# **Groundwater Level Declination in Bangladesh:**

## System dynamics approach to solve irrigation water demand during Boro season

by

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**Thesis**

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# FOREWORD

The experience I gathered through this thesis work would be worthy for my life. My first son born just before my thesis started. My son and my thesis have been gone through many difficulties. But it was tremendous patience and support from my wife and obviously my supervisor, professor ***Erling Moxnes*** kept me moving forward to accomplish this work. You will be always inspiration for the rest of my life.

# ABSTRACT

Groundwater has been declining in Bangladesh since introduction of deep tube wells (DTWs) and shallow tube wells (STWs) in late 1970s. Seasonal variation of groundwater has been shifted upto 4 meters during last 34 years. During Boro seasons groundwater table dropped drastically than other seasons. This study hypothesized that groundwater extraction is much higher than the natural recharge plus percolated irrigated water. Farmer´s perception is that if they dig deeper the supply would not be a problem, which led uncontrolled use of shallow tube wells (STWs) to extract water from lowered zones. This study selected an area that is 20 km away from Dhaka city having intensive Boro production. Analyzing the interview data (to know about the practices by farmers at present and before) and Bangladesh Water Development Board groundwater table data, we tried to simulate the problematic scenario with the help of simulation software called iThink. To address the problem 3 different policies have been investigated to achieve sustainable solution of the problem. The chosen policies were - (1) Harnessing only groundwater; (2) Alternative cropping; and (3) Depending more to surface water. The simulation results show that alternative cropping and going for surface water could solve the problem as well as able to restore the groundwater to its previous condition. But moving to surface water is a passive solution independent to farmers´ decision. Understanding the problem of groundwater declination by farmers was not so apparent. Farmers never thought of possibility of restoring groundwater table. The study suggested that alternative crop cultivation by replacing Boro rice would be the best sustainable solution not only to halt groundwater declination but also to restore the groundwater table.

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# 1. INTRODUCTION

Groundwater has been declining in Bangladesh since introduction of deep tube wells (DTWs) and shallow tube wells (STWs) in late 1970s. Seasonal variation of groundwater has been shifted upto 4 meters on average during last 34 years in our study area. During Boro seasons, groundwater table dropped drastically than other seasons. This study investigated how the problem emerged and could be solved sustainably in response to water stressed condition as well as rapid industrialization and urbanization.

## 1.1 Importance of the problem

Being rich in nutrients, minerals, and vitamins, rice has already become staple food for more than 3 billion people around the world. Now Bangladesh is the fourth largest rice producer in the world. Though declining its arable land since 1971, increasing rice harvesting area (10 million ha in 1995 to 12 million ha in 2010) and increasing yield (2,7 t/ha in 1995 to 4,3 t/ha in 2010) raise the production with the help of expanding irrigation projects over the country. (FAOSTAT, 2012). Especially, large abstraction of water by these irrigation projects has been causing a linear to exponential drop in groundwater level in north-western districts as well as major cities like Rajshahi, Dhaka and sub-urban areas where rice is produced extensively (Haque et al, 2007). Groundwater table is declining in those parts of the country in an unsustainable manner. There is growing concern in food security issue for satisfying demand for food over coming decades will be increasingly challenging (Ingram, 2011). Furthermore, the conversion of agricultural land to other uses is about 1% per year (Quasem, M.A., 2011).

Even though diverse constraints during 2012-2013 Bangladesh has become self-sufficient in rice production (Mainuddin, M & Kirby, M., 2015). To keep continue this success of rice production, irrigation becomes a serious concern as the groundwater started receding in different parts of the country. Growing population and limited arable land does not give us freedom to choose any other options rather than groundwater and surface water. Moreover, groundwater is threatened to arsenic, and surface water is exposed to pollution.

Bangladesh has the highest population density (1016 persons/km$^2$) of any country with the exception of small states such as Bahrain, Malta and Singapore (Mainuddin & Kirby, 2015). Unless we solve the problem of receding groundwater table seriously, it is likely that Bangladesh will have serious problem to feed its huge population where 31,5% people live below national poverty line (ADB, 2015). About 83% of the consumed food grain is rice. The experience of the world food crisis in 2007-08, rice prices increased sharply (as India cut exports to Bangladesh) in Bangladesh which has raised the importance of rice self sufficiency for Bangladesh (Dorosh and Rashid, 2012).

Understanding the essence, national water policy (NWPoB, 1999) expressed the urgency of conjunctive use of surface and groundwater with efficient way. If we can not solve to restore groundwater level to its sustainable level, Bangladesh must have to face food security issues over coming years for its huge population.

## 1.2 Contextualize the study

There are mainly three seasonal rice varieties in Bangladesh- aus, aman, Boro. The following ***table 1*** gives a brief of planting and harvesting period of rice-

**Table 1: Planting time and harvesting time of rice**

| **Type of rice** | **Planting Time** | **Harvesting Time** |
|---|---|---|
| Aus | Apr-May | July-August |
| Aman | Apr-May | Nov-Dec |
| Boro | Dec-Feb | Apr-May |

Currently about 75% agricultural land in Bangladesh is irrigated by groundwater. The demand for both surface and groundwater during Boro season (Jan-April) accounts 58,6% of the total water demand (Ghosh, S.K. & Ullah, M.W., 2015). Boro accounts for nearly 60% of national rice production. The study area is risky to seasonal variation of groundwater table. Groundwater level drops sharply during dry season. Therefore, the study selected the Boro crop variety to observe how it uses groundwater and surface water during the dry season (Jan-April).

The study area named Dhamrai is around 20 km away from Dhaka, the capital of Bangladesh. Declining groundwater during Boro season is becoming number one threat. Therefore, water availability from January to April in groundwater aquifer is must to ensure crop´s growth and development in order to have a good harvest. The demand for agricultural water has been met by both groundwater and surface water. The study area is mainly popular for its fertile arable land. And Most of its part is inundated during rainy season. Farmers usually use both surface water and groundwater during dry season. That was an ideal situation of conjunctive water use. The groundwater has been drawn from shallow aquifer. And surface water has been drawn from the Dhaleswari river passed by the area.

The study is very unique due to certain characteristics- ***Firstly,*** most of the studies considering the groundwater use for irrigation. This study considered both groundwater and surface water for its irrigation. ***Secondly,*** this is the first study considering very specific time interval (dry season) for managing water resources. ***Thirdly***, it assesses best policy options by using simulation model in order to see how declining water table problem could be solved. ***Fourthly***, irrigation area is under threat to urbanization and industrial pollution. This study showed us how these problems need to be addressed and solved smartly while urbanization and industrialization encroaching agricultural land.

## 1.3 Methods of the study

The study used both qualitative and quantitative approaches to understand the dynamics of the problem as well as to reproduce reference mode of the problem by simulation techniques.

### 1.3.1 QUALITATIVE METHODS

1. Literature reviews

   Available literature on groundwater declination, water resource management, agricultural challenges have been studied for finding the ground of the problem and its future perspective.
2. Interviews

   Interviews were conducted among 50 farmers, to understand the cropping pattern and cropping detalis from preparing the seedbeds to either sell or storing foodgrains.
3. Focused group discussion (FGD)

   FGDs were conducted to understand farmers´choices of crops, farming practices as well as worries about future farmings in response to climate change, unavailable groundwater.

### 1.3.2 QUANTITATIVE METHODS

1. To understand whether the problem is real or not; we collected primary data from 1980 to 2014 of our study area to see the status of groundwater table. We analyzed that data to see how groundwater table shifted since 1980 and zoomed in seasonal shift (during Boro season) to define the problem of this study.
2. Through model simulation, we tried to see how the present scenarios of groundwater practices could be changed to face future challenges in such agriculture intensive areas.

## 1.4 Findings of this study

This study investigated the true causes of declining groundwater table. Integrating the causes and practices done by farmers, it proposed the hypothesis that was justified as reproducing historic behavior by simulation model using by the software called iThink. Adding on that, this model tested different policy options suggested by farmers, experts and literature reviews to choose the best alternative policy in the context of growing urbanization and surface water pollution in order to solve groundwater declination sustainably.

## 1.5 Structure of the following chapter

The ***second chapter*** named background and research design, will discuss more about the problem dynamics, historical evidence of the problem, hypothesis, research design and assumptions. The ***third chapter*** is dedicated to model formulation and simulation settings, initial conditions, and equations used in the model. ***Fourth chapter*** will introduce model´s behaviors, sensitivity test, and model fit to reference mode. The ***fifth chapter*** will discuss about policy formulation, its objective and testing their behaviors to forsee how it works in near future. The ***sixth chapter*** is all about choosing the best policy in terms of feasibility and sustainability criteria. The ***seventh chapter*** introduces the limitations of the study, useful findings, prospective research area.

# 2. BACKGROUND AND RESEARCH DESIGN

## 2.1 Field data to support the problem

**Figure 1: Satellite image of the study area**

There are two crops grown in the study area; rice and rapeseed. The land became as a rotation of **Boro rice-Fallow-Mustard seed** every year. During Boro season, short duration varieties of rice (around 120 days) is chosen that spends about 60 days in the vegetative phase, 30 days in the reproductive phase, and 30 days in the ripening phase. Rice is grown under irrigated conditions in which the fields are flooded from planting to harvest that is 2.5-3.0 times higher than the consumption of water by crops like wheat and maize respectively.

