WATER MANAGEMENT IN BANGLADESH AGRICULTURE: OPTIMAL USE AND INVESTMENT POLICIES FOR ADAPTATION TO CLIMATE CHANGE

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Abstract

In Bangladesh, climatic change is likely to impact significantly upon surface and groundwater availability, as well as in other countries. The population of Bangladesh is projected to be double the current 2010 level by 2050. Demand for water will rise with the increasing demand for rice. This paper considers the optimal demand management of irrigation water with stochastic supply under climate change for a 3-year planning horizon. It also identifies the utilization of irrigation water from surface water sources to maximize the expected net social return from rice production. This is done by considering decision on dam release for rice production with reference to climate change. A stochastic dynamic programming model is developed for analyzing the levels and timing of the allocation of surface water for irrigation. The objective is to find the optimal dam release for irrigation which results in the maximum expected present value of the stream of annual net social return from rice production for the 3 years from 2012 to 2014. Net social return in a year consists of the value of rice consumed, measured by consumers' willingness to pay for rice, less the total cost of rice production. The paper also identifies the need for irrigation infrastructure and determines the optimal investment policies for the adaptation to climate change in Bangladesh agriculture.

Key words: climate change, dam release, dynamic programming

Introduction

The impacts of climate change on water requirement for agriculture are high on the research agenda worldwide. In Bangladesh, the effects of climate change on surface and groundwater resources will be severe (IPCC, 2007). The water related impacts of climate change have been identified by the National Adaptation Programme of Action (NAPA) be amongst the most critical for Bangladesh, particularly in relation to riverine and coastal flooding, but also in relation to increased winter droughts in some areas (MOEF, 2005). According to a study of Mirza et al. (1998) the annual rainfall trend has been increasing significantly since 1960, and the surface water of the country varies by season. Winter months, i.e., November to March, are very dry in Bangladesh due to low rainfall whereas about 95% of annual rainfall occurs during April to October. The annual renewable water of Bangladesh from all sources is 1211 cubic kilometer and out of this about 21 cubic kilometer from groundwater. The annual irrigation water requirement in the country is about 19 cubic kilometer (FAO, 2000).

Irrigated agriculture started in the early 1960s in Bangladesh in order to meet the increasing demand for food grains induced by rapidly growing population. The population of the country is about 162 million in 2009 and is projected to be about 215 million in 2040 (FAO, 2009). Demand for water will increase with the rising population for rice production. The water scarcity problem in Bangladesh becomes worse due to expansion and diversification of agricultural crops while maintaining self sufficiency in food grain production. Due to the shortage of surface water during the dry season, groundwater resources are heavily used and have led to a declining groundwater level. Climatic variability particularly which associated with low rainfall and upstream development of the river cause uncertain water availability in most of the irrigation projects that has been constructed since 1963.

To meet existing and upcoming future demands for irrigation water for the increasing population, water use for irrigation needs to be analyzed for making decisions on optimal dam release and expected change in rainfall patterns. In order to ensure the irrigation water availability considering climate change, new water use policies on constructing new infrastructures and building dams over existing policies should be evaluated by applying economic tools to ensure the maximum social return from irrigation water. Climate change is likely associated with reduction in river inflows and increase in the frequency of drought conditions also that is sometimes predictable.

Climatic uncertainty leads costly adaptations that will partially offset the adverse impact of climate change (Adamson et al. 2009, Connor et al. 2009; Griffith et al. 2009). The scientific evidence is now overwhelming: climate change presents very serious global risks, and demands an urgent global response (Stern, 2007). A large number of studies have been conducted aiming at assessing the nature and extent of climate change impact on water resources in specific regions (Jeuland, 2009; Nelson et al., 2009; Clarke, 2008; Vicuna (2007) ; Adamson et al., 2007). There is little research on how to incorporate possible impacts of climate change into future planning for adaptation in terms of construction of new infrastructures or building dams and possible dam releases. Climate change is a real problem now and it is happening according to the prediction of the scientists. Most of the literature based on the scenario of Bangladesh found about climate change, its vulnerabilities and adaptation are very descriptive in nature (Alam, 2003; Agrawala et al., 2003; Ramamasy and Bass, 2007). To date, few studies (climate change cell, 2009; Angus et al., 2009) conducted on mathematical modeling to manage the resources especially water resources to face with the diverse patterns of climate change.

