Optimal Management of Runoff Reservoir Supply:

The Case of Tono Reservoir in Northern Ghana

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Abstract

Erratic rainfall, within and between years, leads to high uncertainty in runoff reservoir operations in many Sub-Sahara African (SSA) countries. Severe food shortages attributed to drought affect millions of vulnerable households, particularly those whose livelihoods depend on agriculture. We construct and successfully simulate a stochastic dynamic model of a small runoff reservoir fashioned after the Tono Reservoir in Northern Ghana. Our model considers a reservoir authority who at the beginning of each season observes the stock of water in the reservoir and, in the wet season, the amount of rainfall, and must decide how much water to release from the reservoir for irrigation and how much acreage to irrigate in order to maximize returns to the agriculture over the three growing seasons. We drive optimal irrigation policies with and without access to emergency groundwater pump irrigation systems and with and without access to rainfall index insurance. The optimal irrigation policies including reservoirs operation policy, deficit irrigation management, and the available water resource allocation could be used to provide decision support for water resources management. Besides, the strategies obtained could help with the risk analysis of reservoirs operation stochastically.

Key Words – Erratic rainfall, runoff reservoir, optimal irrigation policies, index insurance, Ghana

1. Introduction

Erratic rainfall, within and between years, leads to high uncertainty in runoff reservoir operations in many Sub-Sahara African (SSA) countries. Severe food shortages attributed to drought affect millions of vulnerable households, particularly those whose livelihoods depend on agriculture.

In most SSA' countries, small reservoirs supplied exclusively by rainfall runoff are used for supplemental irrigation during the wet season and for full irrigation during the dry season. Weather variability presents acute challenges to the management of most runoff reservoirs, and, in some areas, increasingly so due to climate change. Reservoir authorities often face limited options during droughts, constrained by competing and conflicting interests such as domestic and agricultural demand, and new demands to satisfy environmental requirements (Brown and Carriquiry, 2007). Frequent and sustained droughts often force small reservoirs to reduce the area they irrigate or to shut down altogether until rainfalls return. So how should SSA reservoir authorities manage water supply in the presence of uncertain and increasing demand of water?

The high economic and social costs of hydrologic variability, such as groundwater utilization and the construction and expansion of reservoirs, beg for innovative alternatives. A common approach in the literature is to design optimal irrigation policies based on stochastic dynamic programming models (Dudley, Howell and Musgrave, 1971b, 1971a; Dudley and Musgrave, 1988; Dudley, 1988b, 1988a; Rao, Sarma, and Chander, 1990; Dudley and Hearn, 1993; Unami, Yangyuoru, Alam and Kranjac-Berisavljevic, 2013; Houba, Pham Do and Zhu, 2014). Stochastic dynamic programming allows planners to develop useful insights into the economic impact of random inflows in the reservoir operation. However, the application of formal models only attenuates the consequences of water supply shortages, without eliminating them. Therefore, there is a clear need to explore alternative mechanisms for managing weather risk faced by reservoir authorities.

In developed countries, market-based arrangements such as water rights (sales and temporary leases), water banks and option contracts can be used to address uncertainty in the supply of water. In countries where these markets exist, high value water users can compensate low value users for the right to use their water in times of water shortages. However, in SSA, these markets do not exist or are in early stages of development. Moreover, widespread droughts tend to affect all water users simultaneously within national and regional boundaries, limiting the effectiveness trade of water rights. There is thus a need to find alternative methods for shifting risk outside of national boundaries to the global market. Risk-sharing tools such as rainfall index insurance have the potential to transfer water supply risk to international reinsurers, and thus promote more efficient allocation of water in the SSA, not only over space, but also over time (Leiva and Skees, 2008).

Groundwater pump irrigation (GWPI) is an emerging technology in SSA countries that offers an expensive but reliable means to address severe shortfalls in rainfall and releases of irrigation water from reservoirs. GWPI systems, which are based on lifting or pumping water from the ground for irrigation, allow farmers to access water on demand and to make autonomous production decisions. However, GWPI is expensive, as it requires energy drawn from diesel, petrol, or electricity. The main constraints to the development and utility of GWPI systems are the costs of investing in drilling technology, lack of access to affordable energy and lack of access to credit to finance emergency GWPI operations. Most smallholder farmers cannot afford groundwater pump technology or cover the variable costs of its operation during water emergencies. However, investing in GWPI is within the means of processors, reservoir authorities and nuclear farmers who enter into marketing contracts with large numbers of smallholder farmers, especially if the smallholder famers are willing to cover some of the costs through subscription fees.

In this paper, we explore optimal reservoir irrigation policies when GWPI is available to complement rainfall and reservoir water when is needed. We also explore the use of rainfall index insurance to finance the costs of ground water pumping during times of severe droughts. Index insurance is a relative new financial risk transfer tool whose use in water management, particularly in SSA, has not been thoroughly studied. Rainfall index insurance could be used to smooth the costs of addressing water shortfalls through GWPI. There is a growing literature and practical experiences with the use of index insurance to protect weather-related risks in developing countries (Skees and Zeuli, 1999; Agarwal, 2002a and b; World Bank, 2005; Skees, 2008; Miranda and Gozalez-Vega, 2011; Miranda and Farrin, 2012)). However, few studies have examined the potential use of index insurance to hedge water supply risk in irrigated agriculture.

