

FUTURE WATER TABLE LEVELS UNDER INTENSIFICATION OF
RICE CULTIVATION IN A MONSOON CLIMATE

A Thesis

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ABSTRACT

The long-term response of the groundwater table level to irrigation and climate change is studied using a one-dimensional numerical model employing the Thornthwaite-Mather procedure to calculate the root-zone water balance. The study focuses on rice cultivation at Avanigadda in the Krishna district of the state of Andhra Pradesh, India which experiences a monsoon climate. The effect of intensifying the cultivation is addressed by considering the cases of having one, two, and three crops per year with a single rainfed crop and the rest supported by groundwater irrigation. To address the effect of climate change, three well-known IPCC scenarios SRESA1B, SRESA2, and SRESB1 are simulated. Single crop agriculture is found to be sustainable irrespective of the climate scenario while two and three crop cultivations are found to be unsustainable with the water table level dropping to 200 – 1000 meters at the end of 21st century.

BIOGRAPHICAL SKETCH

Indu Thekkemeppilly Sivakumar was born in the year of 1984 in the state of Kerala in India. She graduated in 2006 with a Bachelor of Technology in Civil engineering from Government Engineering College Thrissur affiliated to Calicut University. After a brief stint in the field of construction engineering she joined the Indian Institute of Science, Bangalore as a junior research fellow in the field of water resources engineering. There she worked on the problem of dam-induced sediment profile changes in rivers. Thereafter in 2010 she joined the soil and water lab in the Department of Biological and Environmental engineering Cornell University as a Master of Science student under the guidance of Professor Tammo Steenhuis. There she investigated the long term response of water table level to irrigation and climate change using numerical simulations.

Dedicated to my family

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CHAPTER 1

INTRODUCTION

Irrigation is one of critical factors that affect the agriculture production in today's world as it supports about 40% of the global agricultural production but especially in Asia (Rosegrant et al., 2009). Groundwater is one of the major sources for water for irrigation which supplies around 40% of the global irrigation water (Aeschbach-Hertig and Gleeson, 2012). While irrigation has boosted the land productivity by more than two-fold (Khan et al., 2006), pumping for groundwater for irrigation has resulted in lowering the water table levels in many parts of world such as the Punjab region in Northern India and the Northern China plain (Konikow and Kendy, 2005). Groundwater depletion has far reaching consequences such as increased pumping costs, damage to eco-systems owing to the reduced discharge to streams and wetlands, land subsidence, and salt water intrusion in coastal areas (Aeschbach-Hertig and Gleeson, 2012 , Konikow and Kendy,2005) and long term sustainability in food production requires stabilization of groundwater levels (Aeschbach-Hertig and Gleeson, 2012) . Thus it is of great importance to predict the long term trends of water table levels in response to irrigation. We address this issue in this work by developing a one dimensional shallow aquifer model which accounts for precipitation, evapotranspiration, percolation and run off. We then apply this model to predict water table levels in the Krishna district of Andhra Pradesh, India under various agricultural practices. We also investigate the effect of climate change in groundwater levels in the same region using projected trends of precipitation (Salvi et al., 2013)

India is one of the countries in which ground water depletion due to over pumping is being observed (Rodell et al., 2009) and documented. The effects of irrigation on water table levels would be severe in the Indian context because agriculture supports 52 % (Census report 2011) of the labor force. The monsoon which brings the major part of precipitation last only for around 120 days a year (Gadgil, 2003). For sustainable agriculture, external supply of water is necessary and since surface water resources like canals and dams are often extremely expensive to implement or at times inaccessible, groundwater has been perceived to be the most reliable source for irrigation water. The use of groundwater was further enhanced during the green revolution of 1960's due to widespread usage electric pumps and subsidization of electricity for farmers. Groundwater irrigation started with only 6.5 million hectares (Mha) in 1950–1951 (CGWB 1992), that has increased to 46.5 Mha in 2000–2001 (Sivanappan, 2002) and approximately 60% of the food production relies on groundwater irrigation (Douglas et al., 2006).

Apart from North China Plain and northwest India, irrigation induced groundwater depletion has been observed in the High Plains and the Californian Central Valley in the United States, Mexico, Iran, Saudi Arabia, Bangladesh, and parts of northern Africa (Aeschbach-Hertig and Gleeson,2012, Taylor et al.,2012). For example in United States, Gravity Recovery and Climate Experiment (GRACE) satellite data and ground-based observations (Famiglietti et al.,2011) revealed a depletion between 24 and 31 km³ in the time period 2006 - 2009 (Taylor et al., 2012). This depletion was due to increased groundwater mining for irrigation happened during the drought happened in California Central Valley in the same time period. In

high plains aquifer the depletion due to irrigation for a time period of 1950 to 2007 is approximately 330km^3 (Scanlon et al., 2012). In Rafsanjan plain within central Iran groundwater extraction for irrigation for pistachio cultivation caused lowering of water table by more than 15 m in a span of 1971-2001 (Motagh et al., 2012, Mousavi et al., 2001). A ground water loss of around 10km^3 per year is reported in Saudi Arabia (Wada et al., 2010). Irrigation accounts of almost 95% of groundwater withdrawal in Yemen where the groundwater use exceed the recharge by 36% in most parts of the country with some regions having rate as high as 150 % (Moore and Fisher, 2012).

The problem of groundwater depletion can be exacerbated by the climate change. Changes in temperature, evaporation and precipitation will result in changes in the distribution of surface and sub surface water (Chiew, 2007). While river discharge and water availability have been predicted to decrease in places such as mid latitudes and dry tropics, high latitudes and wet tropics are predicted to have an increase (Kundzewicz et al., 2008). The direct influence of climate change on groundwater is the change in recharge. In mountain regions the increase in temperature can cause high amount of snowmelt or high amount of rain instead of snow. This makes a shift in river discharge to an early date (Scibek et al., 2007) thus resulting in high water table levels in spring season. Subsequent lowering of river discharge due to the absence or reduction in snow melt water in summer will in turn reduce the groundwater discharge (Taylor et al., 2012).

The indirect influence of climate change is the general change in groundwater use (Taylor et al., 2012) and the over-dependence on groundwater resources in times

of drought as in the case of California Central Valley (Taylor et al., 2012). Researchers have developed global irrigation models (GIM) capable of making long term predictions on irrigation water requirements in response to climate, crop type, and cropping intensity (Doll and Siebert 2002). Using the predicted climate data from global circulation models (GCM) on global irrigation models Doll (2002) have estimated around 15% increase in the irrigation water requirement for Southeast Asia and the Indian subcontinent (Fischer et al., 2007) which is by far the largest increase in comparison to others parts of the world (Doll 2002) . Further study (Fischer et al., 2007) has shown that climate change along with socio-economic developments would worsen the scarcity of irrigation water in the Indian subcontinent. Doll (2002) attributes the increase in irrigation water requirement to the increase in potential evapotranspiration resulting from the increase in temperature and also the heterogeneity in changes in precipitation.

Other than climate change, crop and irrigation practices also have a strong influence on groundwater levels. The primary reason behind irrigation caused groundwater depletion is the evaporative loss of the extracted water (Kendy et al., 2003) and the increase in number of cropped days with irrigation increases the evapotranspiration. For instance, in the Luancheng county of the North China plain where irrigation caused groundwater depletion has been observed, evapotranspiration increased from 46 cm/yr to and remained at 66 cm/yr during a period of 1955 – 1971 owing to the transition from one-crop per year agricultural system to a two-crop per year system. In the meantime, precipitation decreased from 54 cm/yr to 46 cm/yr which means that a net deficit of 20 cm/yr of irrigation was met by extraction from

groundwater consequently lowering the water table. When one-crop per year agriculture was in practice, the precipitation exceeded evapotranspiration and as result, the aquifer was recharged occasionally to the full capacity (Kendy et al., 2003). Thus Kendy et al., (2003) also notes that it is the increase of the actual evapotranspiration that caused groundwater depletion rather than an increase in the potential evapotranspiration and that the amount of pumping has little effect on groundwater levels owing to the percolation of extracted water back to the aquifer. A comparison of the moisture fluxes for a pre-agricultural and a contemporary land covers in India (see Douglas et al., 2006) also corroborate the notion that it is the increased evapotranspiration that leads to groundwater depletion. Douglas et al., (2006) points out that the highest percentage increase of vapor fluxes have been observed in states of Haryana and Punjab in India (137% and 128% respectively) where groundwater levels have been declining significantly (Singh and Singh, 2002).

From the above discussion it is clear that a comprehensive study on the long term response of groundwater table levels to changing climate and agricultural practices is required. In this thesis, we carry out such a study in the Indian subcontinent through a numerical modeling approach.

1.1 Model Selection

The groundwater levels are determined by the overall recharge (infiltration from precipitation and irrigated water minus the evaporative loss) into the aquifer rather than pumping alone and hence predicting the recharge is the key to groundwater level forecasts. Prediction of recharge requires numerical modeling and the major types of models used for estimating the recharge are watershed models, inverse groundwater

models, and unsaturated zone models (Keese et al., 2005, Scanlon et al., 2002). Keese et al., (2005) points out that it is difficult to obtain a unique solution from watershed models owing to the large number of parameters involved. Inverse groundwater models (Stoertz and Bradbury, 1989) on the other hand, estimate only the ratio of recharge to hydraulic conductivity and hence a unique solution requires additional data such as stream base flow (Kendy et al., 2003, Hill, 1998). The unsaturated zone models are one of the most commonly used ones to predict recharge and they are based either on solving the Richards equation (Fayer 2000, Scanlon et al., 2002a) or water balance type of models (Riha et al., 1994; Emerman 1995; Kendy et al., 2003). Solving the Richards equation often presents numerical difficulties (Bierkens, 1998) and requires significantly larger amount of field data in comparison to bucket-type methods (see Emerman ,1995 and Kendy et al., 2003). Without this additional data, the more complex Richard's type models do not provide more accurate results. Since the amount of field data available for the present problem is limited, we resort to a modified water balance-type model to predict the recharge and resulting groundwater levels.