The aim of the paper is to make decision on annual release of water for rice production dependent of current water availability considering climate change for which the present value of allocation is maximized.

Climate change scenarios for Bangladesh

Bangladesh is one of the most vulnerable countries to climate risks, being the most vulnerable to tropical cyclones. Between 1877 and 1995 Bangladesh was hit by 154 cyclones (including 43 severe cyclonic storms and 68 tropical depressions) – one severe cyclone every three to five years. A warmer and wetter future Bangladesh predicted by the General Circulation Models further increases the existing climatic risks, particularly when the climate state goes beyond historical variations. The median predictions from these models are for warming of 1.55^0C and increase in precipitation of 4% by 2050. Current trends for water levels in coastal areas suggest rise in sea levels of over 27 cm by 2050. Further, increased severity of cyclones in the Bay of Bengal is expected to increase risks of inundation in coastal areas by 2050 (World Bank, 2010). River flows have very large seasonal variations. In the monsoon the combined flow of the Ganges and the Brahmaputra reaches a peak between 80,000 to 140,000 m3/s in the July- August or early September period. (NWMP, 2000). Dependable flow (80%) in the Ganges (according to Ganges Water Treaty) can be less than 1,000 m3/s from February to April period. In the river

Brahmaputra flows (dependable) is less than 4,000 m3/s during March and April (NWMP, 2000).

As a signatory the UNFCCC and by following the global initiative, Bangladesh has instituted the preparation of the National Adaptation Program of Action (NAPA) for climate change in Bangladesh. In order to identify adaptation measures, Bangladesh has assumed the following climate change scenarios:

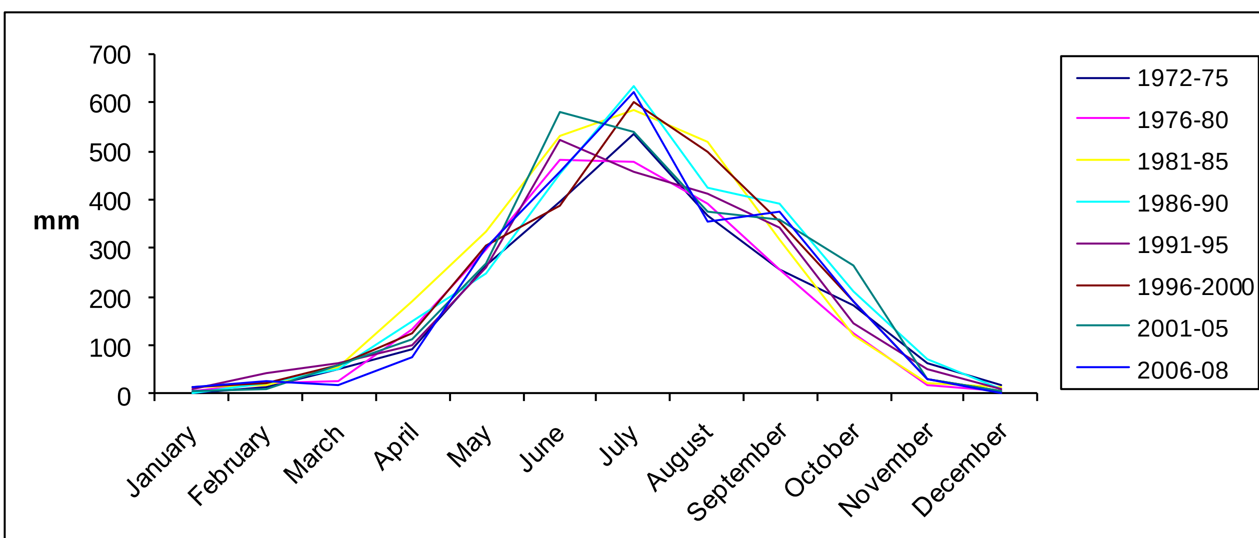
Table1: Climate change scenarios for Bangladesh

Year	Temperature increase (c^0)		Precipitation fluctuation compared to 1990 (%)	
	Monsoon	Winter	Monsoon	winter
2030	+0.8	+1.1	+6	-2
2050	+1.1	+1.6	+8	-5
2100	+1.9	+2.7	+12	-10