We construct and successfully simulate a stochastic dynamic model of a small runoff reservoir fashioned after the Tono Reservoir in Northern Ghana. Our model considers a reservoir authority who at the beginning of each season observes the stock of water in the reservoir and, in the wet season, the amount of rainfall, and must decide how much water to release from the reservoir for irrigation and how much acreage to irrigate in order to maximize returns to the agriculture over the three growing seasons. We drive optimal irrigation policies with and without access to emergency GWPI systems and with and without access to rainfall index insurance. We parameterize the model to reflect the operational conditions of the Tono Reservoir, the Ghana larger irrigation scheme, using available data on reservoir size, irrigation area, returns to water input, and rainfall. We solve the model numerically using orthogonal polynomial collocation methods.

2. Previous Studies on Reservoir Index Insurance

The stochastic nature of reservoir water supply is a major source of risk in irrigated agriculture and has been the subject of many studies in the agricultural economics and engineering literature. However, the main focus has been on release rules under risk and the size of the reservoir as the primary means for managing these risks (Dudley, Howell and Musgrave, 1971b, 1971a; Dudley and Musgrave, 1988; Dudley, 1988b, 1988a; Rao, Sarma, and Chander, 1990; Dudley and Hearn, 1993; Unami, Yangyuoru, Alam and Kranjac-Berisavljevic, 2013; Houba, Pham Do and Zhu, 2014). The risks of inflows of water into a reservoir represent a significantly large risk that impact a large number of individuals at the same time (Leiva and Skees, 2008).

Access to an efficient risk-transfer mechanism is an important economic tool. When producers are able to transfer some portion of their risk exposure, through mechanisms like insurance, they are more likely to specialize, adopt new technologies, and make product or management specific investments that can enhance long-term productivity. Risk averse decision makers for example are less likely to make such investments without the aid of risk transfer given their preference for more predictable, although lower, income (Leiva and Skees, 2008). Index insurance is a relative new risk transfer tool in the financial market that has not be given enough interest in SSA's countries especially in water management and conservation related area. Reservoir index insurance design effectively smooths the costs of water uncertain availability outside the irrigation schemes. Reservoir index insurance provides a nonstructural alternative for satisfying water supply needs during drought. Reservoir index insurance presents a mechanism for smoothing the variability in supply costs that result from relying on market transactions for supply augmentation in drought years. While there is a growing literature and practice focus on the role and potential of index insurance to protect weather-related risks in developing countries (World Bank, 2005; Skees, 2008; Miranda and Gozalez_vega, 2011; Miranda and Farrin, 2012), very few studies have looked at the potential of index insurance to hedge water supply risk in irrigated agriculture fields (Skees and Zeuli, 1999; Agarwal, 2002b, a; Brown and Carriquiry, 2007; Leiva and Skees, 2008).

Skees and Zeuli (1999) study the potential of a rainfall index insurance to protect stakeholders in Australia from the impacts of variability in reservoir storage levels. As noted by Leiva and Skees (2008), despite the fact that Skees and Zeuli explained in excess of 70% of the variance in water levels in the reservoir as a function of the rainfall on three stations surrounding it, the meaning of the findings is unclear. One particular caveat of thier study is the fact that the reservoir storage level is the underlying index. Because the reservoir storage level variable is the outcome of reservoir management decisions, it is subject to manipulation and variable subject to manipulation are also subject to moral hazard problem in insurance. Agarwal (2002b, 2002a) in their study faced the same problem as Skees and Zeuli (1999) while using water tables as the underlying index. Given their strong correlation with groundwater availability, water tables have also been proposed as indexes. Water tables index and the reservoir level index share the same limitation as they are subject to human manipulation and hence the distributions of insurance payouts.

Leiva and Skees (2008) are the first authors to our knowledge to study the use of insurance to protect irrigation water supply risks based on reservoir inflows. The authors looked at the feasibility of introducing reservoir inflow insurance in the management of Rio Mayo Valley reservoir in Mexico as a way for farmers to protect the risk that they will not have enough water to irrigate their crops. Reservoir inflows are directly related to water availability for farming, and are not subject to manipulation by interested parties. While it is true that reservoir inflows are exogenous, indexing rainfall to account for reservoir inflows is not an easy task. Brown et Carriquiry (2007), following Leiva and Skees (2008), explore the performance of reservoir index insurance as risk management strategy for water managers to effectively smooths water supply costs of weather variability for both agriculture and urban water through an option contract purchase of water in drought years. The option contract was designed for the case of two bulk water users, one domestic water supply and the other irrigated agriculture and the insurance indexed on reservoir inflows was proposed as a complementary mechanism for smoothing the variable costs of market provision of water. They applied this to the case of Angat reservoir, the primary water supply for the city of Manila, Philippines and a large irrigation system. Contrary to Skees and Zeuli (1999), Agarwal (2002b, 2002a) and Leiva and Skees (2005), Brown and Carriquity (2007) focus on insurance as a risk management strategy for water managers against large outlays using market or market-like transfers to meet a city's water demand in drought years.