In the present model, the root-zone water balance is calculated through the method outlined by Steenhuis and van der Molen (1985) based on the Thornthwaite-Mather procedure (Thornthwaite and Mather, 1957). This is an excellent method involving fewer parameters and thus does not require lot of observed data to run the model. In this model the evapotranspiration is at potential rate when the moisture content is above the redistribution moisture content. When the moisture content reaches below redistribution the evapotranspiration decreases exponentially until it

reaches field capacity (Saleh et al., 1989). Steenhuis and van der Molen successfully used this method in Long Island, New York, USA and Saleh et al., (1989) used this Bangladesh. Other examples of investigations that employed Thornthwaite-Mather procedure are those by Caballero et al., (2013), Di Giovanni et al., (2013), and Bakundukize et al., (2011). In the first one, the authors used Thornthwaite-Mather procedure to calculate actual evapotranspiration in a semi distributed water balance model for the evaluation of bio-hydrological impact of a cloud forest in Central America. Di Giovanni et al., 2013 used this method to estimate the evapotranspiration from urban green roofs and got a reasonable prediction of actual evapotranspiration (within 10.1% of measured evapotranspiration). Bakundukize et al., (2011) in their study in Burundy found that Thornthwaite –Mather predicts evapotranspiration within 12.9% .

The precipitation data set required for making long term water table levels predictions are obtained from Salvi et al., (2013) in which the authors used statistical downscaling methods to predict precipitation from coarse resolution climate variables from global climate models for all of India at a resolution of 0.5° for three climate scenarios envisaged by the Inter Governmental Panel on Climate Change (IPCC) in their Special Report on Emission Scenarios (SRES, 2000). IPCC defines 40 climate change scenarios grouped in to 4 families A1, B1, A2, B2 with different combinations of factors affecting climate change such as population growth, dependency on fossil fuels, and economic and technological developments. We choose three scenarios that were downscaled by Salvi et al., (2013) for the present study and these scenarios have been conventionally named as SRESA1, SRESA1B, and SRESA2. In addition, we

also consider three different crop practices in this study which involve one crop per year, two crops per year, and three crops per year.

1.2 Site Description

Andhra Pradesh is a major rice growing state in India. According to directorate of rice development, India in 2005 Andhra Pradesh produce 14.4 million tons of rice compared to 10.8 million tons by Punjab. Thus long term prediction on water table levels is important in this place. The model is validated in few sites Krishna districts in Andhra Pradesh, India. The average annual precipitation in Krishna district is 1033mm (Indian Meteorological Department). About 77% of this is during south west monsoon (June-September) and 33% from north east monsoon and summer rains. Figure 1 shows observed annual precipitation at Machilipattanam in Krishna district from 2005 to 2010. In 2005, 2006, 2008 and 2010, the annual rainfall was above normal and 2007, 2009 and 2011 were below.

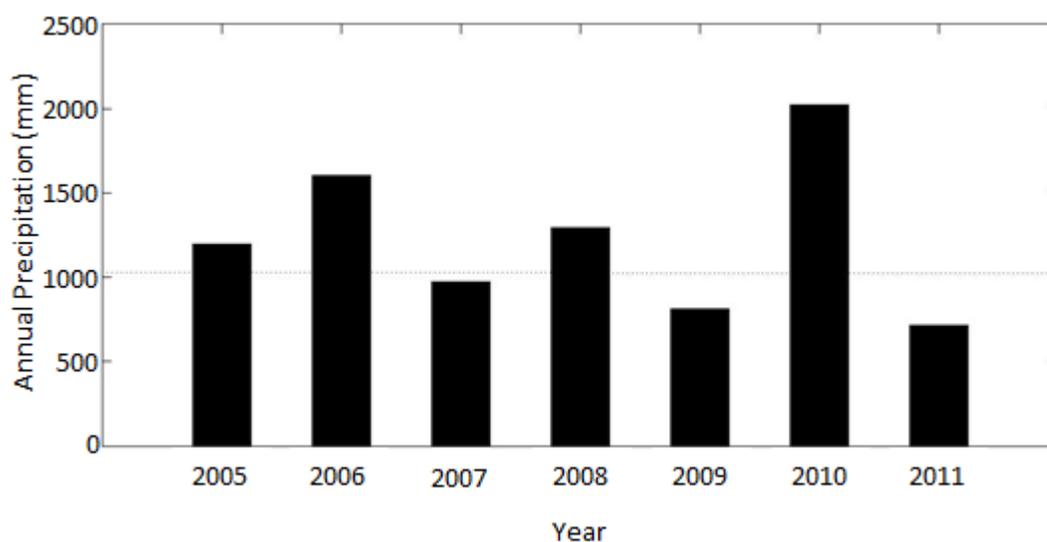


Figure 1: Annual precipitation at Machilipattanam, Andhra Pradesh, India

The main crops in these districts are paddy, pulses, cotton, and summer vegetable. The water for irrigation is partly from surface sources such as canals and partly from ground water. The ground water sources are be shallow dug well, bore wells or tube wells. The maximum depth of bore wells is around 300m.

CHAPTER 2

MATERIALS AND METHODS

The model used in this study is a modification of the watershed irrigation potential estimation (WIPE) model designed by Saleh et al. (1989) to study the impact of irrigation management schemes on ground water levels in tropical climate. This is a one-dimensional model employing the Thornthwaite-Mather procedure to calculate the recharge (Steenhuis and van der Molen, 1985) of the aquifer and is primarily applicable to shallow aquifers. The data required to run this model includes precipitation, soil properties such as the moisture content and the hydraulic conductivity, and the initial ground water level.

2.1 Model description

The model begins by dividing the soil profile into four zones namely the storage zone, puddle layer, transmission zone, and the saturated zone over an impermeable rock bed as shown in Fig 2.

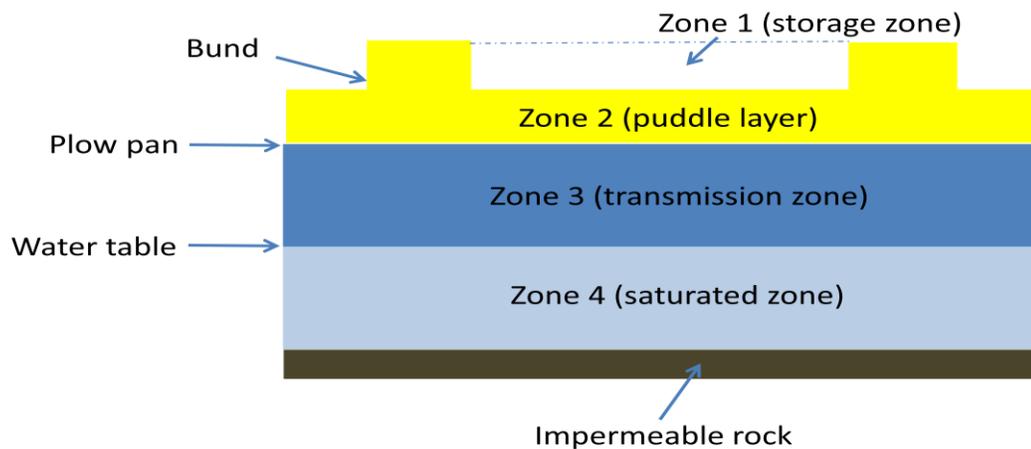


Figure 2: Schematic of the soil profile used in the model

The storage zone (zone 1) is the layer where the water is stored when the field is flooded. The maximum water depth is determined by the height of the bund which typically is 12 – 20 cm. Zone 2 is the puddle layer and has the similar thickness as zone 1. Zone 3 is the unsaturated transition zone below the puddle layer with the lower boundary at water table and the thickness of this layer varies in time according to extraction/evaporation and recharge. Finally, zone 4 is the saturated zone and the interface between zone 3 and zone 4 is regarded as the water table. Soil characteristics are averaged in each zone. Zone 3 is always at the constant moisture content and is equal to the saturated moisture content minus the drainable porosity and zone 4 is always saturated. Zone 2 (the puddle layer) has a variable moisture content depending upon the incoming and outgoing fluxes. The daily mass balance of zone 1 and 2 taken together is

$$S_{T,t+\Delta t} = \begin{cases} S_{1,t} + S_{2,t} + (P_t - PET - J_{23,t} + u_t)\Delta t, & m_2 \geq m_2^r \\ S_{1,t} + S_{2,t} + (P_t - ET_t - J_{23,t} + u_t)\Delta t, & m_2 \leq m_2^r \end{cases} \quad (1)$$

where $\Delta t = 1$ day, $S_{T,t+\Delta t}$ (mm) is the total storage in zones 1 and 2 taken together on the next day, $S_{1,t-\Delta t}$ (mm) and $S_{2,t-\Delta t}$ (mm) are the storages in zone 1 and 2 respectively on the current day, and P_t , ET_t , $J_{23,t}$, and u_t are the precipitation, evapotranspiration, flux from zone 2 to zone 3, and the upward evaporative flux from the water table in mm/day. All the storages are measured in millimeters and the precipitation and other fluxes are measured in millimeters per day. The evapotranspiration ET , the flux J_{23} ,

and the upward flux from the water table u , are all dependent upon the moisture content in zone 2 given by $m_2 = S_2/d_2$ where d_2 is the thickness of zone 2.