Major groundwater shift took place during Boro season (Jan-April) from 1980 to 2013. That was the reason to choose that time period when rice was produced extensively. The shift can be summarized simply as

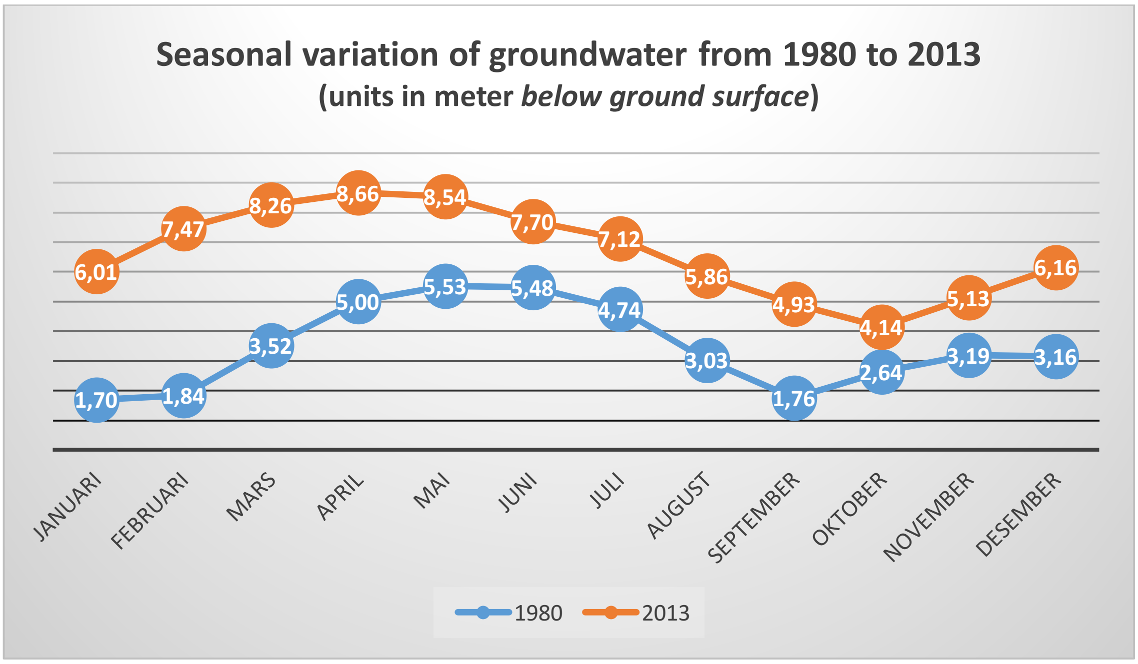

Figure 2: Groundwater level shift from 1980 to 2013 in the study area

There was either mustard seed or fallow before introducing Boro crops in our study area. The deep tube wells have been manifested by the government of Bangladesh since late 1970s in order to catch up the increasing demand by growing population. The farmers started using irrigation water only for Boro production. Eventually the study area was brought under Boro cultivation extensively. The introduction of high-yielding dry-season rice (Boro rice) accelerated the demand for irrigation (Harvey et al. 2002).

Even though study area has been inundated every year for at least 4 months (July-October), the water table has declined almost 6 meters during last 35 years. Farmers has experienced to dig down their wells for last couple of years that increased the cost for irrigated water as well.

Water availability from January to April in groundwater aquifer is must to ensure its growth and development in order to have a good harvest. The change of water table (***reference mode or historical problem***) during Boro season (Jan-April) in this study area since 1980 has been shown in the following figure-

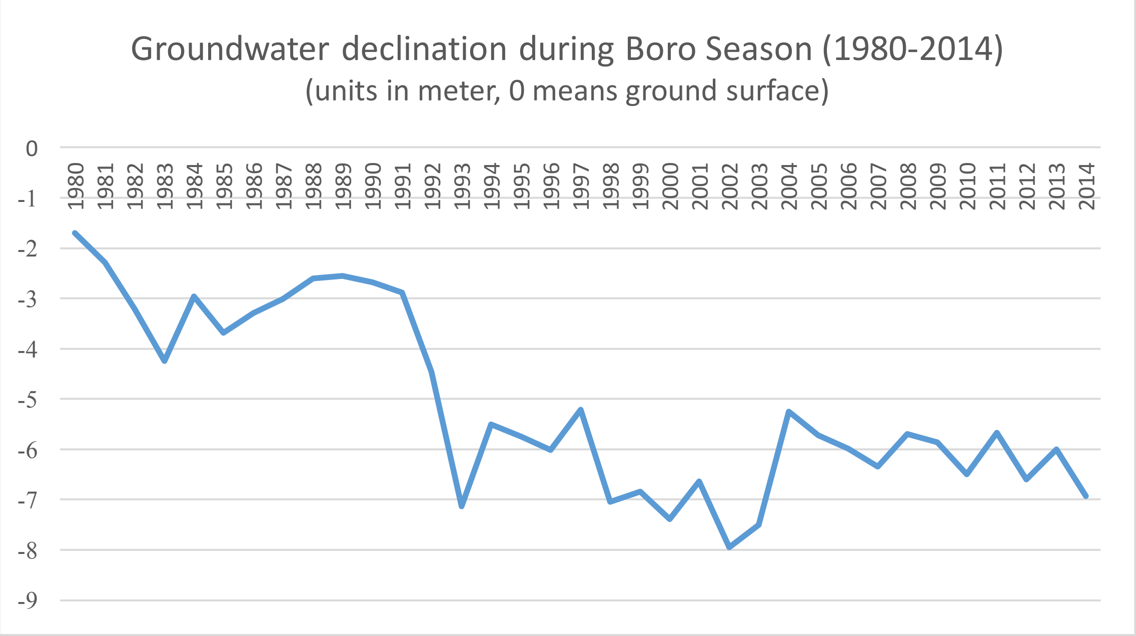

**Figure 3: How water table declined during Boro season since 1980 to 2014 in the study area**

It is clear from the figures that water table declined first slowly in 1980s whereas dropped drastically since 1990s.

## 2.2 Hypothesis

The study hypothesized that ***groundwater extraction is higher than recharge by annual flooding as well as percolated irrigation water during Boro season*** that led to groundwater declination.

From the problem describing figure 3, it is clear that groundwater is declining since 1980 to 2014 in three different phases. Though groundwater has been extensively used since 1960s in Bangladesh to meet up extra demands of a growing population. In our study area deep tube wells (DTWs) were introduced in later 1970s that decrease the groundwater slightly in the 1st phase. During 2nd phase groundwater started to restore until 1992 (started 3rd phase) as shallow tube wells (STWs) were introduced due to compensate the polluted river water. River water has been used before introducing deep tube wells (DTWs) and shallow tube wells (STWs). However, the use of surface water decreased since 1992 due to high level of pollution, discharged from nearby textile industries.

## 2.3 Research Design

The research objectives were to reproduce problematic behavior of groundwater declination; secondly, to provide the means in order to restore the groundwater at sustainable level.

To fulfill the first objective, we collected primary data about groundwater table in our study area from Bangladesh Water Development Board (BWDB). We analyzed the data through Microsoft excel to understand whether the declining is taking place or not. After confirming the problem from collected data, we interviewed farmers and arranged focused group discussions in our study area to understand water consumption behavior in regards to irrigation and household. The sources we identified for irrigation water were groundwater sources by deep tube wells (DTWs) and shallow tube wells (STWs) as well as surface water from the nearby river named Dhaleswari. Literature review helped us to understand the share of water loss by percolation in that type of soil as well as the fraction of evapotranspiration. We incorporated the gathered information into iThink software to build up a model of our interest. And simulated the model to see whether it could reproduce the problematic behavior or not.

To fulfill the second objective i.e. what could be sustainable means not to deteriorate groundwater level anymore-we derived the policy options suggested by the farmers, and experts as well as from previous studies-into our model to find out the best alternative.

## 2.4 Assumptions

Following assumptions were considered during building our model-

1. Size of the aquifer has been considered as same as the study area.
2. Dhamrai formation (composed of alluvial sand, silt and clay) has a thickness varies from 100-200 m (upper aquitard from 6-15m). Our study considered the average thickness of 118 m that has been found in many places nearby Dhaka city (Morris et al. 2003).
3. There was no rain or very little rain during Boro season. Therefore, it should not have contributed percolation during that season.
4. Groundwater from that aquifer has not been used for any other purpose than irrigation and household consumption
5. Moreover, for fine to medium sand, Healy and Cook (2002) list values for specific yield ranging from 0.005-0.19. Specific yield is water holding capacity of soil in the aquifer. It is calculated by volume of water divided by volume of soil. So, it does not have unit. In our study we considered the value of specific yield as 0,14.
6. We assumed homogeneous varieties of rice so that amount of water consumption kept constant throughout the study.
7. Soil profile seems to be same for that accredited fluvial-deltaic land. Therefore, percolation rate thought to be same for the whole study area.
8. It was assumed that 34% of total standing water percolated (observed by other studies) vertically into groundwater zones
9. Groundwater is recharged by annual flood which is considered as constant.
10. Groundwater inflow (rainy season) and outflow (dry season) by river has been ignored.

# 3. MODEL ANALYSIS

## 3.1 Presenting model

From CLD we see that there are three loops existing in our study model. Two of these loops (B1 and B2) actually are balancing in operation whereas one is reinforcing loop (R1). There might have another loop if could have extended from evapotranspiration to cloud followed by rain that again could recharge the groundwater. But the study did not consider that loop as there is no rain during dry season. **B1 loop** is the strongest loop as it contributed mostly to drain out the groundwater. **B2 loop** is very important for this study as it has the power to weaken the **B1 loop** by depending more on to river water than to groundwater as source of irrigational water.