There are no study of an index insurance developed to protect reservoir water supply risk in SSA to our knowledge. In contrary to Brown and Carriquity (2007), this paper analyses the performance of a framework that combines optimal release of water, optimal planting and reservoir rainfall insurance to reduce rainfall variability-induced impacts on reservoir authorities and users. The paper further explore optimal reservoir irrigation policies when groundwater pump irrigation is available to complement rainfall and reservoir water when is needed with the potential to use rainfall index insurance to finance the costs of ground water pumping during times of severe droughts.

3. Irrigation in Ghana and the Tono Irrigation Scheme

Agriculture contributes about 22% of GDP in Ghana and employs 56% of the economically active population. Approximately 2.74 million households are involved in farming, and smallholder farms account for about 80% of the total agricultural output. Only about 38% of agricultural land in Ghana is cultivated and productivity is generally low. Ghana is endowed with sufficient water resources, and estimates of Ghana's irrigation potential range from 0.36 to 2.9 million ha depending on the degree of water control. However, Only 0.4 % of the total cultivated land is irrigated (Statistics, Research and Information Directorate, 2015)[1]. Ghana also has over 56,000

[1] SRID, (2011). Agriculture in Ghana. Facts and Figures 2010. Statistics, Research and Information Directorate (SRID), Ministry of Food and Agriculture, Accra. Ghana.

groundwater abstraction systems (Kortatsi et al. 1995) but its use is still less than 5% of the average annual groundwater recharge in most of the basin (IWMI, 2010)[2].

Currently, there are twenty two irrigations project all over Ghana covering a total of 6,505 hectares (ha). In addition to this, there are twenty two schemes constructed under the Small Scale Irrigation Development Project (SSIDP) and six schemes under the Small Farms Irrigation Project (SFIP). Each of these projects is less than 1,000 ha in size with the exception of the Tono and Kpong Irrigation Projects. The benefits of the irrigation system, however, are more evident in three semi-arid regions of North Ghana (Northern, Upper East and Upper West), circumstantial to the dictates of the semi-arid climatic conditions, rainfall is unreliable in terms of onset, duration, intensity (Dinye and Ayitio, 2013). Thus, the region is characterized by uni-modal rainfall of short duration and excessive evapotranspiration[3] allowing only 4 to 5 months of farming and 7 to 8 months of extended dry season. The main beneficiaries of the irrigation projects have been indigenous small-scale farmers. The outputs have however, not been very encouraging and the lack of maintenance of the projects have rendered most of the schemes unproductive.

The Tono irrigation scheme is a large scale irrigation project executed by the Ghana government through the Irrigation Company of Upper Region (ICOUR), a state enterprise. The Tono irrigation scheme (Figure 1) is a reservoir or storage based gravity-fed irrigation system located in Kassana-Nankana District of Upper East Region, Northern Ghana (coordinates 10052’11.67” N 1008’00.00”W).

The reservoir has a total capacity of 93 million m^3 covering a catchment area of 650 km^2 and supplying irrigation to 2,490 ha devoted primarily to the cultivation of paddy rice. The command area is spread across eight villages (Nonia, Wuru, Yogbania, Yigbwania, Korania, Gaani, Biu and Chuchuliga). There are approximately 4000 smallholder farmers cultivating under the reservoir and each farmers is allocated a plot of land between 0.2-0.6 ha (ICOUR, 2014).

The Tono reservoir collects ephemeral surface flow after torrential rains and seepage flow of subsurface water from the ground during the rainy season. Water from reservoir is diverted to the fields by gravity through intake structures and canal systems. The reservoir is equipped with a concrete spillway.

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[2] IWMI (2010). Agricultural Water management National Situation Analysis Brief: Ghana. DOI: http://awm-solutions.iwmi.org/Data/Sites/3/Documents/PDF/Country_Docs/Ghana/situationanalysisbriefghana.pdf

[3] Annual potential evapotranspiration is about 2000 mm in the north.