When $m_2 \geq m_2^r$ where m_2^r is the redistribution moisture content of zone 2, evapotranspiration will be potential so that $ET = PET$ and the flux J_{23} is given by (Saleh et al., 1989)

$$J_{23} = d_2 \left\{ m_2 + \frac{m_2^s - m_2^d}{C} \ln \left[\frac{Ck_2^s \exp(-C)}{d_2(m_2^s - m_2^d)} + \exp \left(-C \frac{m_2 - m_2^d}{m_2^s - m_2^d} \right) \right] - m_2^d \right\} \quad (2)$$

which is always directed downwards. Here m_2^s is the saturated moisture content of zone 2, m_2^d is the air dry moisture content of zone 2, k_2^s is the saturated hydraulic conductivity of zone 2, and C is a constant equal to 13 (Steenhuis and van der Molen, 1986). In this condition, there will be no upward evaporative flux from the aquifer so that $u = 0$.

When $m_2 < m_2^r$ evapotranspiration will be less than potential and decreases at an exponential rate and its value is given by (Saleh, 1989)

$$ET = d_2 (m_2 - m_2^d) \left\{ 1 - \exp \left[\frac{-PET}{d_2 (m_2^{fc} - m_2^{wp})} \right] \right\} \quad (3)$$

When the moisture content of zone 2 reached the wilting point, ET become negligible.

When $m_2 < m_2^r$ there will not be any downward flux so that $J_{23} = 0$. However, the upward evaporative flux from the aquifer will be non-zero and is a function of depth to water table from soil surface as given by Gardner (1958)

$$u = k_s \left(\frac{e^{-\alpha h} - 1}{1 - e^{\alpha h}} \right) \quad (4)$$

where k_s is the saturated hydraulic conductivity of zone 3, h is the depth to the water table, α is the diffusivity coefficient which is the inverse of air entry value Ψ_h , and Ψ is the matric potential calculated as

$$\Psi = \Psi_h \left\{ \exp \left[5 \left(1.13 - \frac{m_2 - m_2^d}{m_2^d - m_2^d} \right) \right] - 0.93 \right\} \quad (5)$$

The air entry value is calculated using (Saxton et.al 1986)

$$\Psi_h = 100 \left[-0.108 + 0.341 * m_2^s \right] \quad (6)$$

When water table is closer to soil surface the flux will be maximum and as water table goes down the flux will decrease. The limiting depth at which the flux becomes zero is approximately 4.5 meter below ground level. Equation 4 is derived from Gardner's (1958) relationship between upward flux u , suction head S_h , and capillary conductivity k

$$h = \int \frac{dS_h}{1 + u/k} \quad (7)$$

where $k = k_s * \exp(-\alpha S_h)$. This expression of k when substituted in Eq. 7 followed by integration gives the expression for the upward flux given in Eq. 4.

Calculations in the model depend on whether the puddled layer is saturated or not at the end of the time step. Hence we first calculate total storage for the next day $S_{t+\Delta t}$ and introduce a dummy variable $S_1^* = S_{t+\Delta t} - S_{2,max}$ where $S_{2,max} = m_2^s * d_2$ is the maximum storage in zone 2. S_1^* is thus the residual amount of water available for storage in zone 1. If $S_1^* > 0$ then $S_{2,t+\Delta t}$ is set equal to $S_{2,max}$ and if $S_1^* > BH$ also (BH is the bund height) then S_1 will have its maximum value which is the bund height itself and the remaining part of S_1^* becomes the run off $R = S_1^* - BH$. If $S_1^* > 0$ but

less than the bund height, then $S_{1,t+\Delta t}$ is set equal to S_1^* . When $S_1^* < 0$, there is no residual water to be stored in zone 1 and all the water is stored in zone 2. Thus in this situation $S_{1,t+\Delta t}$ is set equal to zero and $S_{2,t+\Delta t}$ is set equal to $S_{t+\Delta t}$. Irrigation using groundwater is simulated by extracting water from the aquifer and adding it to zone 1. Finally, the water table depth is updated as

$$h_{t+\Delta t} = h_t - (1/\eta)(J_{23,t} - u_t - ex_t)\Delta t \quad (8)$$

where ex_t is the extraction rate and η is the drainable porosity.

2.2 Methods used in the study

The model parameters are averaged for each zone. An example of parameters used in one of the validation site-Avanigadda is shown in Table 1. The soil in Krishna delta is black clay and grey clay on top of grey silty clay and fine sand (Saxena.et.al, 2004). The hydraulic conductivities and moisture content are selected to fall within the range of soil type.

Table 1. Soil properties used in model simulation

Description	Symbol	Value
Saturated moisture content	m_2^s	0.5
Redistribution moisture content	m_2^r	0.35
Air-dry moisture content	m_2^d	0.15
hydraulic conductivity of puddle layer in mm/day	k_2^s	6
Thickness of the puddle layer in mm	d_2	120
saturated hydraulic conductivity of vadoze zone in mm/day	k_s	1000
drainable porosity	η	5%
Bund height in mm	BH	150
Initial depth to water table	h_0	2450
potential evapotranspiration in mm/day	PET	5
initial moisture content	m_0	0.35
Constant	C	13
air entry value (cm)	Ψ_h	63

The model is validated using observed precipitation data taken from Global Historical Climatology Network daily database (GHCN) maintained by National climatic data center (NCDC)(Menne et al., 2012) . The weather station data from Machilipattanam, Andhra Pradesh, India is used in the study. The observed water table level data for Krishna district obtained from Central Groundwater Board of India is used to compare the predicted water table levels. Once validated the model is ran for 90 years (21st century starting from 2010 to 2099) for various agricultural practices with data of . from Salvi et.al (2013). In Salvi et al., (2013), predicted the precipitation by a third generation coupled GCM (CGCM3.1) by the Canadian Centre for Climate Modeling and Analysis using data temperature, pressure, specific humidity, two components of the wind at surface for different climate scenarios from the in the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC). Salvi et al., (2009) consequently employed statistical downscaling which involving developing relationships between local climate parameters and large scale variables using regression techniques to obtain data at 0.5 degree from 2.8⁰ resolution in CGCM3

We make groundwater predictions using the model described in the previous section with the precipitation predictions made by Salvi et al. (2009) as the input data. We consider three different climate projections for the time period 2010 - 2099 termed by IPCC as A1B, A2, and B1. These scenarios are based on different levels of global cooperation, environmental consciousness, and economic development which translate into different levels of greenhouse effects. The A1B scenario corresponds to the case of having improvements in energy supply and end use technologies so that the world

does not have to rely too much on a single source of energy. The A2 scenario is based on the assumption of a very heterogeneous world with continuously increasing population and slow economic development. As opposed to a strongly heterogeneous world in A2 scenario, the B1 scenario features a convergent world with population reaching a peak at the mid-century and thereafter decreasing and with economic, social, and environmental sustainability in focus. Among these three scenarios, B1 and A2 have the lowest and highest levels of greenhouse gases.

We run simulations for three different cropping practices to investigate the effects of agricultural practices on water table levels. The first practice assumes a single rain fed crop per year with a life cycle of about 120 days. If there is a requirement of irrigation during this season the additional water is supplied by pumping. The second practice assumes a rain fed crop and an irrigated crop and the third practice assumes a single rain fed crop and two irrigated crops. In all three cases a minimum amount of standing water (2cm) is maintained in the field and whenever water level goes below this a fixed amount of water (up to 1/4th of bund height(15cm)) is pumped from the aquifer and added to the storage zone.

CHAPTER 3

RESULTS

3.1 Model Evaluation

We now calibrate and evaluate the model described in the previous section by comparing the predicted water table levels from the model with observed data. Since the observed water table levels are monthly values, we average the daily water table levels predicted by the model over a month. The observed values of depth to water table are collected from the Central Ground Water Board India. We perform the calibration of the model using data collected from an observation well in Kuchipudi, Krishna district Andhra Pradesh in India. Figure 3 shows the comparison between the observed and predicted data at Kuchipudi and Fig. 4 shows the correlation between them. The line in Fig. 4 shows the case of perfect correlation between observations and model predictions.

