the north to 2000mm in the extreme south. Thus we have assumed different Brownian motions for Bukina Faso and Ghana respectively.

The stock of water in the Lake Volta where hydropower is produced, is denoted by S, is a function of the stochastic water resources and the control variables, the water abstraction rates of both the countries (α^G, α^B). The state equation can be represented as

$$dS = (1-\alpha^G)\left[(1-\alpha^B)W^B + R\right]dt, \tag{2.6}$$
$$S(0) = S_0.$$

We also assume that water reserves exceeds a minimum level (critical level) $\bar{S}$. If the water reserves is above the critical level, then there exits no scarcity of water in Lake volta. However if the constraint is binding, then the scarcity value of water is positive. Consider the benefit of water consumption of the countries as $B^i(w^i)$ for $i = B, G$, where w^i is 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 $\alpha^i, i = B, G$. We consider that as water becomes increasingly scarce in the economy, the government would exploit less accessible sources of fresh water through appropriating and purchasing a greater share of aggregate economic output, in terms of dams, pumping stations, supply infrastructure etc. This leads to higher marginal cost and at a certain point, prohibits the country from making further investment in tapping water resource [6]. Apart from agricultural water usage, Ghana also gets benefits from storing water at Lake volta. We denote $H^G(S)$ as the net consumer surplus or economic benefits from hydropower generation.

Based on the above considerations, the net benefit of both the countries can be written as

$$NB^B = B^B(w^B) - C^B(\alpha^B),$$

for Burkina Faso

and

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

for Ghana.

Let us redefine the above mentioned state, flow and control variables in more mathematical perspective. Let $(\Omega, \mathcal{F}, \mathcal{F}_t, P)$ be a complete filtered Probabilty 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., $\alpha^B, \alpha^G : \Omega \times X \times [0,T] \mapsto U \subset [0,1]$. 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 which describe the realization of the water resources and runoff in Burkina Faso and Ghana respectively. The pay off functions $J^i \in \mathbb{R}^+, i = B, G$, are non-random 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:

$$J^B = E\big[\max_{\alpha^B} \int_t^\infty e^{-r\tau} NB^B \mathrm{d}\tau\big], \tag{2.7}$$

subject to the equation

$$\mathrm{d}W^B = \sigma^B W^B \mathrm{d}z^B. \tag{2.8}$$

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

$$rJ^B = \max_{\alpha^B} \Big\{ NB^B + \frac{1}{\mathrm{d}t} E\big[\mathrm{d}J^B\big] \Big\}. \tag{2.9}$$

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

$$\mathrm{d}J^B = J^B{}_{W^B} \mathrm{d}W^B + \frac{1}{2} J^B{}_{W^B W^B} (\mathrm{d}W^B)^2,$$

which with the help of equation (2.8) reduces to

$$\mathrm{d}J^B = \sigma^B W^B J^B{}_{W^B} \mathrm{d}z^B + \frac{1}{2} \sigma^{B2} W^{B2} J^B{}_{W^B W^B} \mathrm{d}t.$$

Now applying the differential operator $(1/\mathrm{d}t)E$ on the above expression and considering that $E[\mathrm{d}z^B] = 0$, the HJB equation (2.9) can be written as

$$rJ^B = \max_{\alpha^B} \Big\{ B^B(w^B) - C^B(\alpha^B) + \frac{1}{2} \sigma^{B2} W^{B2} J^B{}_{W^B W^B} \Big\}. \tag{2.10}$$

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

$$B^B{}_{\alpha^B} = C^B{}_{\alpha^B}, \text{ or, } W^B B^B{}_{w^B} = C^B{}_{\alpha^B}. \tag{2.11}$$

Solution of the above equation will lead to the optimal α^B, denoted by $\alpha^{B\star} = \alpha^{B\star}(W^B)$. The solution is determined at the point where marginal benefit of water withdrawal is equal to the marginal cost of water withdrawal. The solution clearly indicates the dependence of optimal water abstraction rate α^B on the uncertainty of water supply, and we evaluate the conditions under which Burkina Faso will increase the water abstraction rate with increase in variance by deriving $\frac{\partial \dot{\alpha}^B}{\partial \sigma^{B^2}}$.

Proposition 2.1. *Let us assume that the upstream country, Burkina Faso, has convex marginal benefit function of water withdrawal. Then the country will increase its water abstraction with increase in variance in water supply irrespective of the level of water realization. However, the rate of increase will be lower if the country has concave marginal benefit function.*

Proof. Considering $\alpha^{B\star} = \alpha^{B\star}(W^B)$ along the optimal path, using Itô's Lemma and substituting (2.1),

$$\frac{\mathrm{d}^2\alpha^B}{dtd\sigma^{B^2}} = \frac{1}{2}W^{B^2}\frac{\partial^2\alpha^B}{\partial W^{B^2}}. \tag{2.12}$$

From the above equation, it is obvious that the slope of $\frac{\mathrm{d}^2\alpha^B}{dtd\sigma^{B^2}}$ 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 (2.11) with respect to W^B, and after rearranging, we get

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

which gives

$$\frac{\partial\alpha^B}{\partial W^B} = \frac{B^B{}_{w^B} + \alpha^B W^B B^B{}_{w^B w^B}}{C^B{}_{\alpha^B\alpha^B}}. \tag{2.13}$$

Similarly differentiating again we find,

$$\frac{\partial^2\alpha^B}{\partial W^{B^2}} = \frac{2\alpha^B B^B{}_{w^B w^B} + \alpha^{B^2} W^B B^B{}_{w^B w^B w^B} - C^B{}_{\alpha^B\alpha^B\alpha^B}\left(\frac{\partial\alpha^B}{\partial W^B}\right)^2}{(C^B{}_{\alpha^B\alpha^B})^2}. \tag{2.14}$$

Note that, as the benefit function for Burkina Faso is concave with respect to water consumption, we have $B^B{}_{w^B} > 0$, $B^B{}_{w^B w^B} < 0$, and $B^B{}_{w^B w^B w^B} > 0$. Also due to convex cost function as assumed in the model, we get $C^B{}_{\alpha^B\alpha^B} > 0$ and $C^B{}_{\alpha^B\alpha^B\alpha^B} < 0$. Given such benefit and cost functions in (2.13), we get $\frac{\partial\alpha^B}{\partial W^B} < 0$ as the second term of the numerator of the expression will dominate over the first term, due to the presence of $\alpha^B W^B (= w^B)$, which is large. The implication is very straight forward, and it indicates that for a given decline in water supply, Burkina Faso will increase its water abstraction rate.