Source: Costal Development Strategy 2006, Water Resources Planning Organization, Ministry of Water resources, Bangladesh

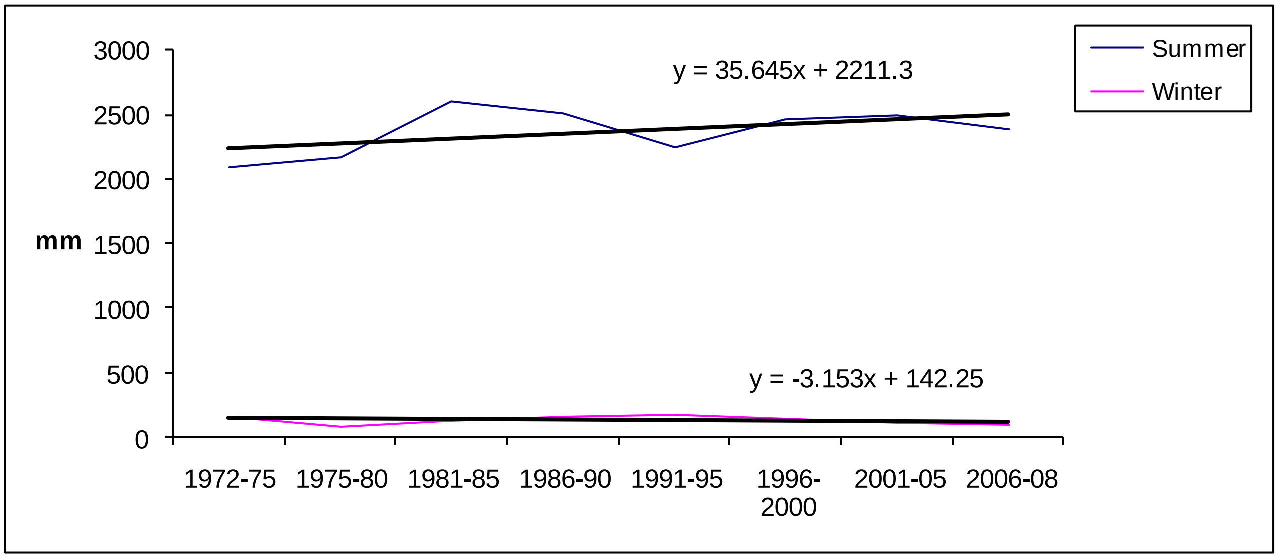
Climate change is a reality and it is a big challenge for Bangladeshi people and government to adaptation to climate change in relation with water resource management. Investment in building

Fig 1: Monthly distribution of Rainfall



winter rainfall shows decreasing trend (Table3). Summer rainfall shows increasing trend whereas winter rainfall showed decreasing trend from 1972-75 t0 2006-2008 (Fig 2).

Fig 2 Trend in summer and winter rainfall



Why is irrigation necessary?

Irrigation is a prerequisite for agricultural cultivation during the dry season because during this season rainfall considerably lower and without irrigation crops could not survive (Asiatic Society of Bangladesh 2006). Boro the dry season rice covers most of the rice production in Bangladesh. The development of irrigation infrastructure has contributed to the expansion of boro rice in both the traditional aus and the deepwater aman areas.

Table2: Trends in rice area, production and yield in different seasons, 1969-2008

Year	Boro rice (summer)			Aus rice (pre-monsoon)			Aman rice (monsoon)		
	Area (000 ha)	Production (000 tons)	Yield (t/ha)	Area (000 ha)	Production (000 tons)	Yield (t/ha)	Area (000 ha)	Production (000 tons)	Yield (t/ha)
1969–71	894	2,853	3.19	3,242	4,254	1.31	5,860	9,866	1.68
1979–81	1,127	3,648	3.23	3,127	4,692	1.50	5,937	11,348	1.91
1989–91	2,183	9,111	4.17	2,348	3,796	1.62	5,689	13,012	2.29
1999–01	3,646	16,750	4.59	1,367	2,634	1.93	5,740	15,202	2.65
2006–08	4,315	23,346	5.41	952	2,382	2.50	5,367	15,657	2.92

Table 2 shows the trend of rice production and contribution of boro rice in total rice production of Bangladesh (Hossain, 2009).