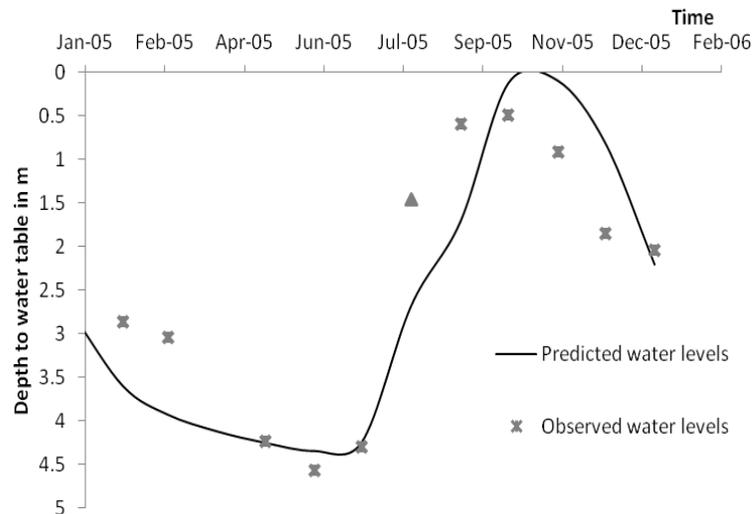


Figure 3: Observed water table heights (symbols) and predicted water table heights in meter by the model at Kuchipudi, Andhra Pradesh, India.

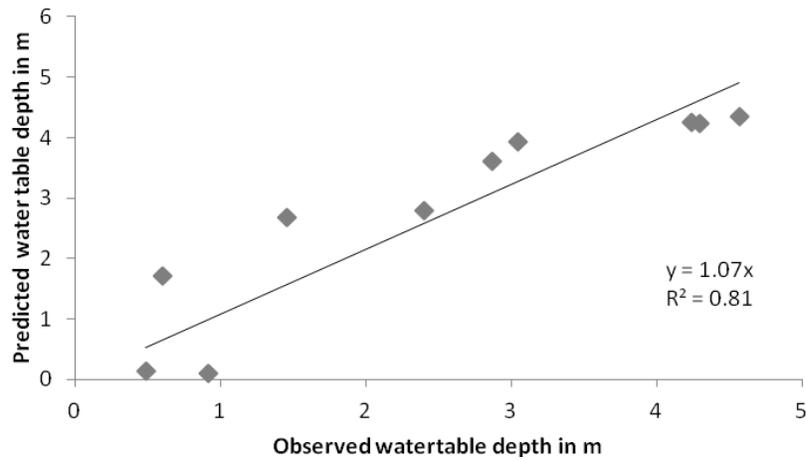


Figure 4: Correlation between model predictions and observed data at Kuchipudi, Andhra Pradesh, India

After calibrating, the model is validated at Avanigadda in Krishna district, Andhra Pradesh India. In Fig. 5 we compare the observed water table depth to the predicted water depths. Figure 6 shows the correlation between predicted data and observe data.

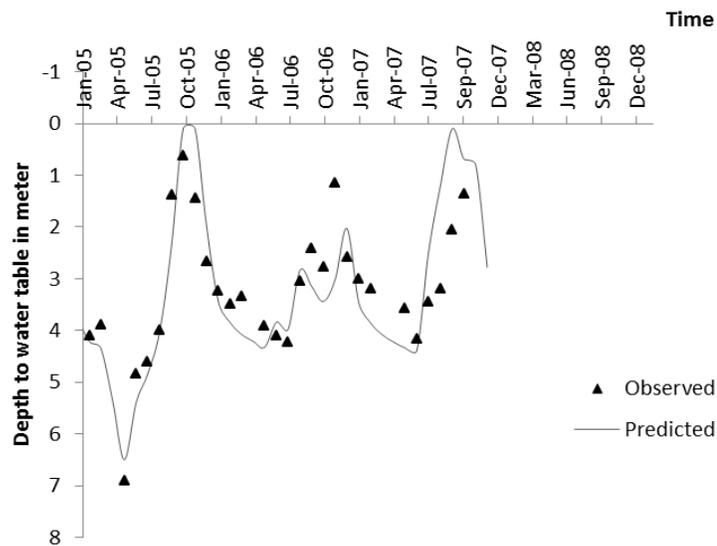


Figure 5: Observed water table heights and predicted water table heights at Avanigadda, Andhra Pradesh, India.

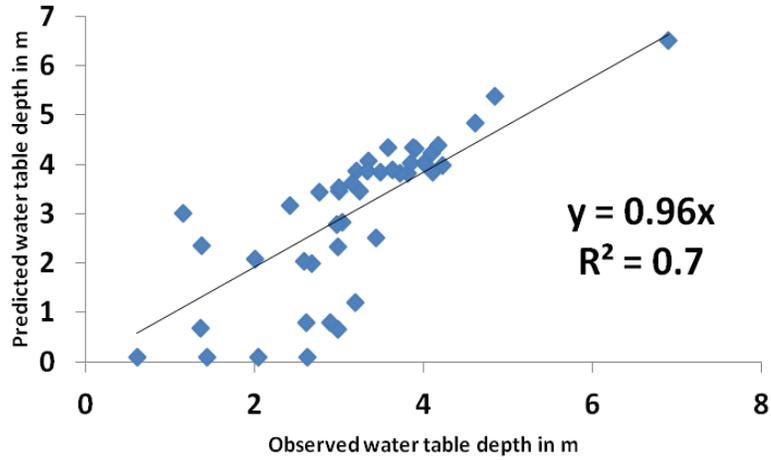


Figure 6: Correlation between model predictions and observed data (symbols) at Avanigadda. The line indicates perfect correlation between them. The correlation coefficient of model predictions and observed data is 0.7.

Figure 7 shows a typical model prediction for the precipitation data given.

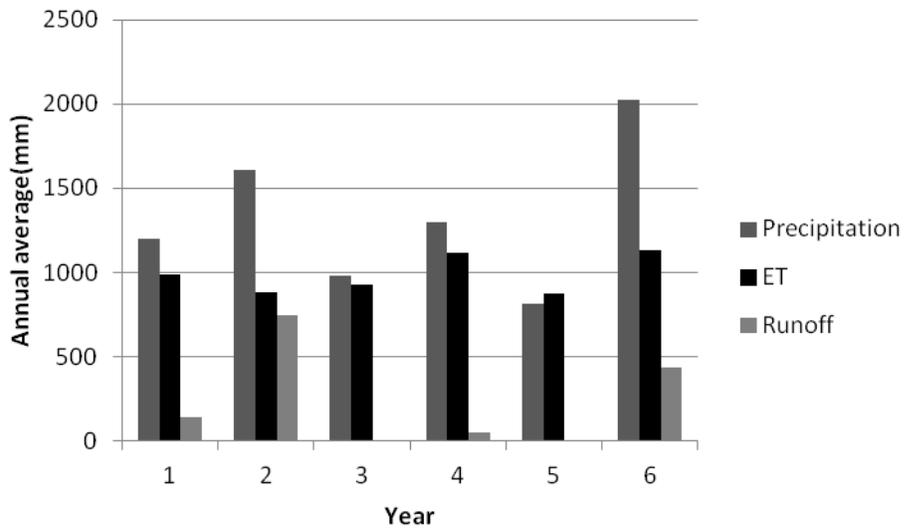


Figure 7 Annual precipitation, evapotranspiration (ET) and runoff at Avanigadda Andhra Pradesh

3.2 Model Application

The ten-year cumulative precipitation data for all the three climate change scenarios mentioned earlier i.e. A1B, A2 and B1) is shown in Fig. 8. As mentioned earlier B1 and A2 are the “best” and “worst” climate scenarios in terms of the greenhouse gas

levels (lowest for B1 and highest for A2) with A1B scenario being somewhere in the middle. Figure 8 shows that while scenarios A1B and A2 show an increasing trend of precipitation, B1 scenario has almost constant precipitation throughout the time period considered.

We now proceed to show the predicted results from model for a nine decade period of 2010 - 2090 for the case of only a single crop in a year which is rain-fed, the case with two crops per year sustained by irrigation using groundwater, and the case of three crops per year again sustained by groundwater irrigation at Avanigadda in Krishna district.

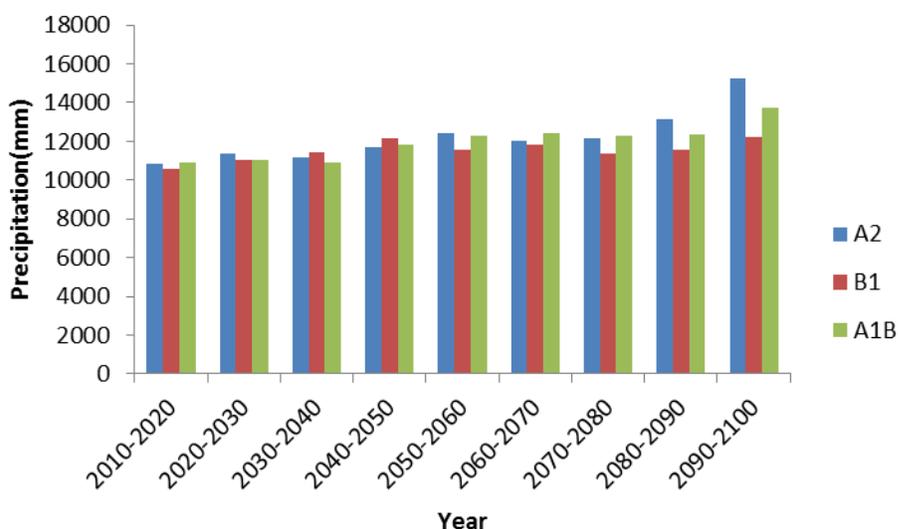


Figure 8 Ten year cumulative predicted precipitation for 21st Century for 3 climate scenarios at Avanigadda, Andhra Pradesh, India.