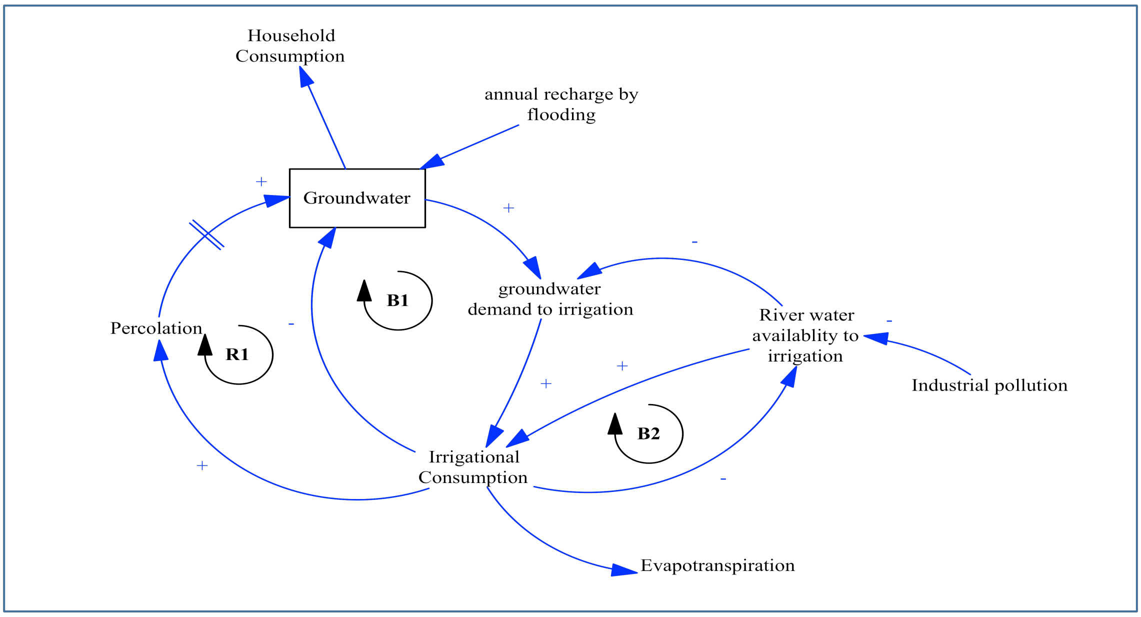

**Figure 4: CLD of the study model**

**R1 loop** is moderately stronger in this model that is actually our focus of interest to contribute recharging groundwater. As the industries recently polluting river water at a very large scale, the river water is odorous and almost got blackish in color. Moreover, as the polluted water is not preferred by the farmers they are depending more on the groundwater source that leads again to deplete the groundwater very sharply. To strengthen the **R1 loop,** less water needs to be harnessed from groundwater by replacing it to river water source which is now limited due to loads of pollution.

Stock Flow Diagram (SFD) started with the stock that produces the problematic behavior i.e. the groundwater. Groundwater has been recharged by the percolated water during Boro season; and by flood water during rainy season. Consumption of groundwater is caused by irrigation and household consumption. Irrigation water has another supply source that comes from river. Demand for surface water is a function of pollution and cost. Less surface water is compensated by groundwater that leads to fluctuation of groundwater level.

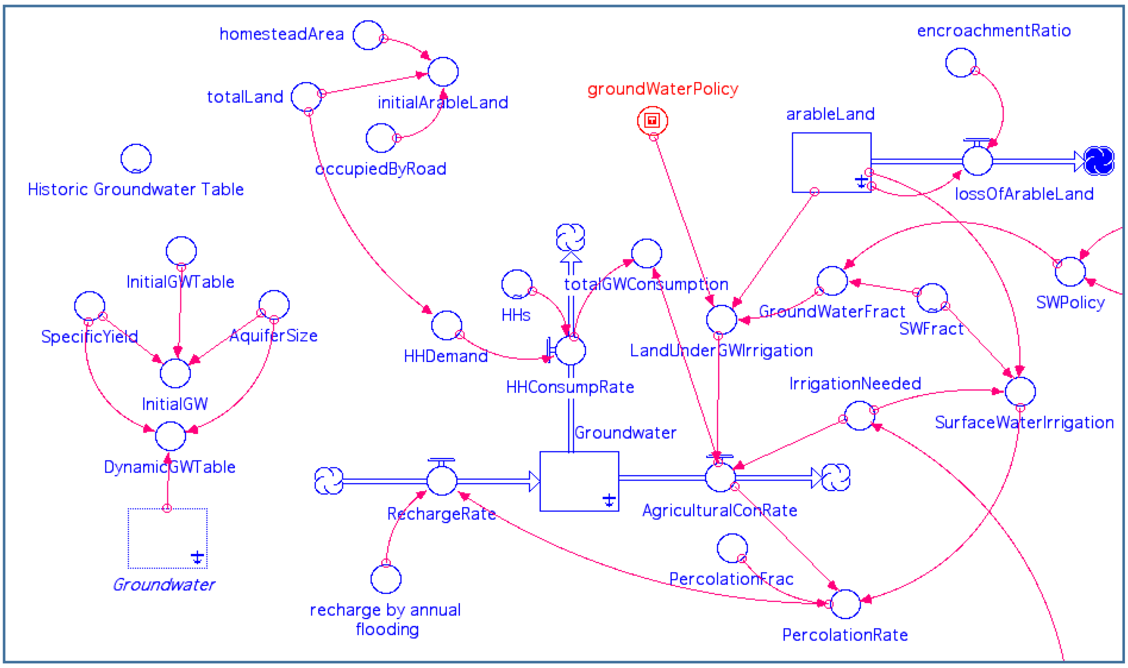

**Figure 5: SFD of the study model**

## 3.2 Simulation settings

The simulation settings in the iThink software has been defined in the following manner:

1. The time measurement is conducted in year and the entire simulation is run from 1980 to 2030.
2. The time step for the model is defined at 1 year.
3. Standard Euler method has been used for integration.

## 3.3 Parameter values and initial conditions

**Table 2: Parameter values and initial conditions**

| **Parameter** | **Value** | **Reference/Remarks** |
|---|---|---|
| Aquifer size | 3,63 $km^2$ | Assumed homogenously distributed beneath the surface |
| Specific Yield | 0.14 $m^3$water/$m^3$soil | Haly & Cook, 2002 |
| Household Water Demand, HHDemand | 37 $m^3$/yr | Every family of 7-8 people |
| Total household, HHs | 27 HHs; 200 HHs | It is a function assumed started with 27 and reached 200 in 2014 |
| Irrigation water needed | 1,3 m | (Brammer, H. & Ravenscroft, P., 2009) |
| Total land | 3634963 | Calculated from GIS map |
| Percolation Fraction | 0,34/yr | Fraction of standing water |
| Annual Recharge by flooding | 600000 $m^3$/yr | Annual flood recharges this much every year. |
| Initial groundwater table/thickness | 118 m | (Morris et al. 2003) |
| Initial homestead area | 5% | It started as 5% of total land area |
| Area occupied by road | 3% | 3% of total land. It was thought to be constant. |
| Encroachment ratio | 0.25%/yr | This was happening due to new human settlement |

## 3.4 Unraveling model

The starting point for explaining model would be the groundwater as it is the area of our focus that leaded the problematic behavior and it is the main variable that the model tries to explain. This variable is defined in the model as

```
Groundwater(t)=Groundwater(t-dt)+(RechargeRate-AgriculturalConRate-
HHConsumpRate)*dt
```

, where groundwater and initial groundwater is measured in ***cubic meter***. Initial groundwater is defined as

`Initial groundwater = Aquifer thickness * Aquifer size * Specific yield`

, where initial groundwater is measured in ***cubic meter***. Recharge rate is defined in the model as

`Recharge rate= Recharge rate (by annual flooding) + Percolation rate (in Boro season)`

, where recharge rate is measured in ***cubic meter/yr***. Every year from July to October the lands get flooded and groundwater aquifers are recharged so. Mostly no rainfall takes place in that period. Therefore, rainy season does not coincide with Boro cultivation. Percolation rate is defined as

`Percolation rate= (Surface Water from River + Agricultural Consumption Rate)* Percolation Fraction`

, where percolation rate is measured in ***cubic meter/yr***. Percolation fraction is a percentage of standing water for irrigation which does not have unit. Agricultural consumption is defined as

`Agricultural consumption rate= Land under groundwater irrigation * Irrigation water needed`

, where agricultural consumption rate is measured in cubic ***cubic meter/yr***. Irrigation water needed is a constant value and the unit is in meter. Household consumption rate is defined as

`Household consumption rate = Total households * Demand of water per household`

, where household consumption rate is measured in ***cubic meter/yr***. And demand of water per household is measured in ***cubic meter/household/yr***. Total household has a unit of ***household*** that is cancelled out by per household and turns to ***cubic meter/yr***. Amount of surface water fraction has been thought to be a function of availability of surface water and land elevation.

`Surface water fraction = f (River head water, land elevation)`

, where surface water fraction is unitless that is likely depends on river head water (as the river head water increases the load of pollution diluted lead to choose more surface water and whatever the load it can not irrigate more than 60% of arable land due to high elevation). Moreover, groundwater fraction is also unitless and is defined by

`Groundwater fraction = 1- Surface water fraction`

Total groundwater consumption is defined by

`Groundwater consumption rate = Households consumption rate + Agricultural consumption rate`

, where groundwater consumption rate is measured in ***cubic meter/yr***. Initial arable land is defined by

`Initial arable land = Total land * Homestead Area * Occupied by road`

, where initial arable land is measured in ***square meter***. Arable land is defined by

`arable Land(t) = arable Land(t - dt) + (-loss Of ArableLand) * dt`

, where loss of arable land is measured in ***square meter/yr*** and depends on encroachment rate that is assumed as 0,25% of arable land every year.

Land under groundwater irrigation is defined as

`Land under groundwater irrigation = Arable land * Groundwater fraction`

, where it is measured in ***square meter***. Arable land is a stock defined by

`Arable land = Initial Arable land - loss of arable land`

, where arable land is measured in ***square meter***. And initial arable land had the same unit having calculated from the product of total land area, percentage of area by road as well as homestead.