Data and Methodology

Sources and collection of data

Data (historical data on climatic factors, water availability, surface and groundwater irrigation, population and rice production) are being collected from the following organizations:

- Bangladesh Water Development Board (BWDB)
- Bangladesh Agricultural Development Corporation, Ministry of Agriculture(BADC)
- Bangladesh Meteorological Department (BMD)
- Bangladesh Bureau of Statistics (BBS)
- Food and Agricultural Organization (FAO)
- Institute of Water Modelling (IWM)
- International Water management Institute (IWMI)
- World Resource Institute (WRI)
- World bank (WB)
- Web and internet resources
- Other organizations that are dealing with water resource management.

Analytical techniques

Stochastic dynamic programming is used for solving optimization problems that include uncertainty. All decision making is based on the outcomes of alternative actions which can only be anticipated to some degree of accuracy. In stochastic problems, the state transformation depends not only on the state of the system and the decision taken, but also on unpredictable events outside the control of the decision maker (Kennedy, 1986 p. 51). A stochastic dynamic programming model will be used to determine the optimal annual application of irrigation water over a 3-year planning horizon given uncertain water availability.

Mathematical programming for optimization of natural resources

Mathematical programming has long been recognized as a vital modelling approach to solve optimizations problems. Currently, various types of mathematical programming are used for decision making and for optimization problems. Linear programming (LP) was the first technique and developed during the Second World War for military planning. There are wide ranges of uses of LP in the planning of economic development and agricultural policies for maximizing profit or minimizing costs with limited resources.

Quadratic programming and chance constrained programming and successfully used in many problems in policy and resource management areas after introducing LP. These techniques overcome some of the LP limitations (i. e., additivity, proportionality, continuity and finiteness). But those mathematical programming were not enough when considering multistage decision problem of resource management.

Introduction of dynamic programming

Bellman introduced dynamic programming in 1949 and is a very powerful dynamic algorithmic paradigm in which a problem is solve by identifying a collection of sub problems based on the principle of optimality:

> "*An optimal policy has the property that , whatever the initial state and initial decision are , the remaining decision must constitute an optimal policy with regard to the state resulting from the initial decision"* (Bellman, 1962 p.83).

State variables and decision variables are key variables in a dynamic programming problem. The complexity of dynamic programming can arise from the exponential growth in the number of possible histories as the number of possible states and possibly the number of decisions variables and decision stages increases. Bellman and Dreyfus (1962) referred to this exponential growth in the number of calculations as the curse of dimensionality.

There are many alternative mathematical approaches to the same problem. The problem of determining the optimal policy is a problem within the domain of adaptive control processes.

The theory of dynamic programming yields a systematic technique for formulating problems of this nature and for obtaining computational solutions (Bellman, 1961)

A time series with distribution parameters which change over time is called non- stationary. The source of the non-stationary in hydrological records can be natural catastrophe or periodicity (e. g., forest fires, el Niño, solar activities), anthropogenic activity (land use change due to deforestation and urbanization) or in changing climate (natural or anthropogenic). The states, decisions, stage return functions and state transition functions in the DP problem are not the same for all decision stages and the problem must be formulated as a finite stage problem.

Dynamic programming and natural resource management

Since the introduction of the dynamic programming theory, many texts on dynamic programming with management applications have appeared (Kennedy, 1986). A large number of books are available on dynamic programming in especially in business or industry related subjects (Beckman, 1968; Denardo, Eric, 1982; Bertsekas and Dimitri, 1987; Bertsekas et al., 1996; Nandalal and Bogardi, 2007 and Judd and Kenneth, 1998). Kennedy (1986) wrote a book on dynamic programming for agricultural and natural resources management from then the dynamic programming has been extensively using in solving multistage decision problems in agricultural and natural resource management.