For the second expression (2.14), if we assume that marginal benefit function is convex, the positive second and third terms of the numerator are large terms and they will mainly contribute to determine the positive sign of $\frac{\partial^2\alpha^B}{\partial W^{B2}}$. It suggests further decline in water supply will strengthen the relationship between α^B and W^B, and Burkina Faso will react strongly to decline in water supply by increasing the water abstraction more. On the basis of this finding, we get $\frac{d^2\alpha^B}{dt d\sigma^{B2}} > 0$ after substituting $\frac{\partial^2\alpha^B}{\partial W^{B2}} > 0$ in (2.12). The result suggests that with increase in variance of water flow , Burkina Faso will increase its water abstraction over time. However if marginal benefit function is concave (i.e. $B^B{}_{w^B w^B w^B} < 0$) 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. $B^B{}_{w^B w^B w^B} > 0$). In such case, as the third term still dominates the second term in the numerator of (2.14), Burkina Faso will still increase its water abstraction with higher variance but at a lower rate[4]. $\square$

2.2. **Ghana's Problem.** The downstream country, Ghana's water consumption depends on the remainder of the water that flows from the upstream country Burkina Faso and also on the runoff in the downstream. Based on the given availability of water which is a function of Burkina Faso water abstraction rate

Ghana maximizes its net benefit:

$$J^G = E\big[\max_{\alpha^G} \int_t^{\infty} e^{-r\tau} NB^G \mathrm{d}\tau\big], \tag{2.15}$$

where the net benefit function

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

subject to the state equation

$$\mathrm{d}S = (1-\alpha^G)W^G \mathrm{d}t = (1-\alpha^G)[(1-\alpha^B)W^B + R]\mathrm{d}t, \tag{2.16}$$

where W^B and R are given by the stochastic equations

$$\mathrm{d}W^B = \sigma^B W^B \mathrm{d}z^B, \tag{2.17}$$

$$\mathrm{d}R = \sigma^R R \mathrm{d}z^R, \tag{2.18}$$

along with the constraint

$$S \geq \bar{S}. \tag{2.19}$$

Note that, here we work with optimum α^B which is a function of W^B.

[4]The magnitude of the third term is larger than that of the second one due to presence of w^{B2} in $\big(\frac{\partial\alpha^B}{\partial W^B}\big)^2$.

The corresponding HJB equation is as follows:

$$rJ^G = \max_{\alpha^G} \left\{ NB^G + \frac{1}{\mathrm{d}t} E\left[\mathrm{d}J^G\right] + \lambda(S - \bar{S}) \right\}. \tag{2.20}$$

Here the parameter λ represents the scarcity value of water. Since $J^G = J^G(S, W^B, R)$, using Itô's formula we can get,

$$\begin{aligned}\mathrm{d}J^G = {} & J^G_S \mathrm{d}S + J^G_{W^B} \mathrm{d}W^B + J^G_R \mathrm{d}R + \frac{1}{2} J^G_{W^B W^B} (\mathrm{d}W^B)^2 \\ & + \frac{1}{2} J^G_{RR} (\mathrm{d}R)^2 + J^G_{W^B R} \mathrm{d}[W^B, R].\end{aligned}$$

Substituting for $\mathrm{d}S, \mathrm{d}W^B$, and $\mathrm{d}R$ and assuming that W^B and R are uncorrelated, we have,

$$\begin{aligned}\mathrm{d}J^G = {} & (1-\alpha^G)[(1-\alpha^B)W^B + R]J^G_S \mathrm{d}t + \sigma^B W^B J^G_{W^B} \mathrm{d}z^B \\ & + \sigma^R R J^G_R \mathrm{d}z^R + \frac{1}{2}\sigma^{B2} W^{B2} J^G_{W^B W^B} \mathrm{d}t + \frac{1}{2}\sigma^{R2} R^2 J^G_{RR} \mathrm{d}t.\end{aligned}$$

Since the mean of the Wiener processes z^B and z^R are zero, we can write,

$$\begin{aligned}\frac{1}{\mathrm{d}t} E\left[\mathrm{d}J^G\right] = {} & (1-\alpha^G)[(1-\alpha^B)\bar{W}^B + \bar{R}]J^G_S \\ & + \frac{\sigma^{B2}}{2} E\left[W^{B2}\right] J^G_{W^B W^B} + \frac{\sigma^{R2}}{2} E\left[R^2\right] J^G_{RR}.\end{aligned}$$

Then the HJB equation yields,

$$\begin{aligned}rJ^G = \max_{\alpha^G} \Big\{ & B^G(w^G) + H^G(S) - C^G(\alpha^G) \\ & + (1-\alpha^G)[(1-\alpha^B)\bar{W}^B + \bar{R}]J^G_S \\ & + \frac{\sigma^{B2}}{2} E\left[W^{B2}\right] J^G_{W^B W^B} + \frac{\sigma^{R2}}{2} E\left[R^2\right] J^G_{RR} + \lambda(S - \bar{S}) \Big\}.\end{aligned} \tag{2.21}$$

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

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

Thus

$$J^G_S = \frac{1}{K}\left[B^G_{\alpha^G} - C^G_{\alpha^G}\right], \tag{2.22}$$

where

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

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 above equation 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 to water reserves in Lake Volta is equal to the net marginal benefit of water consumption. Now, for notational simplicity, we denote

$$\frac{1}{K}\left[{B^G}_{\alpha^G} - {C^G}_{\alpha^G}\right] = A^G(\alpha^G, \alpha^B). \tag{2.23}$$

Now, differentiating equation (2.21) with respect to the state variable S for the optimal values of the control variables α^G and α^B, one finds

$$rJ_S^G = H_S^G + \frac{1}{\mathrm{d}t}E\left[\mathrm{d}J_S^G\right] + \lambda. \tag{2.24}$$

Substituting J_S^G from (2.22) in (2.24),

$$\frac{1}{\mathrm{d}t}E\left[\mathrm{d}A^G\right] = rA^G - H_S^G + \lambda. \tag{2.25}$$

Using Itô's formula once again,

$$\mathrm{d}A^G = {A^G}_{\alpha^G}\mathrm{d}\alpha^G + \frac{1}{2}{A^G}_{\alpha^G\alpha^G}(\mathrm{d}\alpha^G)^2. \tag{2.26}$$

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

$$\begin{aligned}\mathrm{d}\alpha^G = {} & \frac{\partial\alpha^G}{\partial S}\mathrm{d}S + \frac{\partial\alpha^G}{\partial W^B}\mathrm{d}W^B + \frac{\partial\alpha^G}{\partial R}\mathrm{d}R \\ & + \frac{1}{2}\frac{\partial^2\alpha^G}{\partial W^{B2}}(\mathrm{d}W^B)^2 + \frac{1}{2}\frac{\partial^2\alpha^G}{\partial R^2}(\mathrm{d}R)^2.\end{aligned}$$