# 4. BEHAVIOR TESTING

## 4.1 Model behavior

Bottom of the groundwater aquifer has been considered as 0 (zero) that continued towards the surface where it got its maximum at height 118 m from the bottom. Therefore 120 m represents here as surface. ***Figure 6*** shows that after introduction of deep tube wells the groundwater started to fall slightly in the beginning 1980s, but due to bring more area under coverage of surface water the groundwater table started to recover. Around the beginning of 1990s use of surface water declined dramatically. To investigate the reasons, farmers were asked again to investigate the reasons. Then the farmers due to using black river water to irrigation, before the harvesting time the paddy stalks became very weak to stand with its grain. In case if it took little late to cut the paddy stalks, it fell on the ground that cause serious grain loss.

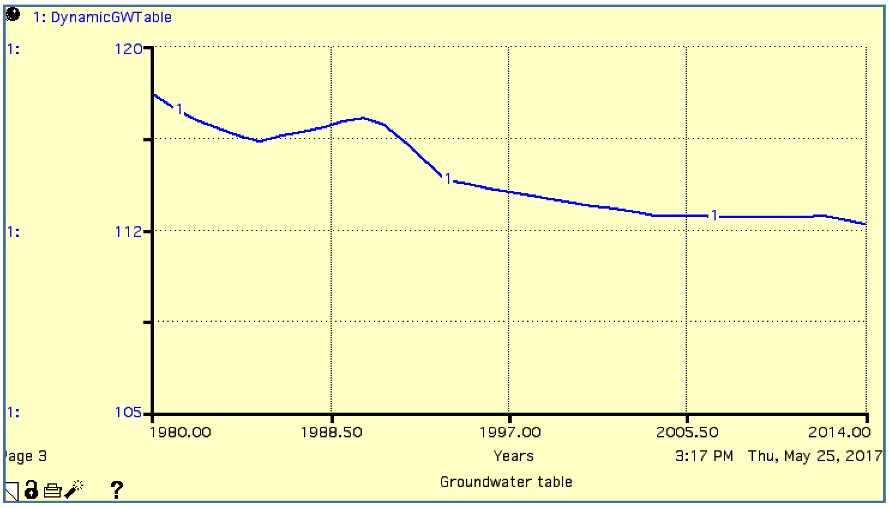

**Figure 6: Simulated groundwater behavior below the surface**

The threat to grain loss started to motivate the farmers in order to go for groundwater therefore many to meet up the extra groundwater demand many shallow tube wells (STWs) came into place. As a consequence, the groundwater kept falling since the beginning of 1990s. Surface water pollution became so vulnerable due to growing textile industries in the upstream localities. This study also figured out from the primary data that water flow through the Dhaleswari river also dropped during that time period might make the water pollution scenario worse to use even though the cost for irrigation was almost half than using shallow tube wells (STWs) or DTWs.

Household consumption rate of groundwater has been increased (Figure 7) almost in an exponential fashion. It could be reason that human settlement has been increased very quickly over last few decades. Whereas, both agricultural consumption rate (Figure 8) and water consumption rate have been decreased over the years due to decrease of arable land. As groundwater consumption depends on the amount of surface water consumption, therefore their behaviors are completely opposite to each other (Figure 8).

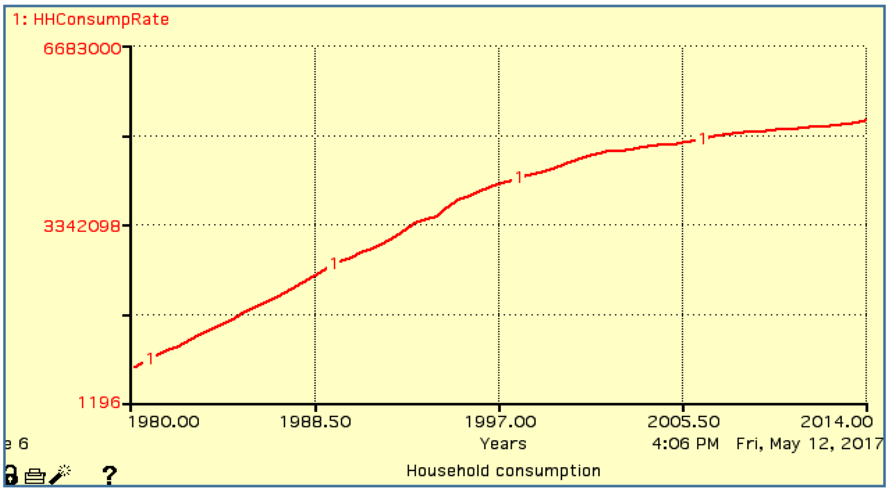

**Figure 7: Household consumption of groundwater**

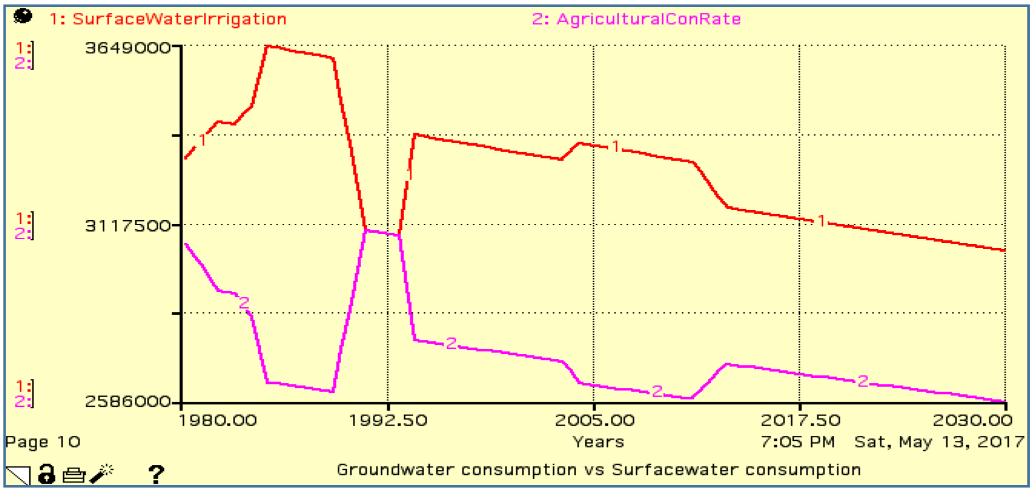

**Figure 8: Consumption of groundwater and surface water**

Total groundwater consumption has been higher than recharge rate that led to drop the groundwater table over the time period. From the figure-9 it also shows while recharge rate was surplus than consumption that actually led to restore groundwater table little higher. This study investigated the reasons behind this behavior. In late 1980s more area was brought under surface irrigation that actually helped to recharge more to groundwater table.

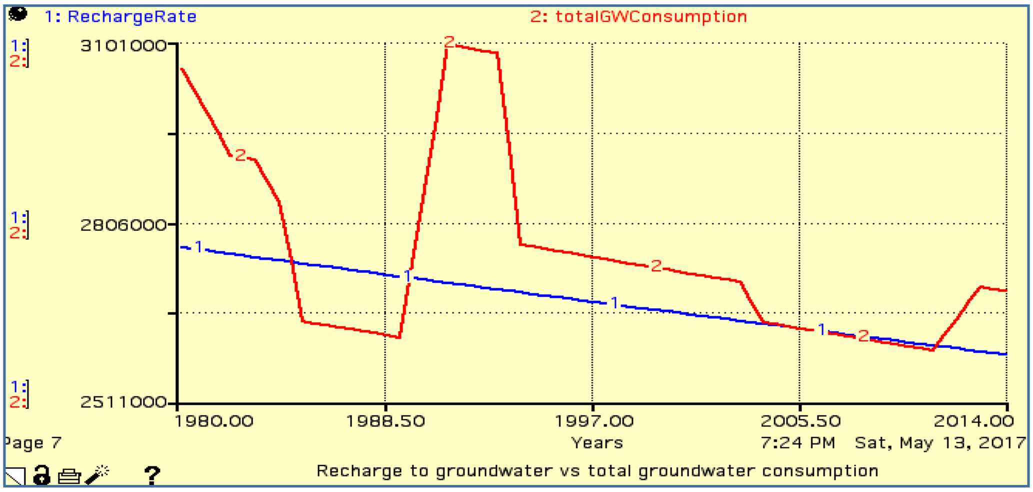

**Figure 9: Groundwater consumption vs recharge rate**

## 4.2 Sensitivity test of the model

Under the sensitivity test, the model is tested in order to see if the groundwater table still fluctuates or not under extreme condition. For that purpose, the variable Total land area in the model is set to its minimum numerical value i.e. 0 which means no households and arable land exists in that particular place. If there are no households and arable land, there should not have any use of water that will make the groundwater table as it was. From the figure we see that groundwater table becomes constant over the time period.

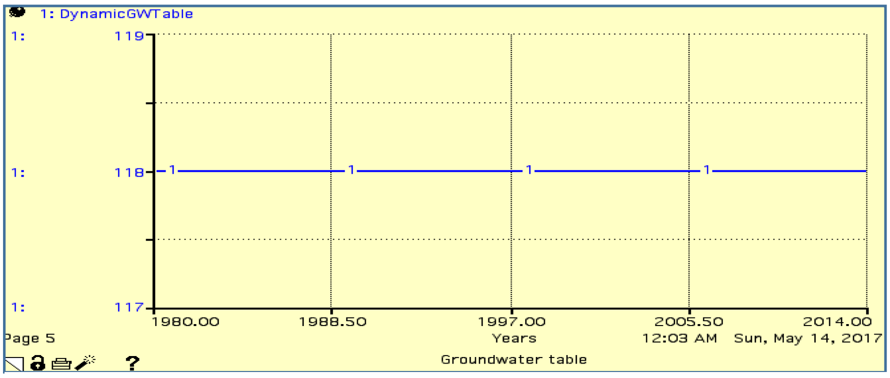

**Figure 10: Sensitivity test of the model**

## 4.3 Fit with respect to the reference mode

The model has been able to successfully illustrate the groundwater problem considering its major consumption to irrigation in our study area which is also subjected to recent urbanization and river pollution by the adjacent industrial zones in Dhamrai. The behaviour obtained after the simulation of the model is very much able to reproduce the reference mode. This is the resultant of the real-time data of our study area and information collected from the interviews to get the details of water consumption pattern from both groundwater source and surface water source. Water consumptions pattern by the study area along with percolation rate interact to each other in such a way so to recharge groundwater leads to reproduce that dynamic groundwater problem.