The case of single rain-fed crop for the three climate scenarios A1B, A2, and B1 are shown in Figs. 9, 10, and 11 respectively and Fig. 10 shows the comparison between them. In Figs. 9, 10, and 11, the ground water levels are shown by lines and the yearly precipitation by bars and in Fig. 12 green, blue, and red colors indicate A2, B1, and A1B climate scenarios respectively. In all these simulations it is assumed that there is

a bund height of 15 cm and a minimum of 2 cm standing water in kept in the field during the growing season. Whenever the water goes below that level, a fixed amount of water ($1/4^{\text{th}}$ of the bund height) is pumped from the aquifer and added to storage (S1) zone. It is clear from a comparison of Figs 9, 10, and 11 that the water table level for a single crop, rain-fed agriculture is relatively insensitive to the climate scenario. In all three climate scenarios, water table level drops to around 6 – 7 m and recovers to level that is dependent upon the yearly precipitation. The average yearly evapotranspiration is around 1200mm for all these cases and as a result, the figures show full recovery of water table levels hen the yearly precipitation is around or larger than the yearly evapotranspiration.

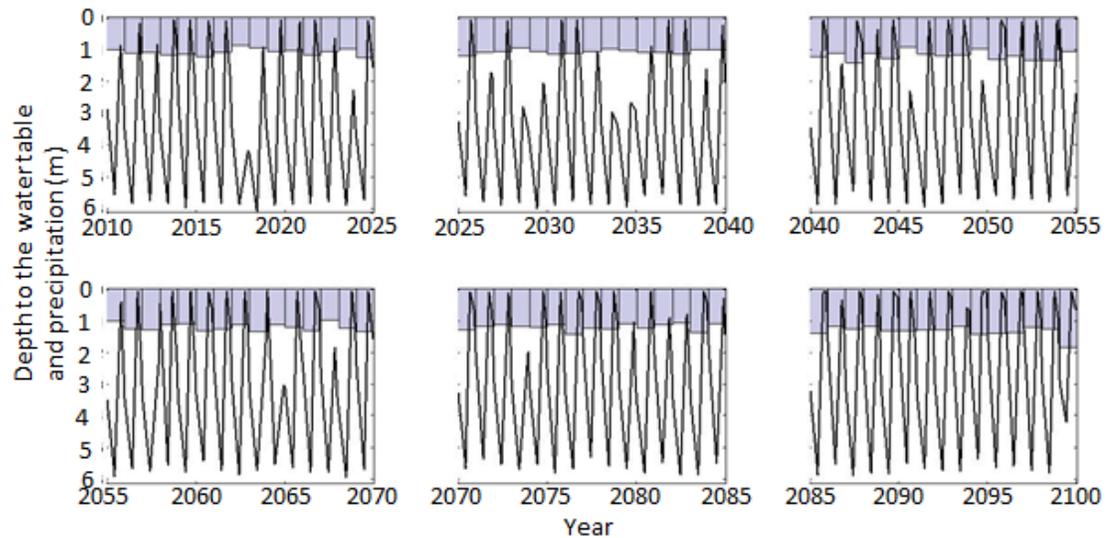


Figure 9: Water table levels (lines) and yearly precipitation (bars) for single crop, rain-fed agriculture for climate scenario A1B in Avanigadda, Andhra Pradesh. The yearly data used to plot water table levels are January 1, pre-monsoon, monsoon, and post-monsoon days. The bund height in the field is 15 cm and a minimum of 2 cm standing water is kept in the field with an extraction from the ground water equal to a quarter of the bund height. The ordinate labels shown for plots on the left side are common for all the figures in their corresponding rows.

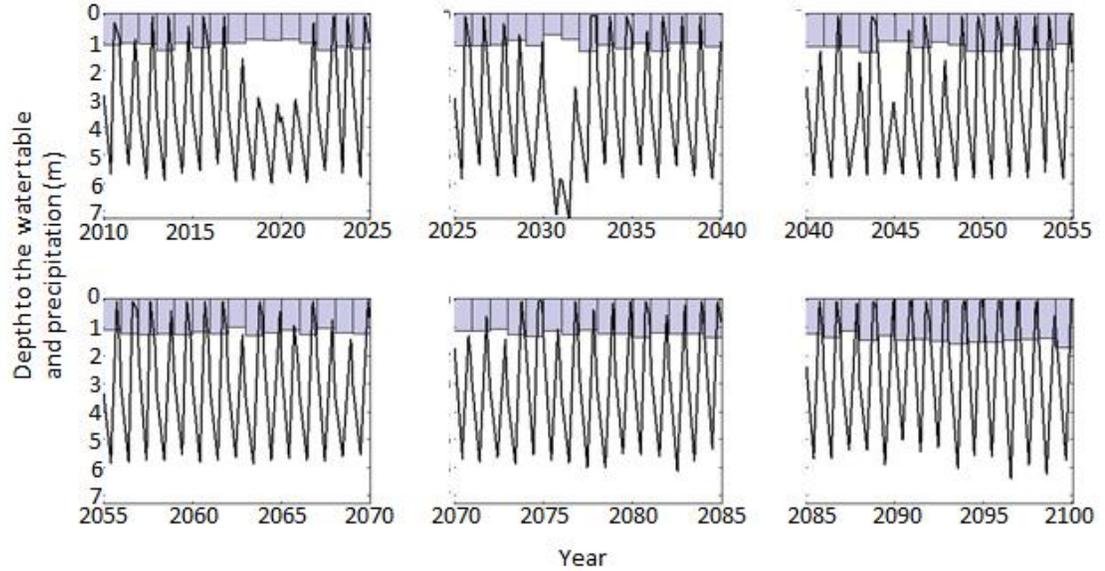


Figure 10: Water table levels and yearly precipitation for single crop, rain-fed agriculture for climate scenario A2 at Avanigadda, Andhra Pradesh. The rest of this figure caption remains same as Fig. 5.

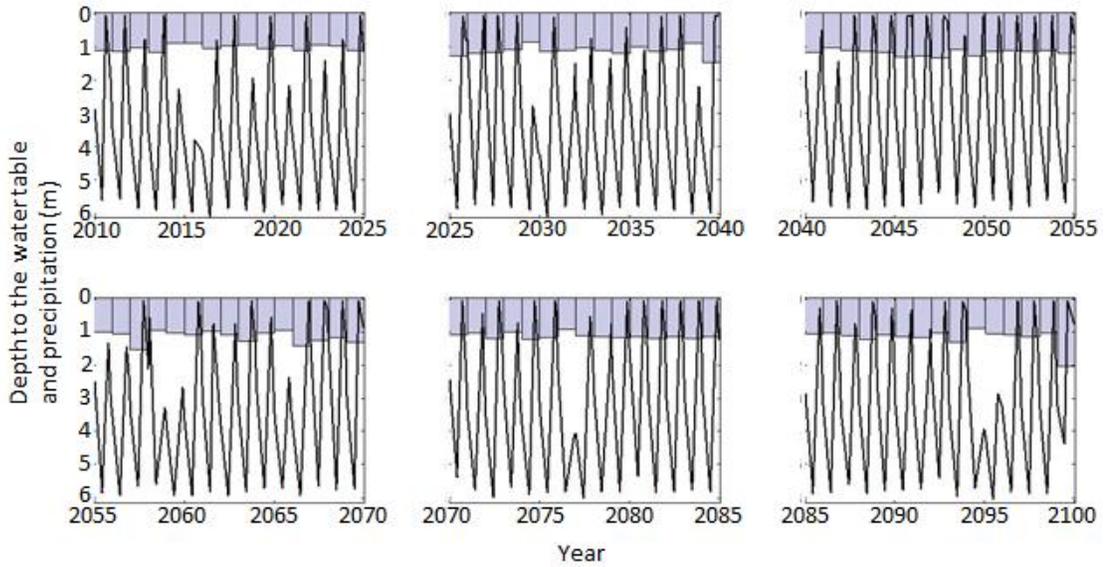


Figure 11: Water table levels (lines) and yearly precipitation (bars) for single crop, rain-fed agriculture for climate scenario B1 at Avanigadda, Andhra Pradesh. The rest of this figure caption remains same as Fig. 5.

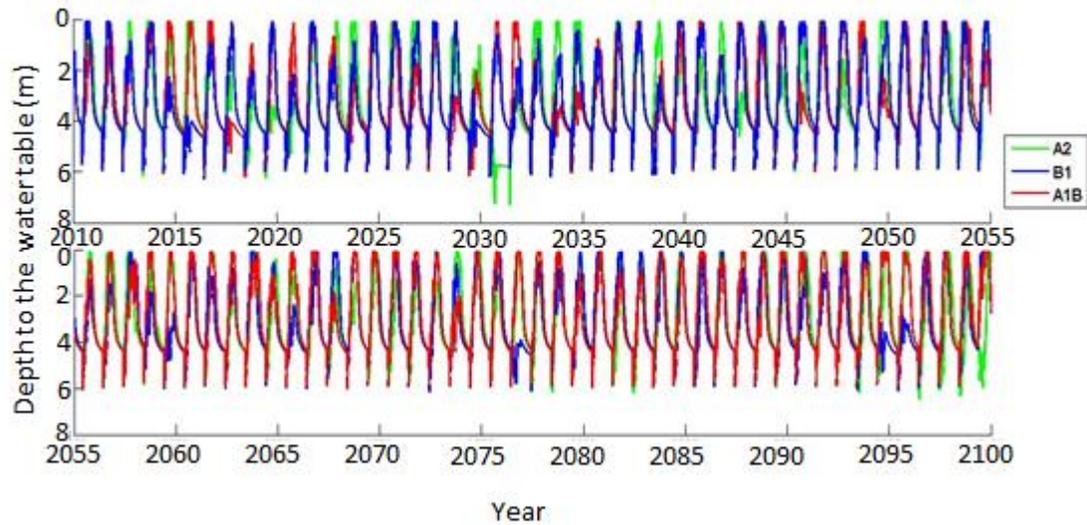


Figure 12: Comparison of all 3 climate scenario in case of one rain fed crop Avanigadda, Andhra Pradesh, India. The three scenarios A2, B1, and A1B are shown by colors green, blue, and red respectively.