Replacing $\mathrm{d}S, \mathrm{d}W^B$, and $\mathrm{d}R$ and using the properties of Wiener processes, we have

$$(\mathrm{d}\alpha^G)^2 = \left[\sigma^{B2}W^{B2}\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]\mathrm{d}t.$$

Thus from equation (2.26)

$$\mathrm{d}A^G = {A^G}_{\alpha^G}\mathrm{d}\alpha^G + \frac{1}{2}{A^G}_{\alpha^G\alpha^G}\left[\sigma^{B2}W^{B2}\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]\mathrm{d}t.$$

Using the differential operator $\frac{1}{\mathrm{d}t}E$ on the both sides of the above expression, we can rewrite the equation (2.25) as

$$rA^G - H^G_S - \lambda = A^G{}_{\alpha^G}\frac{1}{\mathrm{d}t}E\left[\mathrm{d}\alpha^G\right] + \frac{1}{2}A^G{}_{\alpha^G\alpha^G}\left[\sigma^{B2}W^{B2}\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right].$$

For the existence of an equilibrium in the long run steady state distribution the conditions

$$\frac{1}{\mathrm{d}t}E\left[\mathrm{d}S\right] = \frac{1}{\mathrm{d}t}E\left[\mathrm{d}\alpha^G\right] = 0,$$

must be satisfied.

Hence

$$\lambda = rA^G - H^G_S - \frac{1}{2}A^G{}_{\alpha^G\alpha^G}\left[\sigma^{B2}W^{B2}\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]. \tag{2.27}$$

The above equation (2.27) establishes another optimality condition. It can be interpreted by saying 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 opportunity cost of the water consumption. The opportunity cost of water consumption includes the benefits forgone for hydropower generation from higher water abstraction in the upstream, $[H^G_S]$ and also incorporates a term related to the instantaneous variance rate, $\left[\frac{1}{2}A^G{}_{\alpha^G\alpha^G}\left[\sigma^{B2}W^{B2}\left(\frac{\partial\alpha^G}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial\alpha^G}{\partial R}\right)^2\right]\right]$. 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 events of climate change. It leads us to determine the effect on Ghana's optimal water abstraction rate α^G with the changes in variances σ^B, and σ^R during the extreme events. Two possible outcome may occur. First, under low extreme events (drought) in both the countries, Ghana may decrease its water abstraction in upstream to keep the stock of water in Akosombo Dam above the critical level so that hydropower generation is not affected. But this will certainly affect the benefit, B^G, from the water abstraction (mainly from agriculture in upstream Ghana). The other possibility is that under low extreme events, Ghana may increase its water abstraction to maximize its benefit B^G from the water abstraction. In such circumstances, partial hydropower will be generated, and the rest of the needed power can be bought from other countries.

From (2.27), it is evident that the nature of the marginal benefit function plays an important role to evaluate the sign of $\frac{d\alpha^G}{\mathrm{d}\sigma^{B2}}$, and $\frac{d\alpha^G}{\mathrm{d}\sigma^{R2}}$; and thus to determine which action that Ghana will take for higher uncertainty in water flow caused by climate change. Let us assume that the marginal benefit function A^G is convex. Since $K > 0$, and the net benefit function $B^G - C^G$ is concave,we have $A^G > 0, A^G{}_{\alpha^G} < 0, A^G{}_{\alpha^G\alpha^G} > 0$. We also assume that all third and higher order derivatives of A^G are zero. Note that in the long run steady state equilibrium as the scarcity value of reserve water will tend to zero or $\mathrm{d}\lambda = 0$. Then totally differentiating equation (2.27) with respect to S, α^G, σ^{B^2}, and σ^{R^2} we get

$$\begin{aligned} 0 = &\Big[H^G_{SS} + A^G{}_{\alpha^G\alpha^G}\Big[\sigma^{B^2} W^{B^2} \frac{\partial \alpha^G}{\partial W^B}\frac{\partial^2 \alpha^G}{\partial S \partial W^B} + \sigma^{R^2} R^2 \frac{\partial \alpha^G}{\partial R}\frac{\partial^2 \alpha^G}{\partial S \partial R}\Big]\Big]\mathrm{d}S \\ &+ A^G{}_{\alpha^G\alpha^G} W^{B^2}\Big(\frac{\partial \alpha^G}{\partial W^B}\Big)^2 \mathrm{d}\sigma^{B^2} + A^G{}_{\alpha^G\alpha^G} R^2 \Big(\frac{\partial \alpha^G}{\partial R}\Big)^2 \mathrm{d}\sigma^{R^2} \\ &- rA^G{}_{\alpha^G}\mathrm{d}\alpha^G. \end{aligned} \tag{2.28}$$

This gives,

$$\begin{aligned} \frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}} = &\frac{1}{rA^G{}_{\alpha^G}}\Big[H^G_{SS} + A^G{}_{\alpha^G\alpha^G}\Big[\sigma^{B^2} W^{B^2} \frac{\partial \alpha^G}{\partial W^B}\frac{\partial^2 \alpha^G}{\partial S \partial W^B} \\ &+ \sigma^{R^2} R^2 \frac{\partial \alpha^G}{\partial R}\frac{\partial^2 \alpha^G}{\partial S \partial R}\Big]\Big]\frac{\mathrm{d}S}{\mathrm{d}\sigma^{B^2}} + \frac{1}{rA^G{}_{\alpha^G}} A^G{}_{\alpha^G\alpha^G} W^{B^2}\Big(\frac{\partial \alpha^G}{\partial W^B}\Big)^2 \\ &+ \frac{1}{rA^G{}_{\alpha^G}} A^G{}_{\alpha^G\alpha^G} R^2 \Big(\frac{\partial \alpha^G}{\partial R}\Big)^2 \frac{\mathrm{d}\sigma^{R^2}}{\mathrm{d}\sigma^{B^2}}. \end{aligned} \tag{2.29}$$

A similar expression can also be found from (2.28) for $\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{R^2}}$.

Note that the relationship between Ghana's water abstraction rate α^G with the flow variables W^B which is the water resources in upstream Burkina Faso is positive $[\frac{\partial \alpha^G}{\partial W^B} > 0]$. On the other hand, the assumption of $\frac{\partial^2 \alpha^G}{\partial S \partial W^B} < 0$ makes more sense, since it signifies that an decrease (increase) in stock S of water in Akosombo Dam strengthen (weaken) the relationship between the water abstraction rate α^G with the flow variable W^B. By the similar arguments $\frac{\partial \alpha^G}{\partial R} > 0$ and assume $\frac{\partial^2 \alpha^G}{\partial S \partial R} < 0$. Suppose that the variances of water flow in the upstream σ^B, and the variance of runoff in the downstream country, σ^R is uncorrelated, or, $\frac{\mathrm{d}\sigma^{R^2}}{\mathrm{d}\sigma^{B^2}} = 0$.