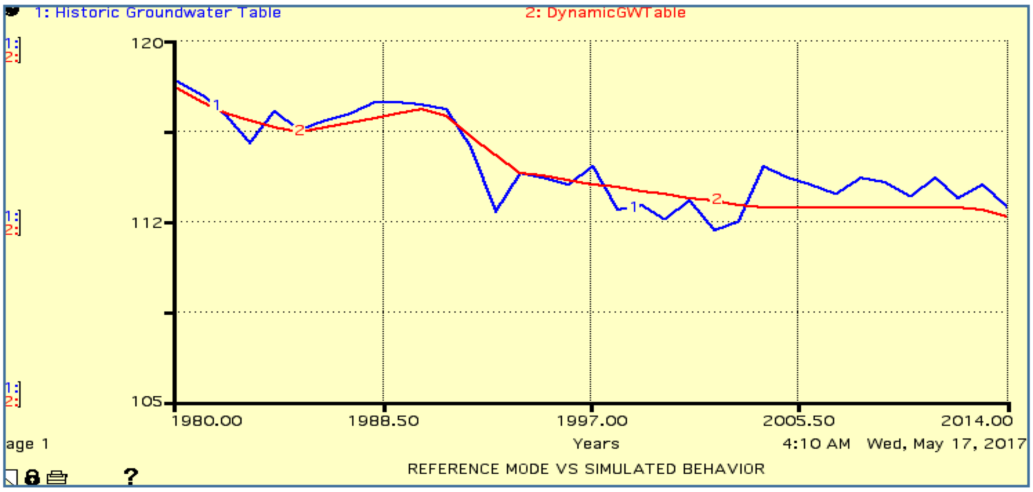

**Figure 11: Fit with the reference behavior**

In the above figure, we see simulated behavior is very close to reference mode. Therefore, the model can be considered as highly reliable for desiging the policy options to solve the problem sustainably.

Recharge rate considered as endogenous variable of the model has two components – recharge by percolation and recharge by annual flooding. From the historical groundwater data we found that groundwater table was almost stable in late 1970s when it was around 20% land brought under deep tube wells (DTWs) coverage. As the groundwater still did not decline we thought that loss of groundwater was being recharged by annual flooding. Therefore, groundwater table did not decline until 1980. We calibrated all the values during that time period and calculated recharge rate by annual flooding having value of 600000 $m^3$/yr. We assumed that the value remained constant for our studied aquifer. The only exogenous variable in the model was surface water flow that contributed the concentration of polluted water. We found farmers took decision whether they go for surface water or groundwater depends mainly on concentration of polluted water indicated by its color. Higher flow of river water obviously dilutes the concentration that influence farmers to go for more surface water. So exogenous variable was translated to farmer in a new way that might not have affected the model very differently than current behavior.

# 5. POLICY DESIGN

## 5.1 Policy Introduction

As per our hypothesis, difference of recharge and consumption of groundwater leading the problematic behavior. The goal of the policy is to solve the problematic behavior of groundwater sustainably. Among three alternative policy options, ***policy 1*** has been derived from farmers´approach to face this groundwater declination scenario. ***Policy 2*** has been derived from few studies already taken in water stressed zones in Bangladesh. And ***policy 3*** has been derived from experts´ interviews and national water policy of Bangladesh. After building up our model, we asked to 12 farmers what would they do if surface water use needed to be reduced. Then all of them suggested that they would go for groundwater irrigation by digging their STWs deeper (***policy 1***). The present study took the opportunity to see how farmers´ suggestion could solve problem of groundwater declination. As groundwater table getting into vulnerable level, many areas of Bangladesh can not go with high water demanding crops. Therefore, many studies have suggested that we should go with alternative cropping to face future challenges of groundwater shortage (***policy 2***). We wanted to see the effect of that policy to solve the problem. Policy 3 has been improvised from national water policy 1999 of Bangladesh where they suggested to go for conjunctive use of both groundwater and surface water. Through these policies' tests we wanted to see whether policies solve the problem or not in response to continued groundwater declination.

### 5.1.1 OBJECTIVE OF POLICY CONSIDERATION

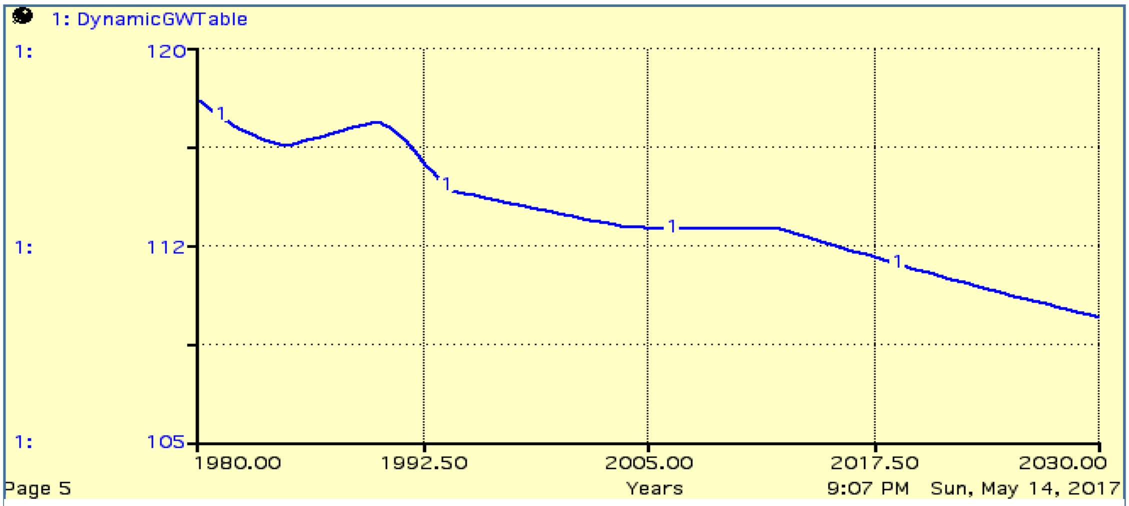

**Figure 12: Simulated groundwater table till 2030**

In business as usual (BAU) scenario, the simulated behavior till 2030 shows a declining groundwater table continued since 2014 that is shown in the above figure 12. ***The objective of our policy options is to halt this declination since 2015 or to restore it at a higher level than 2104.***

In policy considerations, there are recharge side of the policy option and consumption side of the policy option. The goal of recharge side of policy option is to maximize the use of surface water (***policy 3***) so that less groundwater can be withdrawn and more water could take part in percolation. The consumption side of the policy option is to cultivate low water demanding crops rather than rice (***policy 2***) and another one suggested by the farmers i.e. dig deeper through STWs to solve future water problem (***policy 1***).

## 5.2 POLICY 1: Dig deeper

### 5.2.1 GOAL OF THE POLICY

As availability of surface water has been decreased due to higher level of pollution. ***The goal of this policy is to depend gradually more on groundwater***. To harness more groundwater, the STWs needs to dig deeper that will reinforce the cost for irrigational water to become even higher. This is the policy farmers are considering when STWs can not abstract water from its present depth. Therefore, we wanted to test how it would behave for facing future challenge.

### 5.2.2 BACKGROUND OF POLICY 1

Since the beginning of 1990s farmers started to experience that the water table might have been declined as their shallow tube wells´ installation needs to dig deeper. Facing the future risk of water declination and abandoned surface water due to extreme water pollution; farmers have reached to a consensus on dig deeper in order to solve that water crisis. Moreover, they have a very strong belief that water wont be a problem even in the future. Taking into account their consideration, this study proposes its first policy named dig deeper. It is basically digging deeper in response to divert surface water consumption as well as declining groundwater table. Here in the study we translated this dig deeper policy into going from conjunctive use to single source i.e. groundwater for irrigation in the whole study area.

### 5.2.1 DESIGN OF POLICY 1

As we considering shift to surface water use to groundwater use from the year 2015 onward. The parameter ***policy 1*** indicates the use of groundwater completely having value 1 i.e. 100% and is defined as

```
Groundwater fraction = IF (time<2015) THEN (1-SWFract) ELSE Policy_1
```

### 5.2.2 BEHAVIOR TESTING

Under ***policy 1*** in figure 13, groundwater table declines very sharply. In the following figure we see that the thickness of groundwater table has declined 113 m in 2014 to 45m by 2030. In 34 years' period (1980-2014) the water table dropped around 5m. The new policy could drop the water table 68m below the current level that is quite risky to continue with rice production in that area as most of the tube wells need to drill again that could raise the water price so high that the cost of production can not be covered by price of rice until the market price of rice gets extremely high.