We now examine in Fig. 13 the effect of two crops per year for which the number of days in a year with crop in the field exceeds the monsoon season for the three climate scenarios. The bund height, minimum standing water, and extraction are same as that of the rain-fed case which are 15 cm, 2 cm, and a quarter of bund height respectively. Increasing the number of cropped days beyond the monsoon would require significant extraction of groundwater for irrigation along with increasing evapotranspiration. If the yearly evapotranspiration exceeds the yearly precipitation the water table level drops. For all three climate scenarios, the average annual evaporation in case of 2 crops a year is around 1400-1460 mm which is clearly more than the annual precipitation at Avanigadda (around 1100 mm). Hence water table drops more and more as years pass by and by end of century the depth to the water table level is predicted to be above 200m for all climate scenarios. While the A1B and A2 scenarios

indicate an improvement in the after 2090, the B1 scenario predicts further drop in the water table level. This might appear to be surprising considering the fact that B1 scenario is focused towards sustainability. However, a comparison of projected precipitation made in Fig 7 shows that B1 scenario has a significantly lower precipitation than the other two scenarios after 2080.

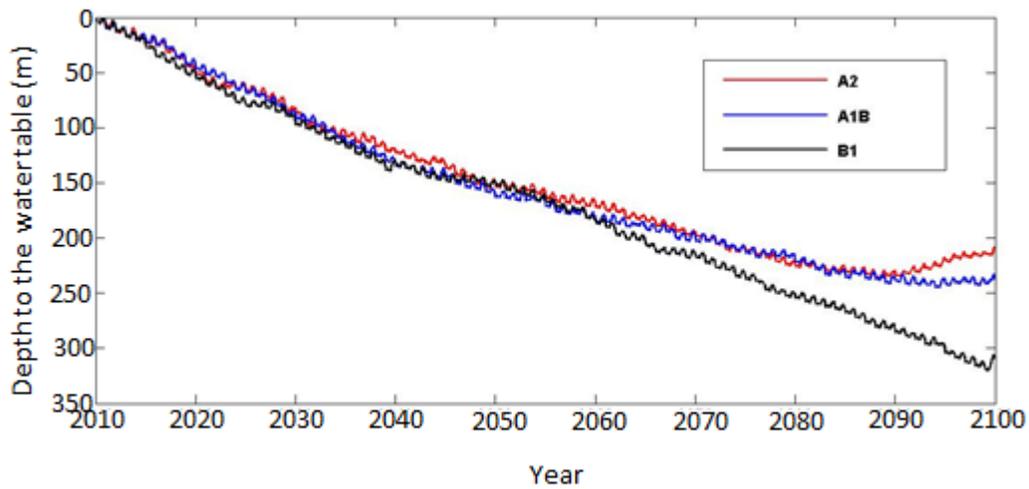


Figure 13: Water table levels for two-crop agriculture for the three climate scenarios A2 (red), A1B (blue), and B1 (black). The bund height, minimum standing water, and extraction levels are same as Fig. 5.

We also investigate the effect of amount of groundwater extracted for irrigation on groundwater levels in Fig. 14.

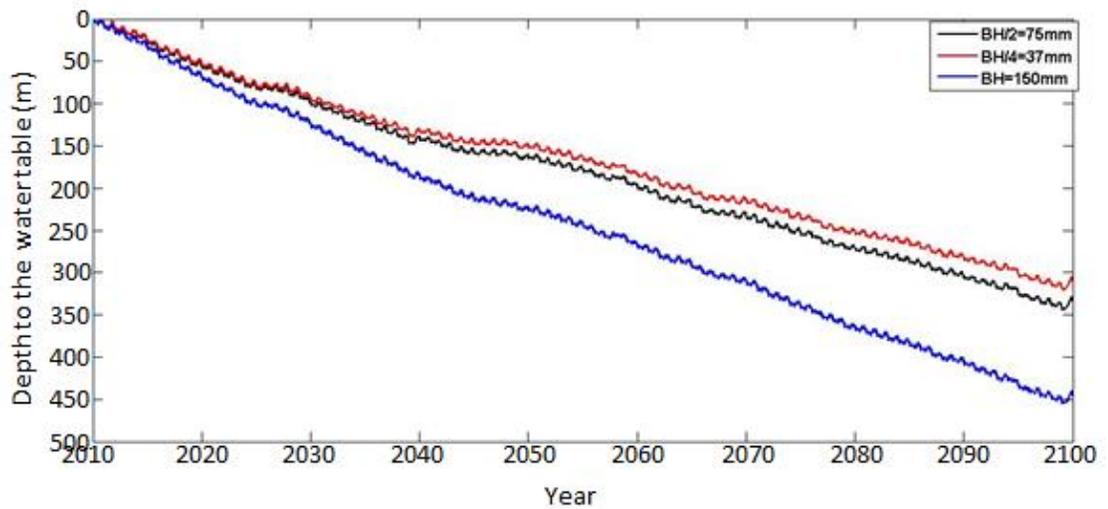


Figure 14: Water table levels for two-crop agriculture for various extraction amounts equal to BH (blue), BH/2 (black), and BH/4 (red) where BH is the bund height which is taken as 15 cm. The simulation is for scenario B1 and the minimum standing water level in the field is the same as in Fig. 8 (2 cm)

To obtain Fig. 14 from the model, we keep constant bund height (15 cm) and the minimum level of standing water (2 cm) and change the amount of extraction to bund height, (BH) half the bund height (BH/2), a quarter of the bund height (BH/4). It is clear from Fig. 14 that the increase in extraction results in a drop in the groundwater level. To explain this observation, we focus on the yearly evapotranspiration and the run-off values for the cases examined in Fig. 14 and show them in Fig. 15 and 16

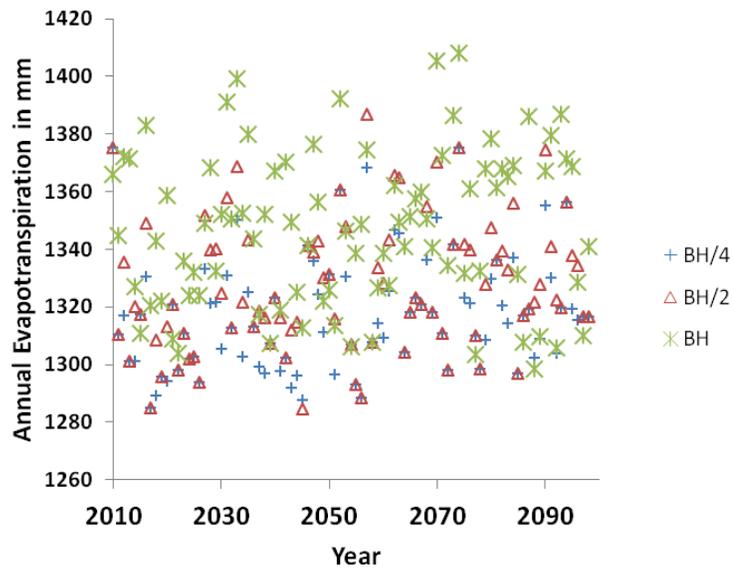


Figure 15: Annual evapotranspiration corresponding to various bund heights BH/4 ('+' symbol), BH/2 (up-triangle), and BH (star) shown in Fig. 10 for scenario B1

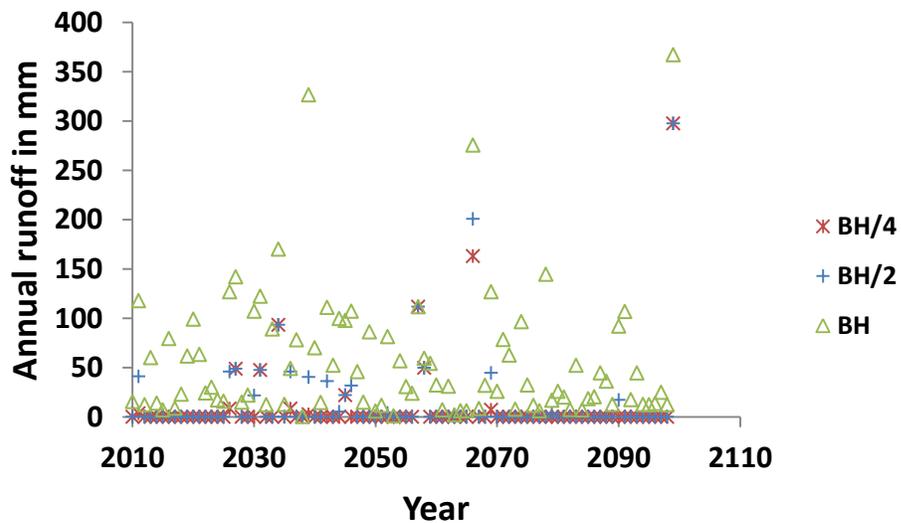


Figure 16: Annual run-off values corresponding to various bund heights BH/4 (star), BH/2 ('+' symbol), and BH (up-triangle) shown in Fig. 12 for scenario B1

Figures 15 and 16 show that while the annual evapotranspiration levels are almost the same for all extraction values, the run-off values are markedly different. The run-off in general increases with increasing extraction since the ponding of extracted water in the storage decreases the available space for storing the rain water. Thus at large

extraction values, the amount of water harvested from precipitation is significantly smaller than that of at smaller bund heights and consequently lowering the aquifer recharge. This results in a sharp decrease in the water table levels.