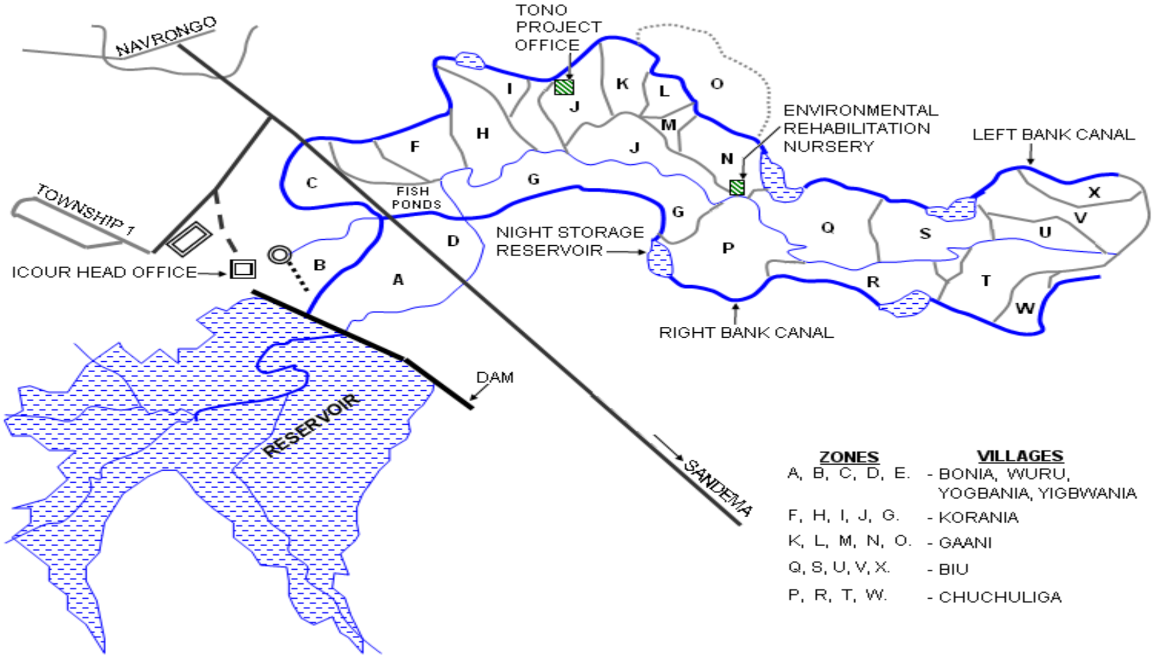

Figure 1: Tono irrigation scheme

In the irrigation scheme, the annual agricultural production cycle is divided into three growing seasons: a wet season (WS), during which rain falls on the land and flows into the reservoir and water from the reservoir is only used to supplement rainfall when rainfall falls to provide enough water for the crops, and two dry seasons (DS), during which it does not rain and agriculture is completely dependent on water released from the reservoir for irrigation. Water from the reservoir is used mainly for irrigation. During water shortages, irrigation must often be curtailed either through reductions in the area irrigated, or, in some years, suspension of irrigation water releases during one or both of the dry seasons.

On average, farmers plant 2490 ha in a year, with about 50% of the planting taking place in WS and about 50% in DS. In terms of cropping patterns, the WS carries the entire production of paddy rice the main crop of the scheme, in addition to a substantial proportion of maize groundnuts and sorghum. The DS has a more large varieties of crops, even though paddy rice is still the dominant crop, there is substantial large proportion of vegetable such as tomatoes, onions, as main crops.

The unreliable rainfall distribution pattern that at times gives rise to complete crop failure that do occur in most of the area to the tune of about one in every five years has many effects in the reservoir management (Friesen, 2002). In some years only part of the land is irrigated, and in some years no irrigation water is supplied during one or both of dry seasons. In 2014 for example the reservoir in dry season was completely shut down because of lack of water. Besides that, the schemes also faces challenges such as high cost of hiring farm machinery, poor water supply, ineffective technical assistance and lack of entrepreneurial skills (Dinye and Ayitio, 2013). Figure 2 shows the close relationship between water released from the reservoirs and the crop land irrigated in the Tono reservoir schemes. We observe with some few exceptions that even though the amount of water released is quiet depending on the amount of land cultivated, there are very inefficient.