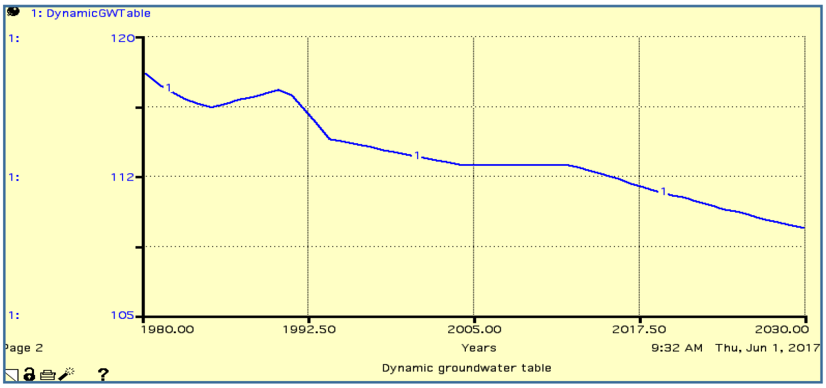

**Figure 13: Behavior testing for policy 1**

## 5.3 POLICY 2: Go for alternative crops

### 5.3.1 GOAL OF THIS POLICY

As high yielding Boro rice needs plenty of water, therefore alternative cropping that might need less water should obviously improve the groundwater stock. Hence, ***the goal of policy 2 is to improve groundwater stock by shifting practices from high water demanding crop to low water demanding crop during Boro season.***

### 5.3.2 BACKGROUND OF POLICY 2

Farmers had been asked what if they could not grow rice in Boro season. The only crop they had little experience was maize during Boro season. Very few farmers actually started producing maize but they did not continue due to lack of profit on that time. The reason they said that market price for maize was not good. Therefore, it was not profitable. From literature review it is found that maize actually has been started in water stressed areas in Bangladesh. Unless farmers in our study area are sure about the good production of maize and its profit, they are not going to start it. In water crisis scenario maize could be environmentally safer because it requires around one third water for irrigation compared to Boro rice (Ali, M.Y. et al, 2008). Therefore, we choose maize as our alternative crop for ***policy 2***.

### 5.3.1 DESIGN OF POLICY 2

Adopt this policy will need some time. From other case studies, it is shown that it takes around 8-10 years to replace a crop with other. Changing from generational culture to a new one takes little time as the farmers are skeptic about to change at first hand. They want to observe whether something really good is coming from a new practice or not for a certain time period. If that practice turns out to be a good one, then very few farmers got interested to learn it. They don´t learn that immediately, it takes little time to adopt that practices. Firstly, very few highly motivated farmers may be interested to start maize production. If these few farmers have good results, then the rest will have the confidence to learn and start practicing themselves. Therefore, considering this gradual change, 10 years have been chosen as adoption time for policy 2. This time has been considered to initiate talk, field exhibitions, trainings, manifestation the cultivation practices to other farmers. If the policy is practiced by all farmers, then our goal of 1/3 water for irrigation could be achieved by 10 years' time period. Therefore, the expectation of this policy is to bring down the irrigation water demand to 1/3 of current demand. We define the expected irrigation demand as stock by the following equation

`Expected irrigation = Initial irrigation demand – change in irrigation demand`

, where initial irrigation demand sets to 1.905 that is the present irrigation demand for producing rice. Expected irrigation demand decreases over time that is attached to policy 2 which is measured as

`Policy 2 = Expected irrigation demand`

Policy 2 has the same unit as expected irrigation demand i.e. ***meters/yr*** and plugged with the parameter called irrigation needed as shown in the following figure-

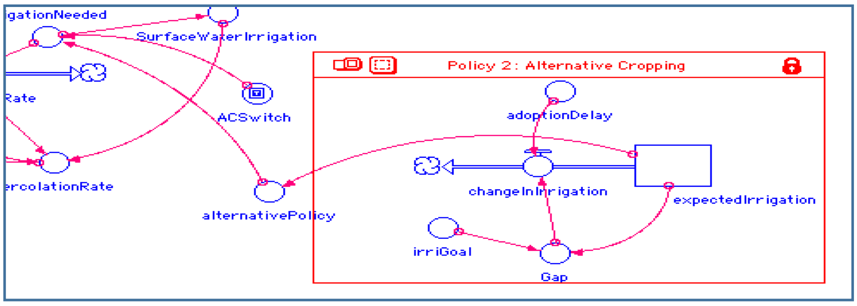

**Figure 14: Stock and Flow Diagram of policy 2**

### 5.3.2 BEHAVIOR TESTING

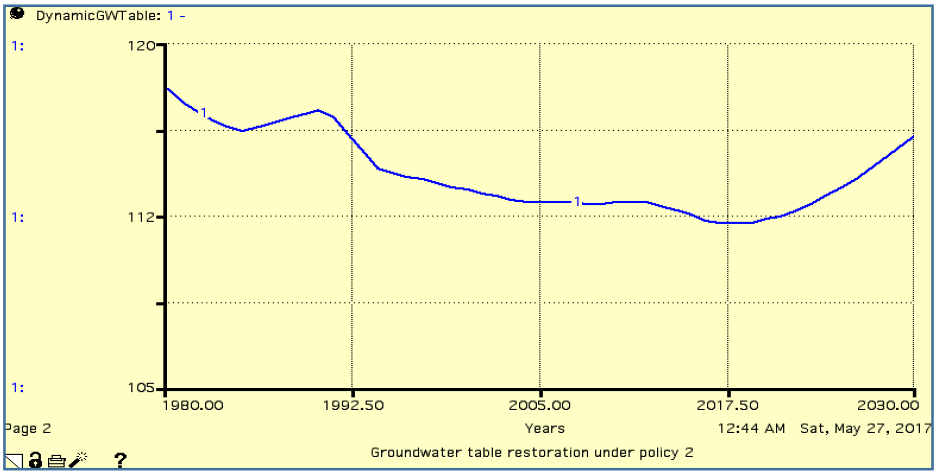

**Figure 15: Groundwater table under alternative cropping**

In the above figure 15, it shows that groundwater table starts to drop in the beginning followed by restoration of groundwater by few years. The behavior shows confidence to restore the groundwater table in a short period of time.

## 5.4 POLICY 3: Maximize surface water use

### 5.4.1 GOAL OF THIS POLICY

As abstraction of groundwater higher than the recharge rate, so the ***goal of policy 3 is to restore groundwater by reducing groundwater abstraction that could be compensated by surface water leading more to percolation, eventually to recharge***.

### 5.4.2 BACKGROUND OF THE POLICY

National Water Policy of Bangladesh (NWPoB, 1999) covers the re-use, conservation, preventing over exploitation as well as pollution and also seen water as an economic resource, so it can be said that the government trying to bring sustainability as its central concept. At its present pace of pollution, conjunctive use of surface and groundwater would not be possible longer. In reality, preventing surface water pollution from ongoing industries are not in action. If the water pollution act could be enforced strictly by law enforcement agencies, surface water might possibly be used at its maximum fraction i.e. 60%. Existing water distribution structure and channels will be enough to supply this water to the fields. Using more surface water could reinforce the R1 loop so that it could stop declining. Taking this understanding into consideration this study investigated policy 3 that considers maximum surface water consumption 60% as its goal. And to implement its goal it will take 15 more years as new industries much better in industrial effluent treatment. We assume that all the new and old industries will be better off by waste water treatment by that time that will reduce the water pollution significantly.

### 5.4.1 DESIGN OF POLICY 3

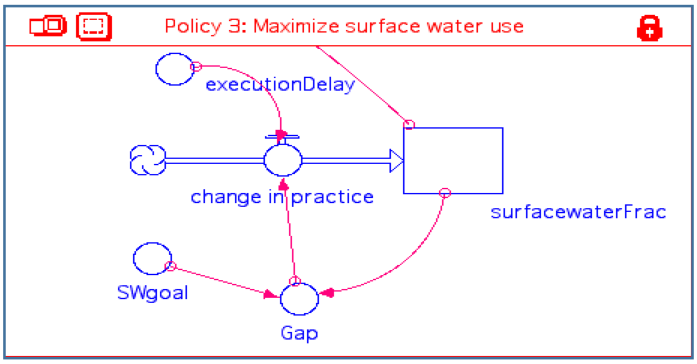

**Figure 16: SFD of policy 3**

In the above figure 16, we see stock and flow diagram of ***policy 3*** where surface water fraction is measured by

Surface water fraction = Initial surface water fraction + change in practice

, where initial surface water fraction was assumed as 54% that was the surface water fraction in 2014. To increase from 54% to 60% the change in practice depends on execution of current laws that is beyond of our study scope.

### 5.4.2 BEHAVIOR TESTING

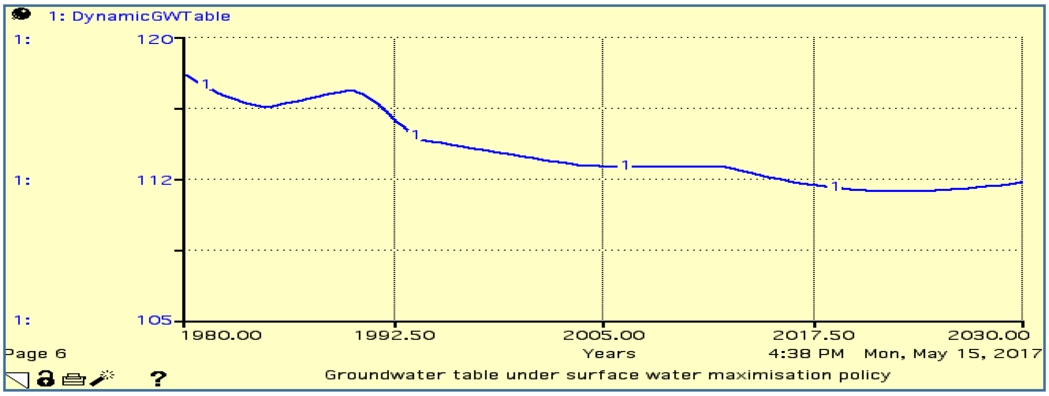

**Figure 17: Groundwater table under policy 3**

In the above figure 17, since introducing this policy groundwater groundwater dropped slightly till 2024 then starts to restore.