Finally, we consider the case of having three crops per year and Fig. 17 provides a comparison between the two-crop and three-crop cases for the three climate scenarios. It is clear from Fig. 17 that the three-crop agriculture is unsustainable as the depth to water table drops sharply and by the end of this century, the predicted depths are around 1000 m for all climate scenarios.

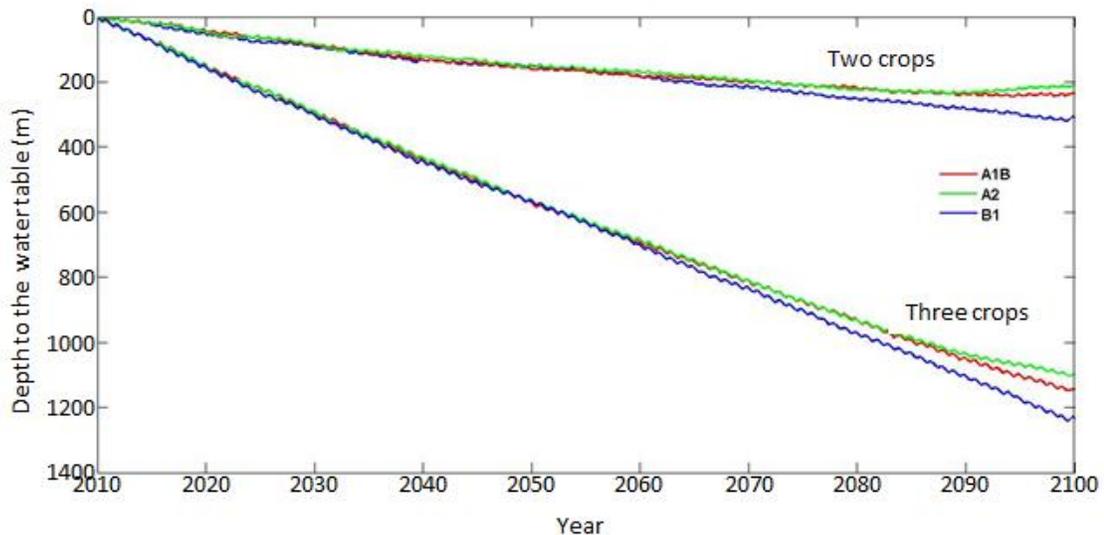


Figure 17: water table depth comparison for two crops per annum to three crops per annum for three climate scenarios A1B (red), A2 (green), and B1 (blue).

One observation in Fig. 17 is that while all the climate scenarios follow more or less the same trend until around 2060, scenario B1 deviates from the trends of A2 and A1B after 60's and A2 and A1B scenarios themselves deviate from each other's trend after 2090. The reason for the deviation of B1 scenario from the other two is that the precipitation of B1 becomes significantly smaller than the other two scenarios after

2060 (see Fig. 6). After 2090 scenario A2 receives significantly larger rainfall than A1B and hence their trends deviate from each other in Fig. 17.

3.3 Discussions and applications

In this work, we have first formulated a shallow aquifer model for predicting groundwater levels under the influence of irrigation and climate change. The model has been validated against observed data in the Avanigadda region of the Krishna district in the state of Andhra Pradesh in India. We then have used the model to predict groundwater levels for three representative climate scenario projections made by the IPCC with number of crops per year varying from one to three. The primary observation from this study is that for all climate scenarios, the single crop agriculture is quite sustainable and the two-crop and three-crop agricultures are unsustainable independent of climate scenario. While the maximum depth to groundwater is 6 – 7 m for the single crop case with frequent recovery, depths of 200 – 300 m has been observed for the two-crop case and for the three-crop case, the depth is of the order of 1000 m, if irrigated continuously for 90 years. For a given bund height increasing the amount of extraction decreases the ground water levels.

The fundamental reason behind the decreasing ground water levels is that the net precipitation is negative. If the latter is positive, even the three-crop agriculture can become sustainable and we demonstrate this here through the example of Kerala state in India where the yearly precipitation is around 3000 mm. Figure 18 shows that the three-crop agriculture scheme is sustainable in Kerala.

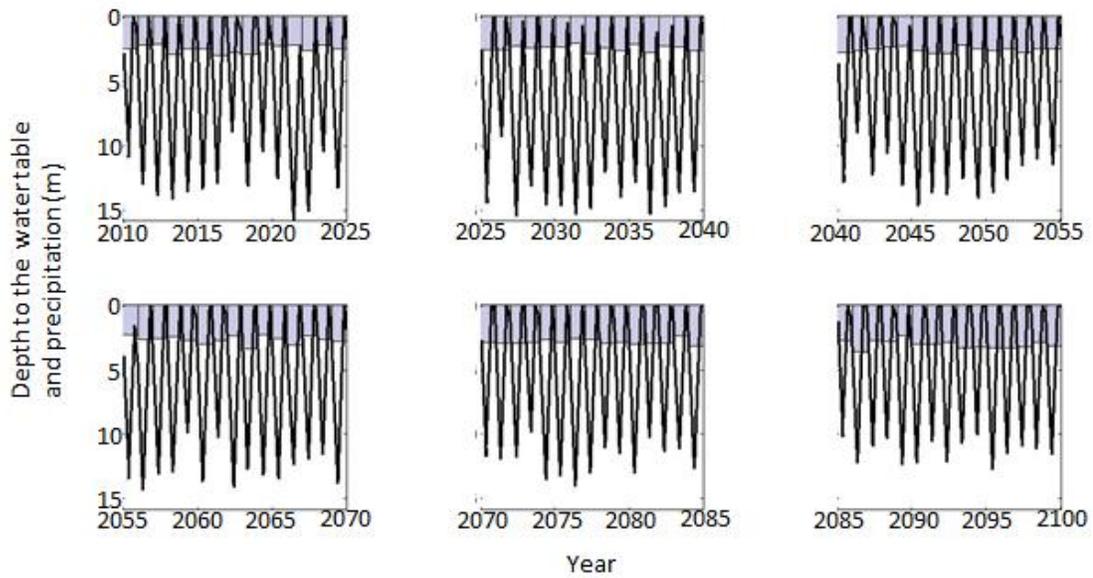


Figure 18: Groundwater levels and precipitation in Beypore, Kozhikode, Kerala ,India for three-crop agriculture scenario B1. The bund height is 150 cm, minimum standing water level is 2 cm, and the extraction is equal to a quarter of the bund height.

3.3.1 Comparison with System of rice intensification method

System of Rice Intensification method (SRI) is an agro-ecological methodology (Satyanarayana et al. 2007, Zhao et.al, 2011) that has been developed to increase the rice yield with reduced amount of irrigation. The key features of SRI method are transplanting the seedlings at a young age (typically less than 15 days old) with reduced plant density and keeping the paddy field non-flooded but moist until panicle initiation. Thereafter the field is flooded with standing water level of around 1 – 3 cm (Satyanarayana, et al., 2007). Previous studies on SRI method have recorded significant reduction of irrigation water — around 25% - 65% (see Zhao et. al., 2011, Chapagain and Yamaji, 2010, and Satyanarayana et al., 2007). It is thus of interest to study the effect of SRI methodology on groundwater levels and we address that here

by simulating a typical SRI irrigation scheme using our numerical model. For comparison, we also simulate the tradition flooded agriculture.

We simulate the SRI agriculture program adopted by Zhao et. al. (2011) in which around 25% reduction in irrigation water use compared to flooded agriculture has been reported using precipitation for climate scenario B1. The field experiments in Zhao et. al. (2011) were conducted in 2005 in Hangzhou, China. In that the transplanting of 15 day old seedlings was done on May 19 and harvesting was done on October 19. The plots were kept saturated (but not flooded) for first week after transplanting (May 19-May 26).The soil was then kept moist until 15 days after panicle initiation (September 1) and a 2cm level of standing water was maintained in the field till the end of growing season. A field with traditional flooded agriculture was used in Zhao et al. (2011) for comparison with the SRI data and our simulations of flooded agriculture are based on it. In that 30 days old seedlings were transplanted and continuously flooded with 2-10 cm standing water till 7 days before harvest.

Figure 19 shows the comparison of our simulation predictions on groundwater levels for the SRI method and the flooded agriculture. For clarity of the plot, we show the results only for a two-year time period and we have observed similar trends from simulations with long time periods. In total flooding method, the water table suddenly drops around the 150th day of every year which is time at which irrigation starts for the transplanted seedlings.