Then under the above mentioned assumptions, from (2.29) we get the following results,

$$\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}} < 0, \text{ and } \frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{R^2}} < 0, \quad \text{for low extremes where } \frac{\mathrm{d}S}{\mathrm{d}\sigma^{B^2}} < 0.$$
$$\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}} > 0, \text{ and } \frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}} > 0, \quad \text{for high extremes where } \frac{\mathrm{d}S}{\mathrm{d}\sigma^{B^2}} > 0.$$

If the marginal benefit function A^G is concave, then under the same assumptions as above, from (2.29) we have the following results,

$$\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}} > 0, \text{ and } \frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{R^2}} > 0, \quad \text{for low extremes where } \frac{\mathrm{d}S}{\mathrm{d}\sigma^{B^2}} < 0.$$
$$\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}} < 0, \text{ and } \frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}} < 0, \quad \text{for high extremes where } \frac{\mathrm{d}S}{\mathrm{d}\sigma^{B^2}} > 0.$$

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 the water abstraction to ensure sufficient water flows to Lake Volta during lower water realization. If the marginal benefit of water consumption is concave, then the Ghana's welfare will increase much from higher water consumption, and this may lead Ghana to increase water abstraction. In the case with high extremes or higher realization of water flow, opposite outcomes were observed. These results can be presented as a Proposition.

Proposition 2.2. *Let us assume that the marginal benefit function of water withdrawal for Ghana is convex. We also assume that* $\frac{\partial^2\alpha^G}{\partial S\partial W^B} < 0$*, and* $\frac{\partial^2\alpha^G}{\partial S\partial R} < 0$*. Then there exists a optimal value for the water abstraction rate of Ghana, which will decrease or increase with the increase in variances during low or high extreme events respectively.*

Remark 2.3. *If we assume that the marginal benefit function* A^G *is convex,* $\frac{\partial^2\alpha^G}{\partial S\partial W^B} > 0$*, and* $\frac{\partial^2\alpha^G}{\partial S\partial R} > 0$*. Then from* (2.29)*, we see that the signs of* $\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B^2}}$ *and* $\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{R^2}}$ *can not be determined clearly.*

It is pertinent to understand how Ghana may response to Burkina Faso 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.

Proposition 2.4. *The downstream country will decrease its water abstraction with increase in the water abstraction rates of the upstream country. The rate of decline will be higher with increase in variance in water supply caused by climate change.*

Proof. We totally differentiate the equation (2.27) with respect to S, α^G, and α^B, rearrange the terms and assume in the long run steady state equilibrium $\mathrm{d}\lambda = 0$,

$$\frac{\mathrm{d}\alpha^G}{\mathrm{d}\alpha^B} = \frac{1}{rA^G_{\alpha^G}} \Big[H^G_{SS} + A^G_{\alpha^G\alpha^G} \Big[\sigma^{B^2} W^{B^2} \frac{\partial \alpha^G}{\partial W^B} \frac{\partial^2 \alpha^G}{\partial S \partial W^B} + \sigma^{R^2} R^2 \frac{\partial \alpha^G}{\partial R} \frac{\partial^2 \alpha^G}{\partial S \partial R} \Big] \Big] \frac{\mathrm{d}S}{\mathrm{d}\alpha^B} - \frac{A^G_{\alpha^B}}{A^G_{\alpha^G}}. \tag{2.30}$$

Let us assume that the marginal benefit function of water withdrawal for Ghana is convex. We also assume that $\frac{\partial^2 \alpha^G}{\partial S \partial W^B} < 0$, and $\frac{\partial^2 \alpha^G}{\partial S \partial R} < 0$. Then

$$A^G_{\alpha^G} < 0, \quad \frac{\mathrm{d}S}{\mathrm{d}\alpha^B} < 0,$$
$$H^G_{SS} + A^G_{\alpha^G\alpha^G} \Big[\sigma^{B^2} W^{B^2} \frac{\partial \alpha^G}{\partial W^B} \frac{\partial^2 \alpha^G}{\partial S \partial W^B} + \sigma^{R^2} R^2 \frac{\partial \alpha^G}{\partial R} \frac{\partial^2 \alpha^G}{\partial S \partial R} \Big] < 0,$$

We also find that,

$$A^G_{\alpha^B} < 0, \text{ if } \left(B^G_{\alpha^G} - C^G_{\alpha^G}\right)_{\alpha^B} < 0,$$
$$\text{and } \left(B^G_{\alpha^G} - C^G_{\alpha^G}\right) < \frac{K}{\bar{W}^B} \left| \left(B^G_{\alpha^G} - C^G_{\alpha^G}\right)_{\alpha^B} \right|.$$

Then from equation (2.30), $\frac{\mathrm{d}\alpha^G}{\mathrm{d}\alpha^B} < 0$, which implies with increase in water abstraction in Burkina Faso, Ghana will decrease its own water abstraction. Moreover we see that, from equation (2.30), with increase in uncertainty (or, with increase in variances), the value of $\frac{\mathrm{d}\alpha^G}{\mathrm{d}\alpha^B}$ will become more and more negative. Taking the differentiation of $\frac{\mathrm{d}\alpha^G}{\mathrm{d}\alpha^B}$ with respect to σ^{B^2} in (2.30), we get

$$\frac{\mathrm{d}^2 \alpha^G}{\mathrm{d}\alpha^B \mathrm{d}\sigma^{B^2}} = \frac{A^G_{\alpha^G\alpha^G}}{rA^G_{\alpha^G}} W^{B^2} \frac{\partial \alpha^G}{\partial W^B} \frac{\partial^2 \alpha^G}{\partial S \partial W^B} \frac{\mathrm{d}S}{\mathrm{d}\alpha^B}. \tag{2.31}$$

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 get $\frac{\mathrm{d}^2 \alpha^G}{\mathrm{d}\alpha^B \mathrm{d}\sigma^{B^2}} < 0$. It means higher variance will increase the slope of the reaction function, $\frac{\mathrm{d}\alpha^G}{\mathrm{d}\alpha^B}$ and Ghana will react more by decreasing its water abstraction if there is an increase in water abstraction in the upstream, Burkina Faso. □

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 cooperation setting, where Ghana offers a discounted price for hydropower export to the upstream country, Burkina Faso, for more water in the downstream. We formulate the problem in the framework of a Differential Stackelberg leader-follower game to determine the optimal share of water between Ghana and Burkina Faso, and to explore the conditions of sustainability of cooperation in water sharing with respect to increasing variances in water flow from climate change.