# 6. IMPLEMENTATION

Policy analysis has given us the ground to implement the best policy. It is clearly shown from behavior testing: ***policy 1*** (dig dipper) suggested by farmers could not solve rather worsen groundwater declination program. Before to weigh the best alternative we need to consider ***policy 2*** and ***policy 3*** through feasibility and sustainability tests. The study conducted round of interviews with the farmers (main stakeholders) over the phone in order to understand the feasibility ground of ***policy 2*** and ***policy 3***.

## 6.1 Social feasibility

We consider the the society as the nearby farmers′ community sharing common culture. Introducing any new practice needs to be understood fully and must achieve farmers′ trust to start and replicate the success among others. Farmers have been asked the following questions to get a sense of social feasibility of potential policies considering future water crisis -

1. **Are you willing to accept this policy?**
   *Answers for alternative crop (policy 2):* They are not ready yet to change their traditional practices as they are uncertain about future.

   *Answers for more surface water (policy 3):* They are ready to use more surface water if the pollution level decreases.

2. **Do you think your existing structure needs to be changed if you adopt this policy?**
   *Answers for alternative crop (policy 2):* They already have little experience on that. Therefore, they think they could adopt that without any change in their social structure. Only they will have needed more training on maize farming.

   *Answers for more surface water (policy 3):* Nothing needs to be changed.

### 6.1.1 SUMMARY

There is enough social cohesion for adopting either policies. Adopting ***policy 3*** is much easier as farmers already experienced it before.

## 6.2 Economic feasibility

Economy is driving force to farmers´ decisions. Most of the current farmers are farming because they have learnt these from their parents. To understand their core motivation of farming, farmers were asked if they could continue farming even though they are making loss every year. Most of the farmers do not want to continue as they don’t have capital to run their family by losing. Only very few farmers want to give few try if they could cover the loss in the following harvesting.

Benefit-cost ratio for Boro rice and maize are 0,82 and 1,62 respectively (Lagos, J.E. & Hossain, T., 2016). So, it is almost double profit for farmers to go for maize production rather than rice. Whereas, bringing 54% to 60% arable land to surface water irrigation will reduce the cost around one-fourth for those few farmers. Because, the rest arable is not possible to be brought under surface water.

### 6.2.1 SUMMARY

***Policy 2*** (alternative cropping) has a lead over ***policy 3*** (more surface water irrigation) in terms of economic benefit which is core motivation for farmers' decision.

## 6.3 Technological feasibility

**´´What could be technological barriers in order to execute either *policy 2* and *policy 3*?** ´´Investigating the answer of this question leaded us to assess the technological feasibility of policies.

Technological knowledge of maize cultivation among all farmers is the only barrier for ***policy 2***. There are staff from department of agriculture extensions who come once/twice in a month to local meeting place during Boro season to provide advice and sometimes show visual demonstration how to do something in a proper way. More training sessions could overcome the barrier facing by policy. There are already existing institutions that could take lead into that.

Reducing surface water pollution by upstream industries need to be confirmed. There has not been seen any positive signs for reducing pollution. So, the reduction of water pollution is uncertain. There is nothing that farmers could do on that.

### 6.3.1 SUMMARY

Barriers facing by ***policy 2*** could be solved by little improvement of existing structure. Whereas, barriers facing by ***policy 3*** needs involvement from both industries to use treatment plant as well as law enforcement agencies to monitor those and bring the defaulters under punishment. Therefore, uncertainty for implementing ***policy 3*** is much higher than ***policy 2***.

## 6.4 Comparison of policies and challenges

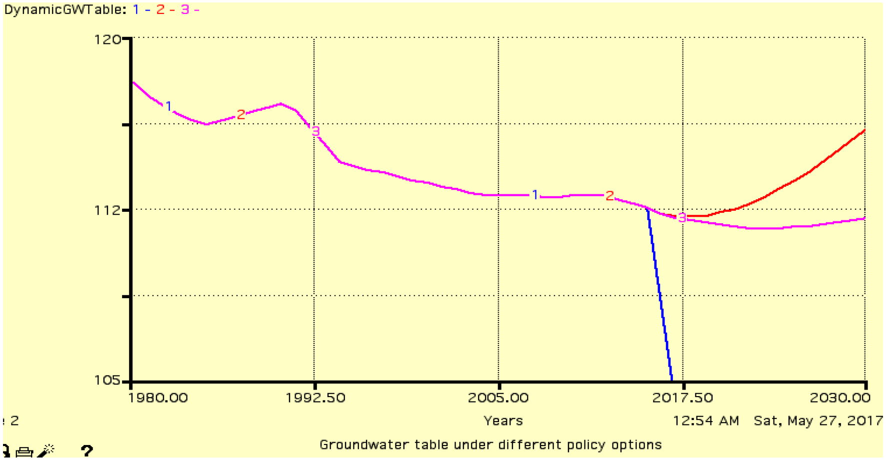

**Figure 18: Result comparison of different policies**

´´Which policy performance could solve the problem? ´´-can lead us to appropriate policy option for groundwater exploitation. Three policies have been represented here with different colors (blue: ***policy 1***; orange: ***policy 2***; pink: ***policy 3***). It is clear from figure 18 that ***policy 2*** has the maximum leverage over other alternatives.

***Policy 3*** has stakeholders like farmers, government agency and industries from where pollution can be controlled or treated. To bring all those stakeholders in a common platform and to work together has very low probability to be happened. As it has been tried since 1990s but still pollution has not stopped or halted at allowable limit.

The real challenge is to divert farmers´ attitude from ***policy 1*** to ***policy 2***. If groundwater starts to drop quickly, it is likely to have the effect of ***policy 1*** as there does not need any extra efforts rather boring STWs at even lower depth. But to implement ***policy 2*** comes at cost and efforts. The cost here is to change their mental models about groundwater stock and its functionality. From the focused group discussions (FGDs) with farmers, we found that they do not understand how the groundwater aquifer (stock) functions. Other studies (e.g. Sterman, 1989; Rouwette, 2004) also have found that people have difficulties to understand and controlling dynamic systems. As farmers do not know properly how the groundwater stock works and can be recovered. Therefore, it is their mental models about groundwater stock that needs to be changed to a proper one. Farmers will willingly go for alternative cropping if they are convinced enough that the current problem has serious negative consequences for future cultivation and there is still much that they can do. To change that mental model into correct ones two most important stakeholders-farmers and department of agricultural extension (DAE) should work in hand to change their mental models into correct one. Common consensus about understanding stock is prior to start necessary trainings and exhibitions.

## 6.5 Sustainability

Water is must for agriculture. Ensuring the water supply for crop production needs to be assured for unlimited time period. If this criterion is met, then we could say that a practice is sustainable. Dams, embankments in upstream rivers as well as diversion of river water for various purposes leading a serious threat to rivers of this country. Along with industrial pollution, water flow through river has been decreased during last 35 years (figure 19).

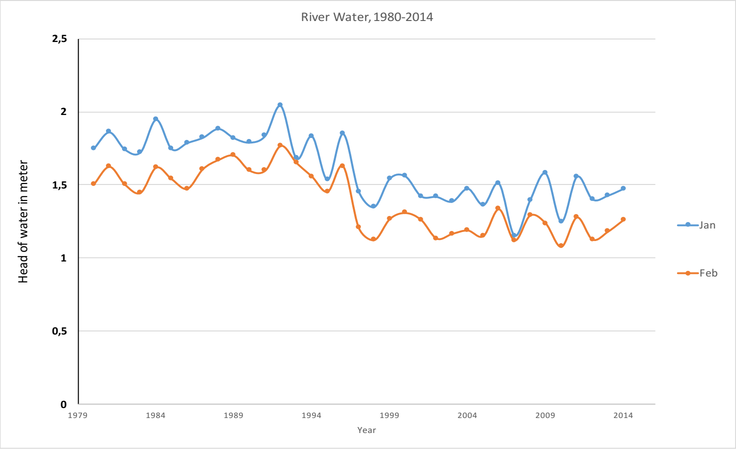

**Figure 19: Water flow in Dhaleswari river for last 35 years**

Therefore, depending on surface water (***policy 3***) can not be a sustainable solution. Harnessing alternative source like groundwater could be the best source if we could halt declining groundwater table. Reaching 1/3 of current irrigation water (by ***policy 2***) could be more sustainable initiative in this regard.

Farmers´consensus was that replacement of rice might reduce the declination but will not be profitable. We found in this study that alternative cropping has huge potential not only to solve water stress problem but also to generate as much double benefits than producing rice. It could be a huge motivation for farmers to start maize production. Such a higher economic and environmental sustainability also prefers to go with ***policy 2***.

# 7. CONCLUSION

## 7.1 Limitations of the study

The places having good quality of surface water, might not have the same solution. In that case ***policy 3*** would be more suitable. The study considered the annual recharge of groundwater by flooding as a constant value. Few studies showed that if the groundwater level declines recharge could be higher during flooding.

Ours is a very unique study area where surface water is available and groundwater is recharged in rainy season by flooding. In many places the geographical context is not like that. So, assumptions along with the model structure might not be suitable for those places.

Solving this problem needs a social transformation. Farmers are the most important stakeholders in this set up. To initiate the process of transformation needs active participation of farmers and government agency. If either of two stakeholders can not meet to a common goal that groundwater declination is happening and needs to be halted right now, then the transformation could be much harder.

## 7.2 Useful findings

The natural tendency of farmers to choose ***policy 1*** rather than normative rationality goes for ***policy 2*** and ***policy 3***. Policy 3 has exogenous variables to be controlled that is beyond farmers´ capacity. The problematic behavior of groundwater declination seems not a serious problem to farmers. They have the perception that groundwater declination is a natural phenomenon that can not be restored at its previous level. There is a common consensus in the community that future is going to be even worse. But farmers have no plans and preparations to face negative outcomes in future. They think everything is beyond their capacity. People in common misperceive basic dynamics of renewable stock (comply with the studies of Sterman, 1989; Rouwette, 2004; Moxnes, 1998). That misperception leads them not to think that stock can be restored with proper planning.