Problem formulation

A model is formulated for optimal allocation of limited annual irrigation water applied to rice production over a given planning horizon taking account of climate variability and change based on changes in precipitation and temperature over time predicted by the IPCC. The management of irrigation water involves multistage decision making with stochastic event (rainfall). Net social return of rice production depends not only on the level of irrigation water applicated, but also on changing climatic factors. The optimal quantity of water to apply for rice production at each of 3 stages over a 3 years planning horizon from 2012 to 2014 is to be determined. The state variable is the amount of water available from storage at the beginning of the year. The stage return function is the expected social net return. Net social return in year t obtained from the value of water consumed that measured by consumers' willingness to pay less total cost of rice production. The amount of water applied in year *t*, (w_t) consists of surface water plus rainfall.

The state of the system at any point in time is described by state variables, water availability in a year (q).

The decision is the annual application of irrigation water (w_t) to be made at each decision stage t.

For simplicity, initially only one crop (rice) and one irrigation season for each decision stage over the planning horizon is considered.

Objective Function, $\underset{u_t}{Max}\ Z = \sum_{t=1}^{T} \alpha^{t-1}\Pi_t + \alpha^T F(q_{T+1})$ ……..…......…………...….(i)

Subject to $q_{t+1} = q_t - u_t + r_t$ ………………...….….……..(ii)

Initial water stock level, $q_1 = \bar{q}_1 > 0$ ………..................…...............................…..(iii)

Where,

t = 1, 2,…………..*T* years,

Π_t = net social return,

$\rho_t(j_t)$ = probability distribution of rainfall,

T = length of the planning horizon of 3years,

α = the discount factor,

$F(q_{T+1})$ = terminal value of irrigation water stock remaining at stage *T+1*

u_t = dam release at the beginning of year *t*

q_t = total amount of irrigation water available in dam at the beginning of year *t*

r_t = rainfall during year *t*

$$w_t = u_t + r_t \quad \text{……………………..………………..(iv)}$$

State transition function, $q_{t+1} = q_t - u_t + r_t$ ………….......................….….……...(v)

A linear demand function for rice is specified with price in period *t*

$$p_t = \eta + \varphi y_t \quad \text{……………..........................…………(vi)}$$

t = 1, 2,…………..T

where,

η and φ are parameters with (-ve) φ <0

p_t = price of rice at the end of year t

y_t = quantity of rice at the end of year t

The total willingness to pay (WTP) for consumption y_t is given by the area under inverse demand schedule:

$$WTP\{y_t\} = \int_0^{y_t} (\eta + \varphi y_t) dy_t \text{ ………………….................……….(vii)}$$

p_t = price of rice at the end of year t

y_t = yield of rice at the end of year t

Quadratic production function of rice is:

$$y_t = A + \phi w_t + \varepsilon w_t^2 \text{ ....(viii)}$$

where,

A= intercept of production function

w_t = irrigation water applied at time t

It is assumed that there is no cost of water charged over the seasons, whatever the amount applied. This is because the dam has been constructed by the start of season 1. The cost of the dam is a sunk fixed cost. It is assumed there are no variable costs are needed to release water.

Rainfall is a random variable in the year t that makes the objective function an expected value by affecting state transformation and stage return is independent and denoted by r_t. For a discrete formulation, r_t limited to a domain m rainfall levels. Allow the domain of r_t to be mapped into j_t, the range of integers 1 to *m*. The probability that *r* takes the *j*-th discrete value in its domain is denoted by $\rho_t(j_t)$. It is used to describe the stochastic process (Kennedy, 1986 p.51).

We are going to allow for changes in the level of the m rainfall levels in line with projected changes in rainfall based on climate change.

Expected net social return,

$$\prod = \sum_{t=1}^{T}\sum_{j_t=1}^{m_t}\rho_t(r_t(j_t))[WTP(u_t + r_t(j_t)) - p_t(y_t)]$$

$$= \sum_{t=1}^{T}\sum_{j_t=1}^{m}\rho_t(r_t(j_t))[[\int\{(\eta-\varphi)(A+\phi(u_t + r_t(j_t)) + \varepsilon(u_t + r_t(j_t))^2\}] - p_t(y_t)] \text{...(ix)}$$

where, Total willingness to pay (WTP) is a function of total water supplied, from release of water u_t and rainfall q_t less consumer payment $p_t(y_t)$. For each j_t values 1 to *m*, the probability of j_t is given by ρ_t, and a rainfall value q_t corresponds to j_t.