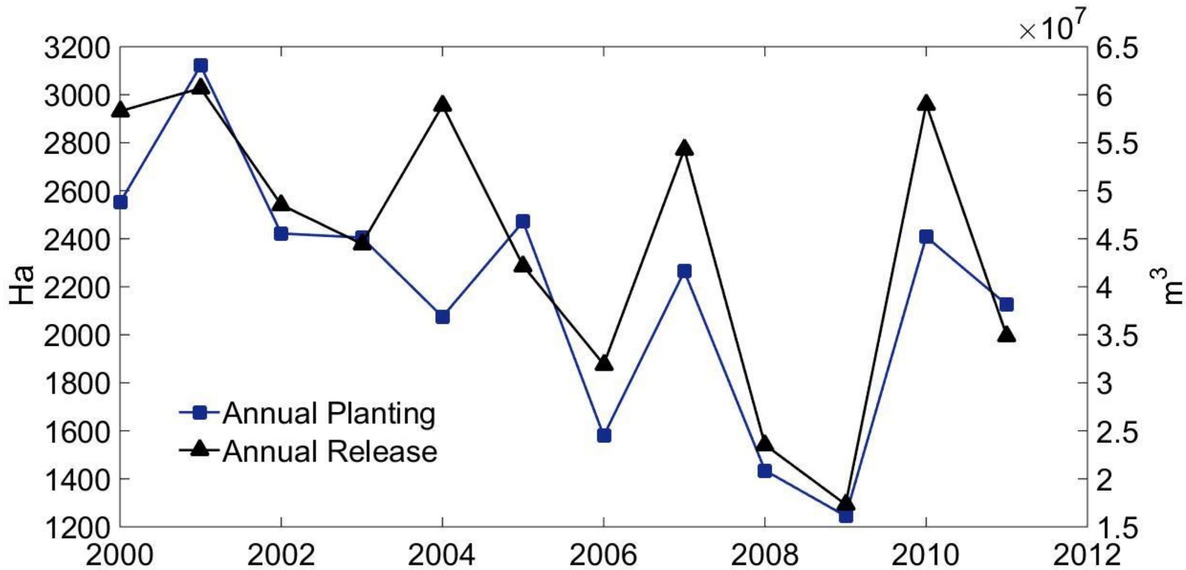

Figure 2. Annual plantings and annual releases in Tono irrigation scheme

In spite of the existence the reservoir, farm income in the reservoir scheme is by no means shielded from the vagaries of weather since the replenishment of the reservoir depends entirely on rainfall, a highly unpredictable hydrological variable. Figures 3&4 show the rainfall intensity and the water level of the reservoir. Approximately 22.6% of the water supply is lost due to evaporation (Hayford et al, 2007). Filling up of the reservoir during the rainy seasons significantly varies from year to year.

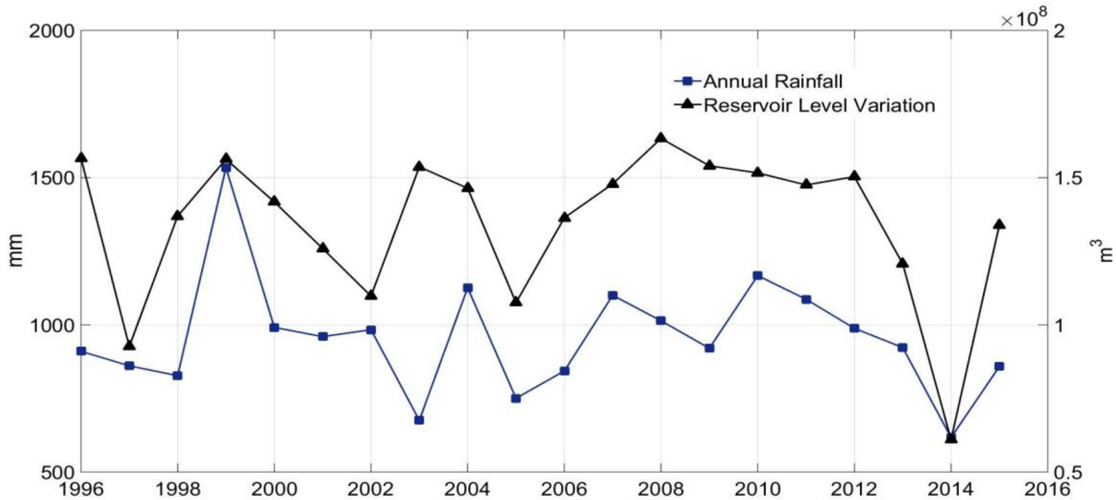

Figure 3. Annual rainfall and Reservoir level Variation in Tono irrigation scheme

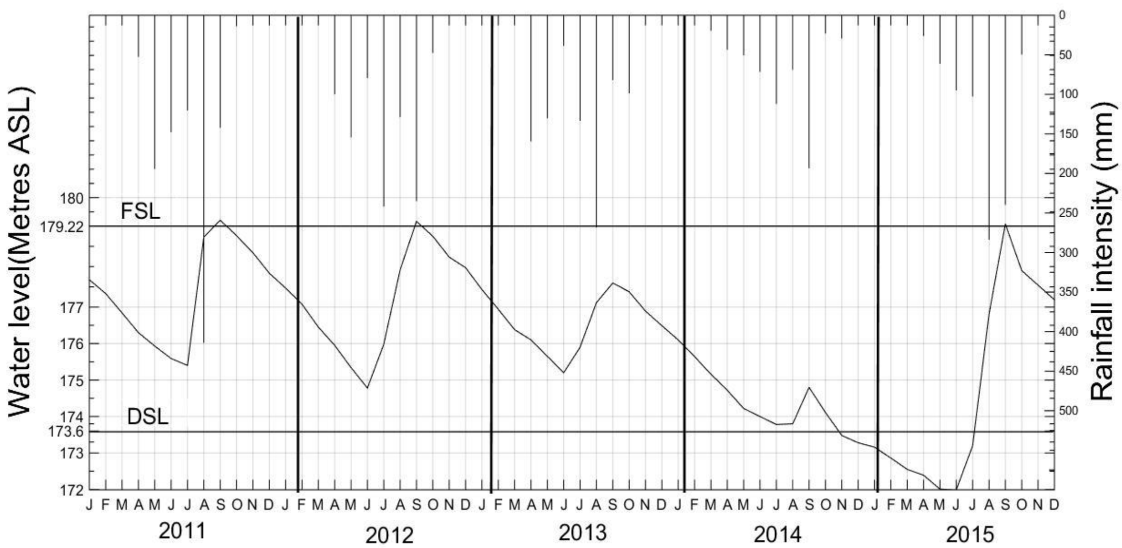

Figure 4. Observed time series data of rainfall intensity and water level of Tono reservoir

The full supply water level (FSL) is set as 179.22 meters above sea level ($93.10^6 m^3$), which is the crest level of the concrete spillway, while the dead-storage level (DSL) is 173.6 meters above sea level ($10.10^6 m^3$) as marked on the water level axis of Figure 4.