Alternative cropping can be popularized by existing institutions in Bangladesh like department of agricultural extension (DAE). Places that have the same geographical characteristics and having groundwater declination problem could easily use this model and check their available policy options. This sort of policy option could help not only to halt groundwater declination but also to restore that quickly.

The appropriate policy is not valid for ever. The best policy, recommended here, might not be the best option if we want to introduce it after 2030 as the groundwater might completely dry up by then. For instance, the maize price before was very low that's why farmers did not have any motivation but the price is now good enough to have handsome profit. Therefore, it is imperative to be correct with appropriate policy at the first hand. And to know about that perfect timing, dynamic modeling is very useful tool to show how to choose the best.

## 7.3 Prospective future

Arsenic accumulation has been aggravated in many water stressed rice producing areas in Bangladesh, whereas maize production does not accumulate arsenic (Ali, M.Y., et al., 2008). Main rivers in Bangladesh are originated in neighboring countries. Building dams and embankments in the upstream rivers made Bangladesh very vulnerable to agriculture. Thousands of shallow tube wells are not working as groundwater source has already dried up. If it is possible to design specific crops according to groundwater status as well as nearby water availability, it would definitely save a populous country from food scarcity in near future.

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# GLOSSARY

**Aquifer**

An **aquifer** is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt) from which groundwater can be extracted using a water well (Wikipedia).

**Food security**

It includes food availability, access to food and nutritional quality (Per Pinstrup-Anderson, 2009).

**Specific yield**

Water holding capacity of soil in the aquifer.

**Aquitard**

It is a bed of low permeability along an aquifer.

# APPENDIX

**Table 3: Crops and their growing seasons**

| | Rabi Season | Pre-Kharif | Kharif |
|---|---|---|---|
| Start | 1-10 October in the extreme west, to 1-10 November in the Northeast, and in central and eastern coastal areas. | March-April | May-June |
| End | 1-10 February in extreme west; 20-31 March in the Northeast. | May-June | Oct-Nov |
| Crops | wheat, maize, mustard, groundnut, sesame, tobacco, potato, sweet potato, sugarcane, lentil, chickpea, grass pea etc. | Sugarcane, maize, jute, amaranths, groundnut, banana, sesame, lady's finger, teasle gourd, sweet gourd, white gourd, bitter gourd, balsam apple, ribbed gourd, Indian spinach, ginger, turmeric etc. | jute, aus, broadcast aman, transplant aman, sesame, different kinds of summer vegetables, ginger, turmeric, pepper, green chili, different kinds of aroids, cotton, mungbean, black gram, etc. |

**Table 4: Groundwater table in our study area from 1980-2014 (below ground surface) (Source: BWDB)**

| Year | Water level in ***meter*** (below surface) |
|---|---|
| 1980 | -1,6975 |
| 1981 | -2,2875 |
| 1982 | -3,205 |
| 1983 | -4,242 |
| 1984 | -2,964 |
| 1985 | -3,68 |
| 1986 | -3,2925 |
| 1987 | -3,015 |
| 1988 | -2,605 |
| 1989 | -2,55 |
| 1990 | -2,678 |
| 1991 | -2,88 |

| | |
|---|---|
| 1992 | -4,46 |
| 1993 | -7,14 |
| 1994 | -5,506 |
| 1995 | -5,742 |
| 1996 | -6,012 |
| 1997 | -5,2075 |
| 1998 | -7,0475 |
| 1999 | -6,845 |
| 2000 | -7,3875 |
| 2001 | -6,644 |
| 2002 | -7,945 |
| 2003 | -7,5 |
| 2004 | -5,2525 |
| 2005 | -5,716666667 |
| 2006 | -5,99 |
| 2007 | -6,35 |
| 2008 | -5,695 |
| 2009 | -5,86 |
| 2010 | -6,5025 |
| 2011 | -5,672 |
| 2012 | -6,604 |
| 2013 | -6,005 |
| 2014 | -6,9275 |

**Table 5: Seasonal variation of groundwater table (unit in meter below the ground surface) (Source:BWDB)**

| | **1980** | **2013** |
|---|---:|---:|
| January | 1,6975 | 6,005 |
| February | 1,8375 | 7,47 |
| March | 3,522 | 8,255 |
| April | 4,995 | 8,66 |
| May | 5,53 | 8,5375 |
| June | 5,482 | 7,7025 |
| July | 4,74 | 7,118 |
| August | 3,03 | 5,8625 |
| September | 1,758 | 4,93 |
| October | 2,6375 | 4,1375 |
| November | 3,185 | 5,125 |
| December | 3,164 | 6,158 |

## Model equations

```
arableLand(t) = arableLand(t - dt) + (-lossOfArableLand) * dt
INIT arableLand = initialArableLand
OUTFLOWS:
lossOfArableLand = arableLand*encroachmentRatio
Groundwater(t) = Groundwater(t - dt) + (RechargeRate - HHConsumpRate - AgriculturalConRate) * dt
INIT Groundwater = InitialGW
INFLOWS:
RechargeRate = if (PercolationRate>0) then (recharge_by_annual__flooding+PercolationRate) ELSE 0
OUTFLOWS:
HHConsumpRate = HHDemand*HHs
AgriculturalConRate = LandUnderGWIrrigation*IrrigationNeeded
expectedIrrigation(t) = expectedIrrigation(t - dt) + (-changeInIrrigation) * dt
INIT expectedIrrigation = 1.905
OUTFLOWS:
changeInIrrigation = Gap/adoptionDelay
expectedSW(t) = expectedSW(t - dt) + (change_in_practice) * dt
INIT expectedSW = 0.54
INFLOWS:
change_in_practice = GapS/executionDelay
ACSwitch = 0
adoptionDelay = 10
alternativePolicy = expectedIrrigation
AquiferSize = 3634963
DynamicGWTable = Groundwater/(AquiferSize*SpecificYield)
encroachmentRatio = 0.0025
executionDelay = 15
Gap = if time>2014 then (expectedIrrigation-irriGoal) else 0
GapS = if (time>2014) then (SWgoal-expectedSW) ELSE 0
GroundWaterFract = if time<2015 then (1-SWFract) ELSE (1-SWPolicy)
groundWaterPolicy = 0
HHDemand = if totalLand>0 then 37 else 0
HHs = GRAPH(TIME)
```

(1980, 27.1), (1981, 31.9), (1982, 36.1), (1983, 39.6), (1984, 44.4), (1985, 48.6), (1986, 54.9), (1987, 61.1), (1988, 66.7), (1989, 72.2), (1990, 77.8), (1991, 82.6), (1992, 87.5), (1993, 94.4), (1994, 103), (1995, 107), (1996, 112), (1997, 119), (1998, 125), (1999, 130), (2000, 137), (2001, 145), (2002, 150), (2003, 156), (2004, 158), (2005, 162), (2006, 168), (2007, 172), (2008, 178), (2009, 183), (2010, 188), (2011, 193), (2012, 195), (2013, 198), (2014, 200)

Historic_Groundwater_Table = GRAPH(TIME)

(1980, 118), (1981, 118), (1982, 117), (1983, 116), (1984, 117), (1985, 116), (1986, 117), (1987, 117), (1988, 117), (1989, 117), (1990, 117), (1991, 117), (1992, 116), (1993, 113), (1994, 114), (1995, 114), (1996, 114), (1997, 115), (1998, 113), (1999, 113), (2000, 113), (2001, 113), (2002, 112), (2003, 112), (2004, 115), (2005, 114), (2006, 114), (2007, 114), (2008, 114), (2009, 114), (2010, 114), (2011, 114), (2012, 113), (2013, 114), (2014, 113)

homesteadArea = 0.05

initialArableLand = totalLand-(homesteadArea*totalLand+occupiedByRoad*totalLand)

InitialGW = SpecificYield*AquiferSize*InitialGWTable

InitialGWTable = 118

IrrigationNeeded = if (time>2014 and ACSwitch=1) then alternativePolicy
ELSE 1.905

irriGoal = 0.635

LandUnderGWIrrigation = if time>2014 AND (groundWaterPolicy=1)
THEN (groundWaterPolicy*arableLand)
ELSE (GroundWaterFract*ArableLand)

occupiedByRoad = 0.03

PercolationFrac = 0.34

PercolationRate = (SurfaceWaterIrrigation+AgriculturalConRate)*PercolationFrac

recharge_by_annual__flooding = 600000

SpecificYield = 0.14

SurfaceWaterIrrigation = ArableLand*SWFract*IrrigationNeeded

SWFract = GRAPH(TIME)

(1980, 0.52), (1981, 0.53), (1982, 0.54), (1983, 0.54), (1984, 0.55), (1985, 0.58), (1986, 0.58), (1987, 0.58), (1988, 0.58), (1989, 0.58), (1990, 0.54), (1991, 0.5), (1992, 0.5), (1993, 0.5), (1994, 0.55), (1995, 0.55), (1996, 0.55), (1997, 0.55), (1998, 0.55), (1999, 0.55), (2000, 0.55), (2001, 0.55), (2002, 0.55), (2003, 0.55), (2004, 0.56), (2005, 0.56), (2006, 0.56), (2007, 0.56), (2008, 0.56), (2009, 0.56), (2010, 0.56), (2011, 0.56), (2012, 0.55), (2013, 0.54), (2014, 0.54)

SWgoal = 0.6
SWPolicy = if (SWSwitch=1) THEN (expectedSW) ELSE .54
SWSwitch = 0
totalGWConsumption = AgriculturalConRate+HHConsumpRate
totalLand = 3634963