In the model Burkina Faso, as a leader moves first, and it *a-priori* knows that follower country, Ghana, observes its actions and moves accordingly. We follow the usual way to solve the Stackelberg leader-follower game, where we first solve the follower's problem to maximize its pay-off function; and then using follower's reaction function, the leader's objective function is maximized[5]. 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 sub game-perfect equilibrium for every possible value of $S(t)$, and the strategy defines an equilibrium set of decisions dependent of previous actions.

In this section, we denote Burkina Faso's benefit or net consumer surplus from power imported from Ghana as $H^B(S,\alpha^B)$. It is a function of the stock of the water at Lake Volta, S as higher stock will reduce the price of power at which Ghana is exporting to Burkina Faso. This will allow Burkina Faso to gain from higher S. However, the benefit, H^B, also depends on Burkina Faso action of restricting water abstraction. If Burkina Faso increases its water abstraction then Ghana will increase the price of power, and it will reduce the net consumer surplus of Burkina Faso. The net consumer surplus or economic benefit from power, $H^B(S,\alpha^B)$, is thus a function of both stock of water and its own rate of water abstraction. Hence $\frac{\partial H^B}{\partial S} > 0$ and $\frac{\partial H^B}{\partial \alpha^B} < 0$[6]. 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

[5] 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.

[6] 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 not only depends on stock S, but also on its own action α^B.

the degree of cooperation between the countries. If H^B is large, then the true net benefit of Burkina Faso will take into account more of the benefits gained from cooperating with Ghana. If H^B tends to zero, then the cooperative case degenerates into the original non-cooperative situation as modeled in section 2 of the paper.

As part of the agreement, Burkina Faso cooperates with Ghana, in increasing the level of water level at Lake Volta, by reducing or restricting its water abstraction. Suppose Burkina Faso, the leader announces to the follower a policy rule that it will use throughout the game. Let this policy rule be denoted by $\alpha^B(t) = \phi^B(S(t))$. The follower, 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 knowing this reaction function, then chooses among all possible rules $\phi^B(\cdot)$ one 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 [5]. One of the ways to resolve this problem is to restrict the space of functions from which Burkina Faso, the leader can choose the strategy $\phi^B(\cdot)$. One possible restriction is that $\phi^B(\cdot)$ can be a quadratic function of the state variable, the stock of water. Let the policy rule be denoted as

$$\alpha^B = \phi^B(\cdot) = aS^2 + b, \tag{3.1}$$

where a and b are control parameters and independent of time[7].

3.1. **Ghana's Problem.** Given such response function of Burkina Faso, as given in (3.1), Ghana will maximize its net benefit as follows:

$$J^G = E\big[\max_{\alpha^G} \int_t^\infty e^{-r\tau} NB^G \mathrm{d}\tau\big], \tag{3.2}$$

where the net benefit function is given by[8]

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

subject to the state equation

$$\mathrm{d}S = (1-\alpha^G)[(1-\alpha^B)W^B + R]\mathrm{d}t,$$

[7]The policy rule also reflect the preferences that Burkina Faso expresses 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 non-linearities of such preference, we have assumed the policy rule as quadratic.

[8]As a follower Ghana is observing Burkina Faso's move and accordingly adjusting the discount price for power to export, and hence Ghana's Hydropower function H^G depends only on stock of water, S.

and other constraints given in the equations (2.1), (2.3), (2.5), and (3.1). Here we also assume that water reserves (S) exceeds the critical level ($\bar{S}$), i.e. $S \geq \bar{S}$.

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

$$rJ^G = \max_{\alpha^G} \left\{ NB^G + \frac{1}{\mathrm{d}t} E\left[\mathrm{d}J^G\right] + \lambda(S - \bar{S}) \right\}, \tag{3.3}$$

where the parameter λ represents the scarcity value of water in the Dam.

Since $J^G = J^G(S, W^B, R)$, applying Itô's formula on J^G, using the equations (2.2),(2.3)and (2.6), and rearranging one can get an equation similar to (2.21),

$$\begin{aligned} rJ^G = \max_{\alpha^G} \Big\{ & B^G(w^G) + H^G(S) - C^G(\alpha^G) \\ & + (1-\alpha^G)[(1 - aS^2 - b)\bar{W}^B + \bar{R}] J^G_S \\ & + \frac{\sigma^{B2}}{2} E\left[W^{B2}\right] J^G{}_{W^B W^B} + \frac{\sigma^{R2}}{2} E\left[R^2\right] J^G{}_{RR} + \lambda(S - \bar{S}) \Big\}. \end{aligned} \tag{3.4}$$

Let us denote

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

Then differentiating the equation (3.4) with respect to α^G we can get the optimality condition,

$$B^G{}_{\alpha^G} - C^G{}_{\alpha^G} = K(a,b,S) J^G_S. \tag{3.5}$$

We denote

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

For notational simplicity, we will not write the functional dependence in every step. Now differentiating equation (3.4) with respect to the state variable S for the optimal values of the control variable α^G,

$$rA^G = H^G_S + \frac{1}{\mathrm{d}t} E\left[\mathrm{d}A^G(\alpha^G, a, b, S)\right] + \lambda.$$

We can proceed in the similar fashion as before (see Ghana's problem in the previous section) and in the long run steady state distribution (i.e. $\frac{1}{\mathrm{d}t} E\left[\mathrm{d}S\right] = \frac{1}{\mathrm{d}t} E\left[\mathrm{d}\alpha^G\right] = 0$) we obtain an expression of λ,

$$\lambda = rA^G - H^G_S - \frac{1}{2} A^G(\alpha^G, a, b, S)_{\alpha^G \alpha^G} \left[\sigma^{B2} W^{B2} \left(\frac{\partial \alpha^G}{\partial W^B} \right)^2 + \sigma^{R2} R^2 \left(\frac{\partial \alpha^G}{\partial R} \right)^2 \right]. \tag{3.6}$$

The above equation leads us to derive the optimal Markov strategy of Ghana, and to evaluate the latter country's 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 3.1. *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 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 at Lake Volta from the change in water abstraction of Burkina Faso. Under such situation, Ghana will increase it water abstraction to prevent Burkina Faso to gain from further increasing water abstraction under agreement.*

Proof. We totally differentiate equation (3.6) with respect to S, α^G, a, b, rearrange the terms and assume in the long run steady state equilibrium $\mathrm{d}\lambda = 0$,

$$\frac{\mathrm{d}\alpha^G}{\mathrm{d}a} = \frac{1}{rA^G{}_{\alpha^G}}\Big[-rA^G{}_S + H^G_{SS} + A^G{}_{\alpha^G\alpha^G}\Big[\sigma^{B^2} W^{B^2} \frac{\partial\alpha^G}{\partial W^B}\frac{\partial^2\alpha^G}{\partial S\partial W^B} + \sigma^{R^2} R^2 \frac{\partial\alpha^G}{\partial R}\frac{\partial^2\alpha^G}{\partial S\partial R}\Big]\Big]\frac{\mathrm{d}S}{\mathrm{d}a} - \frac{A^G{}_b}{A^G{}_{\alpha^G}}\frac{\mathrm{d}b}{\mathrm{d}a} - \frac{A^G{}_a}{A^G{}_{\alpha^G}}. \tag{3.7}$$