When the annual accumulation of inflows is not adequate to restock the reservoirs, water scarcity is felt throughout the rural economy, but rural smallholders bear the major burden due to a heavy reliance on irrigation to sustain their livelihoods. In essence, the annual variability of the water supply represents the most important source of risk for irrigated agriculture in the North of Ghana.

Although decision making in an irrigation district is an extremely complex process, two broad decision making levels can be identified that jointly determine all aspects of water use for irrigation purposes. First, there are decisions about how much water to release from a reservoir, which involves tradeoffs in space (e.g., demand from competing uses), time (e.g., water released for the current planning season is not available for future use), and subject to certain constraints (e.g., uncertain inflows and reservoir capacity). This decisions level is exclusively controlled by the dam authority (ICOUD). The second decision level involves distribution of the water stock across the different villages that make up the irrigation scheme. This is a critical decision level because there are opportunity costs for water used for different villages that make up the irrigation scheme.

4. Basic Model

Consider a water authority who must decide how much water to release from a reservoir for irrigation and how much land to irrigate in order to maximize benefits to the agricultural sector. The annual agricultural production cycle is divided into three growing seasons: a wet season, during which rain falls on agricultural land and flows into the reservoir, and two dry seasons, during which it does not rain and agriculture is completely dependent on water released from reservoir for irrigation.

Denote the wet season by $i=1$, the first dry season by $i=2$, and the second dry season by $i=3$. At the beginning of each season, the water authority observes the stock of water in the reservoir s and, in the wet season the amount of rainfall y, and must decide how much water q to release per unit of land from the reservoir for irrigation, and how much quantity of land to irrigate a. The benefit realized per unit of the agricultural land in the wet season is a function $f_1(q+y)$ of water released from the reservoir plus rainfall; the benefits realized during dry seasons 1 and 2 are exclusively functions $f_2(q)$ and $f_3(q)$ of the water released from the reservoir. The total benefit realized by the agricultural sector is a function $g(q,a)$ which involves the optimal amounts of both water and land for the existing crops.

$$g(a,q)=\max_{\substack{0\le a\le A\\0\le q\le s}}\left\{a^{1-\eta}.f(q)\right\}$$

where $\eta<1$ is water loss coefficient due to evaporation and infiltration in the canal. Annual rainfalls during the wet season $\tilde{y}\ge 0$ are i.i.d. Annual inflow into the reservoir $\gamma\tilde{y}$ is proportional to rainfall. The reservoir possesses a maximum capacity of $\bar{s}$; excess inflow is channelled away from the reservoir with neither cost nor benefit to the agricultural sector. Water in the reservoir experiences losses due to evaporation, and only a portion $\theta_i < 1$ of water retained in the reservoir in season *i* survives to the following season.

The water authority's optimal irrigation policy is characterized by three Bellman equations, one for each season i. Let $V_1(s, y)$ denote the maximum present value of current and expected future benefits from irrigation at the beginning of season 1, given the reservoir stock s and rainfall y; similarly, $V_2(s)$ and $V_3(s)$ denote the maximum present value of current and expected future benefits from irrigation at the beginning of seasons 2 and 3, respectively, given the reservoir stock s. Then:

$$V_1(s, \tilde{y}) = \max_{\substack{o \le a \le A \\ 0 \le q \le s}} \left\{ a^{1-\eta_1} . f_1(q + \tilde{y}) + \delta_1 V_2(\theta_1(s - a.q)) \right\}$$

$$V_2(s) = \max_{\substack{o \le a \le A \\ 0 \le q \le s}} \left\{ a^{1-\eta_2} . f_2(q) + \delta_2 V_3(\theta_2(s - a.q)) \right\}$$

$$V_3(s) = \max_{\substack{o \le a \le A \\ 0 \le q \le s}} \left\{ a^{1-\eta^3} . f_3(q) + \delta_3 E_{\tilde{y}} V_1(\min(\bar{s}, \theta_3(s - a.q) + \gamma\tilde{y}), \tilde{y}) \right\}$$

Here, δ_i denotes the discount over season *i*; these may differ, as the lengths of the growing seasons may not be uniform.