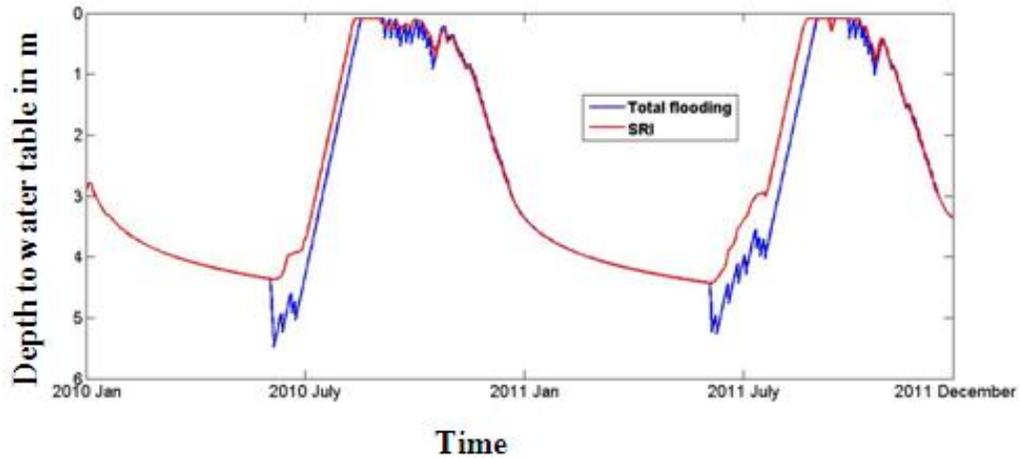


Figure 19: Comparison of depth to water table (in m) between total flooding method (blue) and SRI method (red) for climate scenario B1 at Avanigadda, Andhra Pradesh, India

Nevertheless, the water table recovers quickly owing to the recharge from percolated water indicating the recycling of water and that the irrigation induced drop in the water table is only temporary. It is just that in flooded agriculture, the amount of water equivalent to the drop in the water table level is stored within the bunds instead of the aquifer as in the case of SRI method.

This can be further illustrated by looking at the difference of evapotranspiration between two methods. The sum of evapotranspiration for 2 years is 2154mm in case of total flooding method and 2145mm for SRI method. In our simulations we found only negligible run-off both cultivation methods so that evapotranspiration is the dominant mechanism by which water is lost in the system. Now since the evapotranspiration for both cases have been found to be almost same, we can conclude that the net loss of groundwater is the same for both cultivation methods and the only difference between the SRI method and the total flooded method is whether water is stored in the aquifer

or within the bunds. Thus SRI does not result in any net saving in the amount of water used. However, a caveat here is that the present simulation considers irrigation solely by the groundwater and in situations where surface water irrigation is employed, SRI method can possibly make a difference compared to flooded agriculture.

APPENDIX

Matlab code and input files

The mat lab code used to predict water table levels for an irrigated rain fed crop ('rainfed.m') is given below. The aquifer parameters are defined in the code itself. Additional data required for running the model is precipitation and this is input as a .mat file. The same code is used to predict water table levels in case of two crops a year and three crops a year by changing the number of days irrigated. The process is given in the flow chart shown in figure 21

Mat lab code

```
%written by Indu Thekkemepilly Sivakumar on 02/27/2013
%this program calculates daily water table levels in an aquifer
when aquifer parameters and daily precipitation is known. The
parameters used to model aquifer are given below. Precipitation
data is store as P.mat

clear all;
S1star_min = 20;% minimum standing water in bund. This value
changes with different water management practices.
Extr = 150/4; %the amount of water pumped from aquifer
ms = 0.5;%saturated moisture content
mr = 0.35;%re distribution moisture content
md = 0.15;%air dry moisture content%
k2s = 10; % hydraulic conductivity of puddle layer in mm/day
d2 = 120; % depth of puddle layer in mm%
ks =1000; %saturated hydraulic conductivity in mm/day%
BH =150; %Bund height in mm
hi = 2400; %Depth of water table below ground level in day 1 in
mm;
PET = 3.5; %potential evapotranspiration in mm/day
m_init = 0.5;%initial moisture content%
C = 13;% a constant (Steenhuis and Van der Molan 1986)
load P.mat %enter daily precipitation data in mm%
S1(1) =0 ; %water level in zone 1(Storage zone) at day 1 in mm
(Maximum value is BH)%
S2(1)=m_init*d2;% storage in day 1 in zone 2
h(1)=hi;% depth to water table on day 1.
S2max=ms*d2;%maximum storage in zone 2
phi_h= 637.8;% air entry value
c = 0.002; %diffusivity constant
extr(1)=0;
%u=upward flux from water table
```

```

j = 0;
i=1;
m(1)=m_init;
count=0;
u=0;
extr(1)=0;
dp=0.05; %drainable porosity
J12(1)=S2max-S2(1);
while(i<=1100)
    if(j==365)j=1; else j = j+1; end
    if(m(i)>= mr)
% if present-day moisture content is greater than
redistribution moisture content

        ET(i)=PET;
        J23(i)=d2*(m(i)+(ms-md)/C*log(C*k2s*exp(-C)/d2/(ms-
md)+exp(-C*(m(i)-md)/(ms-md)))-md);

%calculation of downward flux to aquifer as in steenhuis and
van der molan1986,saleh 1989
        u=0;
    else
        ET(i)=d2*(m(i)-md)*(1-exp(-PET/d2/(ms-md)));

%calculation of evapotranspiration as in steenhuis and van der
molen(1986),saleh (1989).
        J23(i)=0;
        phi(i)=phih*(exp(5*(1.13-((m(i)-md)/(ms-md))))-0.93);
% calculation of matric potential,saleh 1989
        u = ks*(exp(-c*phi(i))-1)/(1-exp(c*h(i)));%upward flux
equation derived from gardner 1958
        if(u>PET)
            u=PET;
        end;
    end;

    S2star=S1(i)+S2(i)+P(i)-J23(i)-ET(i)+u;
% here layer 1 and 2 are assumed to be combined
    S1star=S2star-S2max;
% water available after filling zone 2

    if(S1star>0)

        if (S1star>BH)
            J12(i+1)=S2max-S2(i);
            S2(i+1)=S2max;
            R(i+1)=S1star-BH;% runoff
            S1(i+1)=BH;
            extr(i)=0;

```

```

else
    if(S1star<S1star_min && ( j>150 || j<270))
% || OR operator; && AND operator; varying j determines number
of days irrigated.

        extr(i)=Extr;
% the amount of water removed from aquifer
        S1(i+1)=S1star+extr(i);
        S2(i+1)=S2max;
        J12(i+1)=S2max-S2(i+1);

    else
        extr(i)=0;
        S1(i+1)=S1star+extr(i);
        S2(i+1)=S2max;
        J12(i+1)=S2max-S2(i+1);

    end;

    R(i+1)=0;
end;

else
    R(i+1)=0;
    if ( j<0 || j>365)

        extr(i)=Extr;
        S1(i+1)=extr(i);
        S2(i+1)=S2star;
        J12(i+1)=S2max-S2(i+1);
    else

        S1(i+1)=0;
        S2(i+1)=S2star;
        extr(i)=0;
        J12(i+1)=S2max-S2(i+1);
    end;
end;
U(i)=u;
    m(i+1)=S2(i+1)/d2 ;
    h(i+1)=h(i)-((J23(i)-u-extr(i))/dp); %dp is the
drainable porosity
    if(h(i+1)<100)
        h(i+1)=100;
    end;
    i=i+1;

end;

```

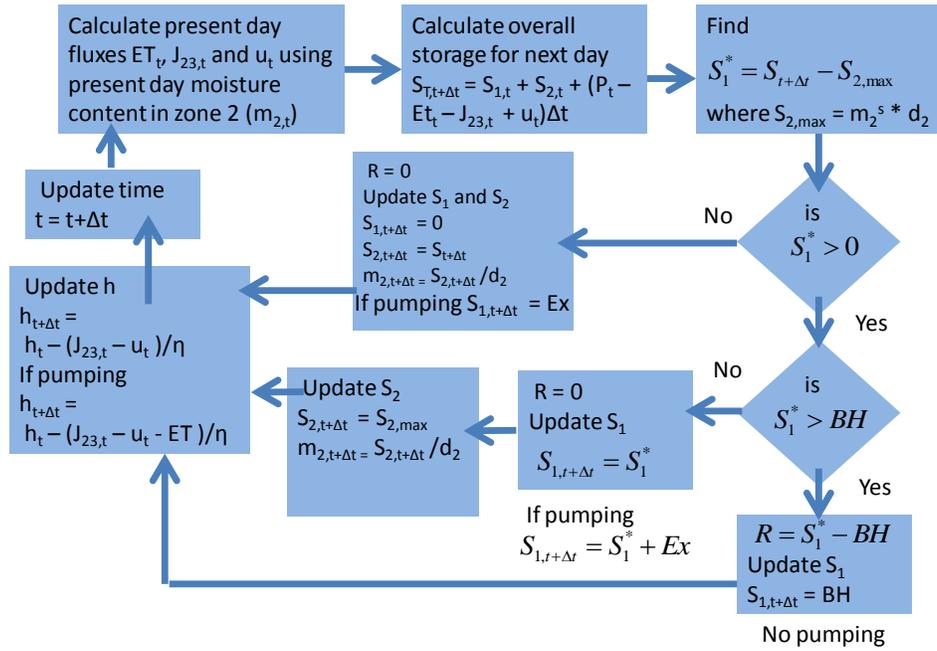


Figure 20: Flow chart of the processes in calculating daily water table levels

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