Let us assume that the parameters a and b are mutually independent so that $\frac{\mathrm{d}b}{\mathrm{d}a}$ is zero. As before, we also assume that the marginal benefit function A^G is convex, $\frac{\partial^2\alpha^G}{\partial S\partial W^B} < 0$, and $\frac{\partial^2\alpha^G}{\partial S\partial R} < 0$. Then we find that for $a > 0$, the sign of $\frac{\mathrm{d}S}{\mathrm{d}a}$ and the expression in the bracket on the right hand side of the above equation are both negative, and $A^G{}_a > 0$.

Then the following results hold:

If

$$rA^G{}_a < \Big[-rA^G{}_S + H^G_{SS} + A^G{}_{\alpha^G\alpha^G}\Big[\sigma^{B^2} W^{B^2} \frac{\partial\alpha^G}{\partial W^B}\frac{\partial^2\alpha^G}{\partial S\partial W^B} + \sigma^{R^2} R^2 \frac{\partial\alpha^G}{\partial R}\frac{\partial^2\alpha^G}{\partial S\partial R}\Big]\Big]\frac{\mathrm{d}S}{\mathrm{d}a}, \tag{3.8}$$

then

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

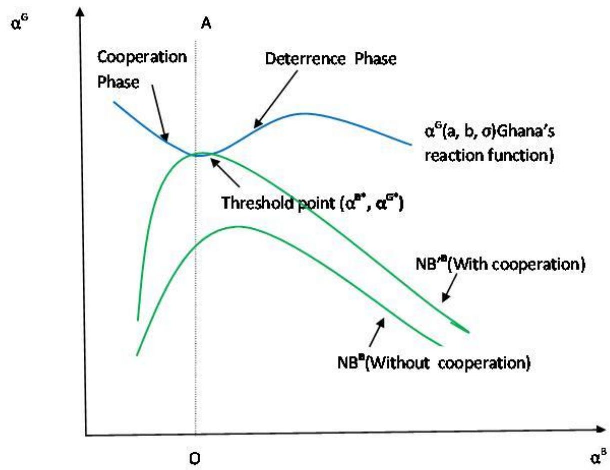

FIGURE 3. Response function of Ghana and Burkina Faso's Net Benefit Function

It suggests that, if decrease in Burkina Faso's water abstraction rate from higher cooperation (i.e. part of the graph of Ghana's reaction function which is on the left of the vertical line OA in Fig 3.) decreases the marginal benefit of water consumption in agriculture for Ghana less than the decrease in marginal benefit from increase in the stock of water at Lake Volta, then Ghana will increase its water abstraction with further decrease in Burkina Faso's water abstraction(decrease in a for a given level of b). However, if the inequality sign of the condition (3.8) is reversed, then the change in marginal benefit of water consumption in agriculture will be more than the change in marginal benefit of water stock at Lake Volta from an increase in water abstraction rate of Burkina Faso, and we get

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

It implies that under such condition, Ghana will increase its water abstraction with increase in water abstraction of Burkina Faso. If we differentiate both sides of (3.7)with respect to a, we observe that $\frac{\mathrm{d}^2\alpha^G}{\mathrm{d}a^2} > 0$ for low values of a (i.e. in the left part of the line OA) and $\frac{\mathrm{d}^2\alpha^G}{\mathrm{d}a^2} < 0$ for high values of a ((i.e. in the right part of the line OA). It suggests that 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 3 . It implies that for a high level of cooperation, Ghana will have an opportunity to increase water abstraction. However, if Burkina Faso increases it water abstraction during this period, Ghana will reduce its water abstraction initially, due to higher level of cooperation, to ensure sufficient amount of water flows to Lake Volta. However, after reaching a point called “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 from increase in water abstraction rate of Burkina Faso. Under such situation, Ghana will increase it water abstraction to deter Burkina Faso to gain further from increasing its water abstraction. Otherwise, if Ghana further decreases its water abstraction, then Burkina Faso can increase its water abstraction, and still enjoy the benefits of hydropower from higher stock of water. This phase can be labeled as a ”deterrence Phase”, and it will continue till the marginal benefits of Ghana from increasing its water abstraction with higher water abstraction of Burkina Faso is equal to its opportunity cost. After that Ghana will reduce its water abstraction again.

We get similar results for the relationship between α^G and b. Similar kind of condition (replace the derivatives with respect to a by b in inequality (3.8)) is also required to show $\frac{d\alpha^G}{db}$ is negative and positive for low and high values of b respectively.

□

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

$$J^B = E\big[\max_{a,b} \int_t^\infty e^{-r\tau} NB^B \mathrm{d}\tau\big], \tag{3.9}$$

where the net benefit function of Burkina Faso is given by

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

subject to the state equation

$$\mathrm{d}S = (1 - \alpha^G(a,b))[(1-\alpha^B)W^B + R]\mathrm{d}t,$$

and given other equations (2.1), (2.3), (2.5), (2.6), and (3.1). Here α^G is obtained from the optimality condition (3.5). The HJB equation for the above formulated problem can be written as:

$$\begin{aligned} rJ^B = \max_{a,b} \Big\{ & B^B(w^B) + H^B(S,\alpha^B) - C^B(\alpha^B) \\ & + (1-\alpha^G)[(1-aS^2-b)\bar{W}^B + \bar{R}]J^B_S \\ & + \frac{\sigma^{B2}}{2} E\left[W^{B2}\right] J^B{}_{W^BW^B} + \frac{\sigma^{R2}}{2} E\left[R^2\right] J^B{}_{RR} \Big\}. \end{aligned} \tag{3.10}$$

As before we denote

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

Then differentiating the equation (3.5) with respect to a and b we can get the optimality conditions,

$$B^B{}_a - C^B{}_a + H^B{}_a - K(a,b,S)\frac{\partial \alpha^G}{\partial a} J^B_S - (1-\alpha^G)S^2\bar{W}^B J^B_S = 0, \tag{3.11}$$

$$B^B{}_b - C^B{}_b + H^B{}_b - K(a,b,S)\frac{\partial \alpha^G}{\partial b} J^B_S - (1-\alpha^G)\bar{W}^B J^B_S = 0. \tag{3.12}$$

From the above two equations one obtains

$$\begin{aligned} J^B_S &= \frac{B^B{}_b - C^B{}_b + H^B{}_b}{K\frac{\partial \alpha^G}{\partial b} + (1-\alpha^G)\bar{W}^B} = \frac{B^B{}_a - C^B{}_a + H^B{}_a}{K\frac{\partial \alpha^G}{\partial a} + (1-\alpha^G)S^2\bar{W}^B}, \\ &:= A^B(\alpha^G, a, b, S). \end{aligned} \tag{3.13}$$

The above equation can be interpreted by saying that during cooperation at the margin, the value of the water stock at Lake volta for Burkina Faso is equal to its opportunity cost of increasing water abstraction in terms of agricultural benefits forgone.