5. Computational Method and Application

To compute an approximate solution to the Bellman equation we use a collocation method, which consists of approximate the value function of the bellman equation by a linear combination of *n* known basis functions $\varphi_1, \varphi_2, ..., \varphi_n$ defined on the state space S whose coefficients $c_1, c_2, ..., c_n$ are to be determined:

$$V(s) \approx \sum_{j=1}^{n} c_j \phi_j(s)$$

We then determine the basis function coefficients $c_1, c_2, ..., c_n$ by requiring the value function approximation to satisfy the Bellman equation, not at all possible states, but rather at *n* judiciously chosen collocation nodes $s_1, s_2, ..., s_n$ in S. We can then rewrite the approximate form of the bellman equation as follow:

$$\sum_{j=1}^{n} c_j \varphi_j(s, \tilde{y}) = \max_{\substack{0 \le a \le A \\ 0 \le q \le s}} \left\{ a^{1-\eta_1} . f_1(q + \tilde{y}) + \delta_1 \sum_{j=1}^{n} c_j \phi_j(\theta_1(s - a.q)) \right\}$$

$$\sum_{j=1}^{n} c_j \varphi_j(s) = \max_{\substack{0 \le a \le A \\ 0 \le q \le s}} \left\{ a^{1-\eta_2} . f_2(q) + \delta_2 \sum_{j=1}^{n} c_j \phi_j(\theta_{21}(s - a.q)) \right\}$$

$$\sum_{j=1}^{n} c_j \varphi_j(s) = \max_{\substack{0 \le a \le A \\ 0 \le q \le s}} \left\{ a^{1-\eta_{31}} . f_3(q) + \delta_3 E_{\tilde{y}} \sum_{j=1}^{n} c_j \phi_j(\min(\bar{s}, \theta_3(s - a.q) + \gamma \tilde{y}), \tilde{y}) \right\}$$

The decision variables in the model are the cultivated areas and the irrigation releases per unit of land while the state variable is storage. We solve the model numerically using orthogonal polynomial collocation methods (Miranda and Fackler, 2002).

As a consequence of the discussions in the preceding sections, the model parameters are determined as summarized in Table 1.

Table1. Key parameters used for model of the Tono irrigation scheme

Season	S	A	τ	Y_{mean}	$W_{\min}$	σ	(1-θ)	β	γ
Wet	93.10^6 m^3	2490 ha	τ_1=0.4	894 mm	10.10^6 m^3	0.21	0.226		
Dry1	93.10^6 m^3	2490 ha	τ_2=0.3		10.10^6 m^3				
Dry2	93.10^6 m^3	2490 ha	τ_3=0.3		10.10^6 m^3				

Notes: S=Tono reservoir capacity; A=Tono reservoir command are surface; τ = Tono irrigation district length of seasons in years; Y_{mean}=Tono irrigation district mean annual rainfall (from 1980 to 2015); $W_{\min}$ = Minimum water requirements which corresponds to the dead-storage level (DSL). σ=Rainfall volatility calculated using the annual rainfall data for a period of 36 years (1980 t0 2015); (1-θ)=Annualized continuous evaporation rate; β = Per-acre benefit function decay term, per season; γ = Rainfall to reservoir inflow conversion factor. β and γ parameters are yet to be estimated.

6. Preliminary results

The results presented here are those of the basic scenario. We are still gathering the data for the parameterization of the model to reflect the operational conditions of the Tono Reservoir, the Ghana larger irrigation scheme. Table 2 below provides basis scenario parameters.

Table 2. Basic Scenario Parameters

Season	S	A	τ	Y_{mean}	$W_{\min}$	σ	(1-θ)	β	γ
Wet	3	1	τ_1=0.4	1.0	$W_{\min 1}$ =0.3	0.3	0.0	β_1=2	1
Dry1	3	1	τ_2=0.3		$W_{\min 2}$ =0.3		0.0	β_2=2	
Dry 2	3	1	τ_3=0.3		$W_{\min 3}$ =0.3		0.0	β_3=2	

1. Water Release and Agricultural Sector Benefit

We used a logistic function to describe the relationship between water availability and the per-acre benefit condition to the minimum water requirement. Deficit irrigation could result in the lower crop yields and reduce the net benefits of the irrigation district. However, it is unavoidable because of water resources shortage. Figure 5 below shows the benefit of the agricultural sector in respect to the quantity of water release per season. Rainfall appears to have a great impact on the agricultural sector benefit in wet season. In high rainfall scenario, the benefit of the agricultural sector is at 90 per cent of its maximum attainable benefit without release, compared to 70 and 50 per cent for average and low rainfall respectively. Therefore, during high rainfall very little quantity of water is needed to be released from the reservoir to supplement shortfall of rainfall on agricultural land compared to average and low rainfall scenario. Indeed, the result of the optimal release of water during wet season presented in figure 6 indicates that no release is needed during wet season when rainfall is high or average and less the 5 % of the available water in the reservoir is release during wet season when the rainfall is low.