The corresponding recursive equation for solving the problem is

$$V_t\{q_t\} = \max_{u_t}\{\sum_{t=1}^{3}\sum_{j_t=1}^{3}\rho_t(r_t(j_t))[[\int\{(\eta-\varphi)(A+\phi(u_t + r_t(j_t)) + \varepsilon(u_t + r_t(j_t))^2\}] - p_t(y_t)] + \alpha V_{t+1}\{q_t - u_t + r_t(j_t)\}\}$$

.............(x)

(t = *3* to 1)

subject to $\sum_{j_t=1}^{3}\rho_t\{j_t\} = 1$ with $V_4(q_4) = 0$

A simple rice crop irrigation problem

A farmer grows rice in Boro season (January to April) in a year over three year planning horizon on 100 hectare. The yield of rice (in 400 tons per 100 hectare) is given by the estimated quadratic production function that is selected as yield and water response function. Quadratic production function is estimated by using national data from International Rice Research Institute analyzed by PASW18. Estimated yield water response function is:

$$y_t = 3484.79 + 0.13w_t - 0.000016w_t^2 \text{ ....(xi)}$$

(0.00) (0.02)

Irrigation water received by the rice crop in the *t*-th year depends on the height of the water released from storage at the beginning of each year (u_t in metres) and rainfall received during each season (r_t in centimeters). The dam is full at the beginning of the first season with a water height of 3 metre. The amount of water which can be released at the beginning of any season is limited to integer values of meters of water, and by the amount in storage. Rainfall augments the water in storage. The catchment area is 100 hectare, so 1 cm of rainfall raises the level of the dam (q_t) by 1 metre, provided the dam is not full.

Table 3: Rainfall probabilities

j	Decision stage					
	1		2		3	
	$p_1\{j_1\}$	r_1^j	$p_2\{j_2\}$	r_2^j	$p_3\{j_3\}$	r_3^j
1	0.25	2	0.25	1	0.25	0
2	0.50	3	0.50	2	0.50	1
3	0.25	4	0.25	3	0.25	2

Rainfall is treated as a random variable, r_t^j, where j =1, 2 or 3. In the t-th year, r_t^j occurs with probability $p_t\{j_t\}$ shown in Table 3. Expected rainfall in 2010, 2011 and 2012 are 3, 2, 1 cm, respectively. Expected rainfall is decreasing because rainfall showed decreasing trend in winter season and we are considering winter season for boro rice production.

The results are obtained from applying the equation recursively by using solution routines for solving general-purpose dynamic programming (generally referred as GPDP) problem written by Kennedy, 1986 and 1989.

Table 4 shows that if the dam is full at the start of the growing season, the maximum return is BDT. 220.26 million. In stage 3, the maximum return is BDT. 102.66 million. The optimal levels of dam release are R3, R2 and R3.

Table 4: Stochastic dynamic programming solution

Problem ---RISF---					
Problem parameters: No. of decision stages = 3 Rate of discount (per cent) = 5.26					
Stochastic Solution For Stage 3					
State		Decision		Stage Return	Expected Value
No.	Level	No.	Release		
1	L0	1	R0	27.38	27.38
2	L1	2	R1	54.76	54.76
3	L2	3	R2	82.14	82.14
4	L3	4	R3	102.66	102.66
Stochastic Solution for Stage 2					
State		Decision		Stage Return	Expected Value
No.	Level	No.	Release		
1	L0	1	R0	26.46	78.49
2	L1	2	R1	52.92	104.95
3	L2	3	R2	79.37	131.40
4	L3	3	R2	79.37	155.78
Stochastic Solution for Stage 1					
State		Decision		Stage Return	Expected Value
No.	Level	No.	Release		
1	L0	1	R0	31.98	156.32
2	L1	2	R1	51.16	175.50
3	L2	3	R2	76.74	201.08
4	L3	4	R3	95.91	220.26

Conclusion

In Bangladesh, rice covers the major portion of agricultural production. Growth of agriculture and the growth of the economy depend on the growth performance of the rice sector. Boro rice contributes a large share of rice production. As a dry season crop, irrigation is essential. The objective of the study is to make decision on the optimal water release of irrigation, based on the availability of annual water considering climate change. A stochastic dynamic programming model is developed based on irrigation water and probable rainfall patterns, with the objective of maximizing net social return.

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