Now differentiating equation (3.10) with respect to the state variable S for the optimal values of the control variables α^G, a and b,

$$rA^B = H^B_S + \frac{1}{\mathrm{d}t} E\left[\mathrm{d}A^B\right].$$

Finally in the long run steady state distribution (i.e. $\frac{1}{\mathrm{d}t}E\left[\mathrm{d}S\right] = \frac{1}{\mathrm{d}t}E\left[\mathrm{d}a\right] = \frac{1}{\mathrm{d}t}E\left[\mathrm{d}b\right] = 0$) we obtain the following expression,

$$rA^B = H^B_S + \frac{1}{2}A^B{}_{aa}\left[\sigma^{B2}W^{B2}\left(\frac{\partial a}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial a}{\partial R}\right)^2\right] + \frac{1}{2}A^B{}_{bb}\left[\sigma^{B2}W^{B2}\left(\frac{\partial b}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial b}{\partial R}\right)^2\right]. \tag{3.14}$$

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, $\left[\frac{1}{2}A^B{}_{aa}\left[\sigma^{B2}W^{B2}\left(\frac{\partial a}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial a}{\partial R}\right)^2\right] + \frac{1}{2}A^B{}_{bb}\left[\sigma^{B2}W^{B2}\left(\frac{\partial b}{\partial W^B}\right)^2 + \sigma^{R2}R^2\left(\frac{\partial b}{\partial R}\right)^2\right]\right]$. The sign of the latter term depends on the convexity of net marginal benefit from cooperation.

Note that the optimal $a^\star$ and $b^\star$ can be achieved from the optimality conditions (3.11)-(3.12). 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.

Proposition 3.2. *Let us assume that the marginal benefit function of water withdrawal for Burkina Faso is convex.Then there exists an optimal value for the water abstraction rate of Burkina Faso, which will decrease or increase during low extreme events with the increase in variances at higher and lower level of water abstraction respectively.*

Proof. 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,

$$\frac{\mathrm{d}a}{\mathrm{d}\sigma^{B2}} = \frac{X_1\frac{\mathrm{d}S}{\mathrm{d}\sigma^{B2}} + X_2}{rA^B_a - H^B_{Sa}}, \quad \frac{\mathrm{d}a}{\mathrm{d}\sigma^{R2}} = \frac{X_1\frac{\mathrm{d}S}{\mathrm{d}\sigma^{R2}} + X_3}{rA^B_a - H^B_{Sa}}, \tag{3.15}$$

where

$$X_1 = \Big[-rA^B{}_S + H^B_{SS} + A^B{}_{aa}\Big\{\sigma^{B2}W^{B2}\frac{\partial a}{\partial W^B}\frac{\partial^2 a}{\partial S\partial W^B} + \sigma^{R2}R^2\frac{\partial a}{\partial R}\frac{\partial^2 a}{\partial S\partial R}\Big\} + A^B{}_{bb}\Big\{\sigma^{B2}W^{B2}\frac{\partial b}{\partial W^B}\frac{\partial^2 b}{\partial S\partial W^B} + \sigma^{R2}R^2\frac{\partial b}{\partial R}\frac{\partial^2 b}{\partial S\partial R}\Big\}\Big],$$

$$X_2 = \frac{1}{2}\Big[A^B{}_{aa}W^{B2}\Big(\frac{\partial a}{\partial W^B}\Big)^2 + A^B{}_{bb}W^{B2}\Big(\frac{\partial b}{\partial W^B}\Big)^2\Big],$$

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

Let us assume that the marginal benefit function $(B^B - C^B + H^B)_{\alpha^B}$ 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 (3.13), $A^B_S > 0, A^B_a < 0, A^B_{aa} > 0$, 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 $X_3 > 0$[8]. 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, $\frac{da}{d\sigma^{B2}} > 0$ 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 where 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, $\frac{da}{d\sigma^{B2}} < 0$ 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 (3.14) with respect to S, b, σ^B, and σ^R and rearranging the terms

[8]We omit details of mathematical calculations for interested readers. Determination of signs are not trivial, but one has to understand and identify the effect of large and small terms in an expression to determine the exact sign.

to get,

$$\frac{\mathrm{d}b}{\mathrm{d}\sigma^{B2}} = \frac{X_1 \frac{\mathrm{d}S}{\mathrm{d}\sigma^{B2}} + X_2}{rA^B_b - H^B_{Sb}}, \quad \frac{\mathrm{d}b}{\mathrm{d}\sigma^{R2}} = \frac{X_1 \frac{\mathrm{d}S}{\mathrm{d}\sigma^{R2}} + X_3}{rA^B_b - H^B_{Sb}}, \tag{3.16}$$

and proceeding in a similar manner as above one has the similar results.

Then for $\alpha^{B\star} = \alpha^B(a^\star, b^\star)$,we get

$$\frac{\mathrm{d}\alpha^B}{\mathrm{d}\sigma^{B2}} = \frac{\mathrm{d}\alpha^B}{\mathrm{d}a}\frac{\mathrm{d}a}{\mathrm{d}\sigma^{B2}} + \frac{\mathrm{d}\alpha^B}{\mathrm{d}b}\frac{\mathrm{d}b}{\mathrm{d}\sigma^{B2}} = S^2\frac{\mathrm{d}a}{\mathrm{d}\sigma^{B2}} + \frac{\mathrm{d}b}{\mathrm{d}\sigma^{B2}}.$$

Using the above equation and combining the above results 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 $\frac{\mathrm{d}S}{\mathrm{d}k} < 0, k = \sigma^{B2}, \sigma^{R2}$), $\frac{\mathrm{d}\alpha^B}{\mathrm{d}k} > 0$, for $\frac{\mathrm{d}\alpha^G}{\mathrm{d}i} << 0, (i = a, b)$ (i.e. for low values of a^* and b^*). But $\frac{\mathrm{d}\alpha^B}{\mathrm{d}k} < 0$ for $\frac{\mathrm{d}\alpha^G}{\mathrm{d}i} > 0, (i = a, b)$ (i.e. for high values of a^* and b^*). □

Given the Markovian strategy of Ghana and optimal level of water abstraction, we can deduce the optimal level of water abstraction in Ghana. We are in a position to determine the effect of climate change on optimal water abstraction of Ghana.We demonstrate the conditions and evaluate the effect of changes in variances σ^B and σ^R on α^G.