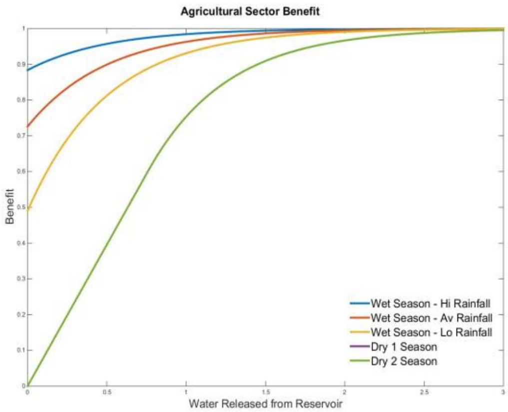

Figure 5. Agricultural Sector

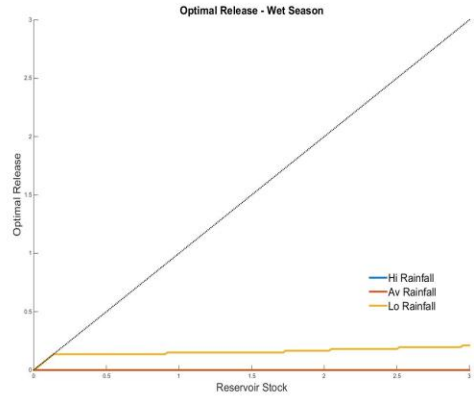

Figure 6. Optimal Release Wet

The benefit of the agricultural sector during dry season is entirely dependent on the quantity of water released from the reservoir (figure5). Figure 7 presents the optimal release of water for dry season. We observe that based on the stock of water in the reservoir at the beginning of the dry season, water can be released for both dry1 and dry2 seasons. As shown in figure 7, the priority dry season is dry season 1, dry season 2 is only.

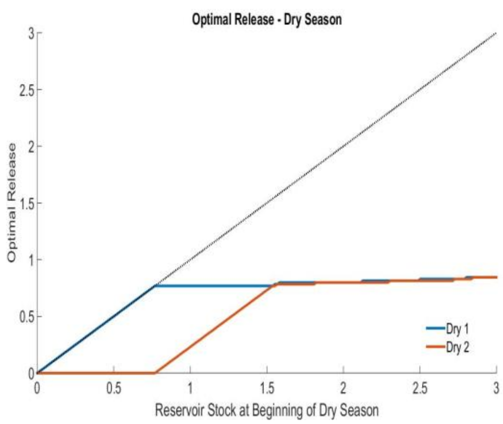

Figure 7. Optimal Release Dry season

2. Simulation of Water Release and Reservoir Levels

We simulated the optimal release and reservoir level for 15 years. Figure 8 and 9 present the results of the simulations for the optimal releases and reservoir levels respectively. As it is shown in figure 8, water is released every year for dry season while water is only released for 3 years out of 15 years for the wet season and every time that water is been released for wet season cropping, the second dry season cropping is compromised.

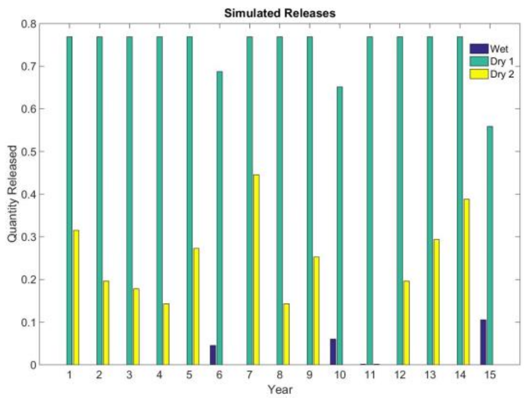

Figure 8. Simulated Water Releases

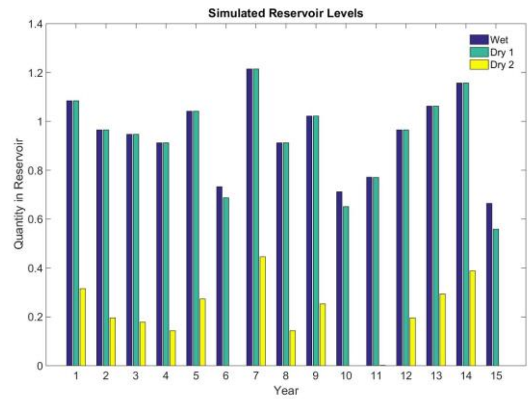

Figure 9. Simulated Reservoir

7. Preliminary Conclusion

This paper applies a stochastic dynamic model approach to the optimal water management of a runoff reservoir irrigation scheme consisting of a reservoir, a command area, and water intake facilities. The model considers a reservoir authority who at the beginning of each season observes the stock of water in the reservoir and, in the wet season, the amount of rainfall, and must decide how much water to release from the reservoir for irrigation and how much acreage to irrigate in order to maximize returns to the agriculture over the three growing seasons. No inflow is expected into the reservoir and the evaporation is extremely high during the dry seasons.

We found that deficit irrigation results in the lower crop yields and reduces the net agricultural benefits of the irrigation district. In many cases, sufficient water was available in the reservoir to meet the agricultural water demand for wet and the first dry season. However, many a time water was not available to supply the agricultural water demand for the second dry season.

The optimal irrigation policies including reservoirs operation policy, deficit irrigation management, and the available water resource allocation could be used to provide decision support for water resources management. Besides, the strategies obtained could help with the risk analysis of reservoirs operation stochastically.

Note: This paper is not to be cited as we are still working toward the results.

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