Proposition 3.3. *Let us assume that the marginal benefit function of water withdrawal for Ghana is convex. We also assume that* $\frac{\partial^2\alpha^G}{\partial S\partial j} < 0$ *for* $j = W^B, R$. *Then there exists an optimal value for the water abstraction rate of Ghana, which will decrease in low extreme event (drought), with the increase in variances. However, the rate of decline will be lesser with lower water abstraction rate of Burkina Faso.*

Proof. Totally differentiating the equation (3.6) with respect to S, α^G, a, b, σ^{B^2}, and σ^{R^2}, we find

$$\frac{\mathrm{d}\alpha^G}{\mathrm{d}\sigma^{B2}} = \frac{X_4\frac{\mathrm{d}S}{\mathrm{d}\sigma^{B2}} - rA^G{}_a\frac{\mathrm{d}a}{\mathrm{d}\sigma^{B2}} - rA^G{}_b\frac{\mathrm{d}b}{\mathrm{d}\sigma^{B2}} + X_5 + X_6\frac{\mathrm{d}\sigma^{R2}}{\mathrm{d}\sigma^{B2}}}{rA^G{}_{\alpha^G}}. \tag{3.17}$$

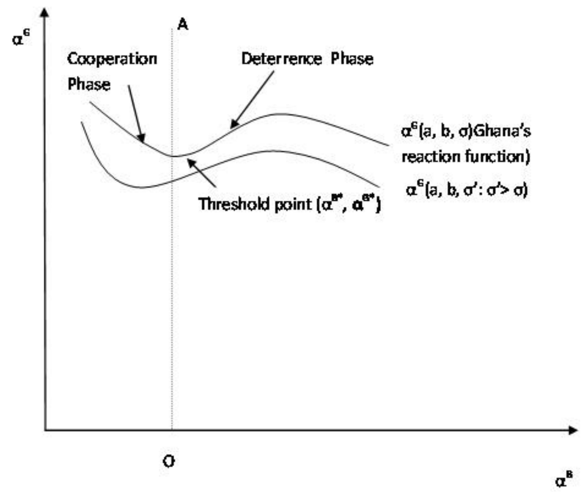

FIGURE 4. Change in response function of Ghana with changes in σ

where

$$X_4 = -rA^G{}_S + H^G_{SS} + A^G{}_{\alpha^G\alpha^G}\Big[\sigma^{B2} W^{B2} \frac{\partial \alpha^G}{\partial W^B}\frac{\partial^2 \alpha^G}{\partial S \partial W^B}$$
$$+ \sigma^{R2} R^2 \frac{\partial \alpha^G}{\partial R}\frac{\partial^2 \alpha^G}{\partial S \partial R}\Big],$$
$$X_5 = \frac{1}{2} A^G{}_{\alpha^G\alpha^G} W^{B2}\Big(\frac{\partial \alpha^G}{\partial W^B}\Big)^2,$$
$$X_6 = \frac{1}{2} A^G{}_{\alpha^G\alpha^G} R^2\Big(\frac{\partial \alpha^G}{\partial R}\Big)^2.$$

A similar expression can also be found for $\frac{d\alpha^G}{d\sigma^{R2}}$. 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 (3.17) by using the proposition 3.2 we obtain the following results,

$\frac{d\alpha^G}{dk} < 0, (k = \sigma^{B^2}, \sigma^{R^2})$, 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 $\frac{di}{dk} < 0$. □

4. Conclusion

In this paper we have studied how countries can cooperate in a sustainable way given the effects of climate change. The motivation of this study is based on the the perception that climate change increases the variability in water flow and might exacerbate conflict between countries sharing same river basin. We illustrate the case of water sharing of the Volta River between the upstream and downstream countries, Burkina Faso and Ghana respectively, where Ghana faces a tradeoff of water use between agriculture in the north and production of hydro energy in the south. In the framework of a stochastic Stackelberg differential game, we have shown how the issue of water sharing could be linked to hydropower export, that can make water sharing between the countries sustaining in the event of climate change. We consider that the downstream country, Ghana, offers a discounted price for energy export to the upstream country, Burkina Faso, to restrict its water abstraction rate in the upstream. We model water availability as stochastic process and focus on the scope and sustainability of cooperation. We find that without cooperation Ghana will decrease its water abstraction with increasing variance in drought situations to ensure sufficient water flows to Lake Volta for Hydropower generation. This holds under the case where the marginal benefit function of Ghana is convex. However cooperation will give Ghana an opportunity to increase water abstraction for agriculture without losing water at Lake Volta. If Burkina Faso increases it water abstraction, then Ghana will reduce its water abstraction initially due to higher level of cooperation. However, after a certain point where the change in the marginal benefit of water consumption in agriculture is equal to the change in marginal benefit from higher water stock, it will increase it water abstraction to prevent Burkina Faso to gain from increasing water abstraction under agreement. We also find that the equilibrium strategies in the long run steady state distribution are stable even with increasing variances of water flow; and the optimal value for the water abstraction rate of Burkina Faso will decrease or increase during low extreme events with the increase in variances at higher and lower level of water abstraction of Burkina Faso respectively.

We present our summary of the results under the cooperation and non-cooperation cases in the tabular form:

Without co-operation	With co-operation
Marginal Benefit of Burkina Faso convex; $\sigma \uparrow \Rightarrow \alpha^B \uparrow$. irrespective of low or high extreme events.	Marginal Benefit of Burkina Faso convex; $\frac{\partial^2 \alpha^B}{\partial S \partial j} < 0$ for $j = W^B, R. \Rightarrow \alpha^{B^*}$ exists. low extreme: $\sigma \uparrow \Rightarrow \alpha^B \downarrow$ at higher level of water abstraction of Burkina Faso. $\sigma \uparrow \Rightarrow \alpha^B \uparrow$ at lower level of water abstraction of Burkina Faso.
Marginal Benefit of Ghana convex; $\frac{\partial^2 \alpha^G}{\partial S \partial j} < 0 \Rightarrow \alpha^{G^*}$ exists. low extreme: $\sigma \uparrow \Rightarrow \alpha^G \downarrow$.	Marginal Benefit of Ghana convex; $\frac{\partial^2 \alpha^G}{\partial S \partial j} < 0 \Rightarrow \alpha^{G^*}$ exists. low extreme: $\sigma \uparrow \Rightarrow \alpha^G \downarrow$ 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.
For a given $\sigma : \alpha^B \uparrow \Rightarrow \alpha^G \downarrow$.	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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