CROPPING SYSTEMS FOR GROUNDWATER SECURITY IN INDIA: GROUNDWATER RESPONSES TO AGRICULTURAL LAND MANAGEMENT

By

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ANGRAU	Acharya N.G. Ranga Agricultural University: located in Hyderabad, India; partner university in this research
AQUASTAT	This is the global web-based information system on water resources and agriculture, developed by the Land and Water Division of the United Nations FAO
ARS	Agricultural Research Service of the USDA
CDF	Cumulative distribution function
CGWB	Central Groundwater Board of India: a Ministry of Water Resources organization responsible for monitoring and maintaining sustainable groundwater resources in India
CN	Curve Number: an empirically-based parameter used in the prediction of CN runoff and infiltration; developed by the Natural Resources Conservation Service (NRCS, formerly SCS) of the USDA
CSIRO9	Commonwealth Scientific and Industrial Research Organization: climate model
CT	Conventional Tillage
DEM	Digital Elevation Model: a raster-based representation of topography
DRASTIC	A groundwater vulnerability mapping method
ET	Evapotranspiration: the combination of plant transpiration and evaporation of water from soil, surface water, and vegetation surfaces
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	A database of time-series information on food and agriculture: developed and supported by FAO
GAML	Green-Ampt Mein Larson: physically based infiltration equations developed by Green and Ampt (1911) and improved by Mein and Larson (1973)
GEV	Generalized Extreme Value: a family of probability distributions that includes the Gumbel, Fréchet and Weibull distributions as special cases

GIS	Geographic Information System: software tools used in the development and analysis of spatial data
GLUE	Generalized Likelihood Uncertainty Estimation: a simple, generic numerical method for use in calibration and uncertainty analyses of models of systems
GRACE	Gravity Recovery and Climate Experiment: twin orbiting satellite system used for observations about TWS
GSA	Global Sensitivity Analysis
HYETOS	A computer program used for stochastic disaggregation of rainfall to shorter time scales
IAHS	International Association of Hydrological Sciences
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IDF	Intensity, duration, frequency: relationships describing the rainfall pattern of a certain location
IPCC	Intergovernmental Panel on Climate Change
LSA	Local Sensitivity Analysis
LULC	Land use and land cover: describes the natural and human-made landscapes
MDS	Maximum depression storage: the greatest area-averaged depth of water that can be stored on the surface of a land area before runoff occurs
MSP	Minimum Support Price: an Indian national agriculture policy that sets the lowest prices for selected crops
NASA	National Aeronautics and Space Administration of the United States government; responsible for aerospace research
NSE	Nash-Sutcliffe Efficiency: a model evaluation quantity
NSS	Near surface storage: depth of water stored in surface depressions, comparable to MDS
PBIAS	Percent bias: a model evaluation quantity
PUB	Predictions in Ungauged Basins: and IAHS initiative to reduce model prediction uncertainty

RSR	The ratio of the root mean square error in model predictions to the standard deviation of measured data: a model evaluation quantity
SCS	Soil Conservation Service of the USDA; now called the Natural Resources Conservation Service (NRCS)
SINTACS	A groundwater vulnerability mapping method adapted from DRASTIC for improved performance in Mediterranean areas
SWAT	Soil and Water Assessment Tool: a distributed-parameter, landscape-scale, open-source hydrologic model
TAW	Total available water: depth of water in soil that is extractable by plants
TR	Tied-Ridge tillage
TWS	Terrestrial water storage: total amount of water stored in a specified land area during some time
UKHI	United Kingdom Meteorological Office High Resolution General Circulation Model: a global climate model
USDA	United States Department of Agriculture
WAVES	A biophysically based water balance model

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The total annual groundwater withdrawals in India (251 billion km^3) are the highest of any nation. Depletion of groundwater resources is increasingly common in much of India, and farmers bear significant costs and greater vulnerability resulting from the loss or reduction of a reliable irrigation source. Three hypotheses were tested: (1) current rice cropland extent and management practices are depleting groundwater supplies, (2) tillage for water harvesting can significantly increase groundwater recharge in rainfed croplands, and (3) there are combinations of tillage, crop selection, and irrigation that are likely to increase groundwater recharge and reduce groundwater withdrawals. In order to test these hypotheses, there was the objective to evaluate improvements to the Green-Ampt infiltration routines of a hydrologic model, the Soil and Water Assessment Tool (SWAT), through the addition of a dynamic surface storage depth used for tillage parameterization. Also, the final objective was to assess the social and economic impacts of alternative agricultural land management. SWAT was used for simulating the groundwater balance (recharge – irrigation pumping) of a 512 ha watershed to examine a variety of possible agricultural management options for groundwater

sustainability. The best options for groundwater sustainability were evaluated based on predictions of groundwater recharge and withdrawals, evapotranspiration, and estimated household incomes. Reductions in rice cropland areas significantly improved the groundwater balance of the study area; water harvesting tillage simulated in all rainfed areas increased groundwater recharge by about 30 mm/year. Surface storage depth was shown to be the most important parameter for infiltration prediction in agricultural systems having 1.5 to 5.0 cm of surface storage capacity; surface storage depth was still important for infiltration prediction in systems having 0 to 1.0 cm of surface storage capacity. The vast extent of rice cropland areas and their highly negative groundwater balance suggest that irrigation from groundwater resources has caused much of the observed groundwater decline in India. Sensitivity analyses suggest that the addition of a variable surface storage depth head to the Green-Ampt infiltration routine can reduce uncertainty in infiltration simulations. Evidence of rainfall characterized by storms of greater intensity suggests that surface storage of runoff will become increasingly important for maintaining or improving current levels of groundwater recharge. Estimates of the economic impacts of selected management scenarios show promise that moderate management changes to improve the groundwater balance can still maintain or increase total watershed-scale income.

CHAPTER 1
PROJECT OVERVIEW, GROUNDWATER MANAGEMENT, AND REASONS FOR GROUNDWATER DEPLETION

Introduction to Study Area

There is general agreement that water scarcity in India is severe (Alcamo et al., 2000; Yang et al., 2003). Total (761 km^3) and agricultural (688 km^3) water withdrawals for India in are the highest in the world (AQUASTAT, 2010). Groundwater in India is a highly important resource for irrigation and household use, and its extensive use is resulting in widespread groundwater depletion (Shah et al., 2003; CGWB, 2007; Rodell et al., 2009). More than half of the irrigation requirements of India are met from groundwater (CGWB, 2002; Shah et al., 2003), and the number of mechanized borewells in India has increased from less than 1 million in 1960 to 26-28 million in 2002 (Mukherji and Shah, 2005).

India is characterized by substantial diversity in climate zones and landscapes. One of the highest annual rainfall averages occurs in Cherrapunji in northeastern India: 11,430 mm. Western Rajasthan of northwestern India averages only 37 mm of annual rainfall; the national average annual rainfall is 1083 mm/year. India is the second most populous and seventh largest country in the world (1.18 billion people, 328 Mha of total area and 180 Mha agricultural area; FAOSTAT, 2010).

The study area being considered here is in the Wargal mandal (a mandal is a local organizational unit, similar to a county) of Medak district, Andhra Pradesh, in the southern, central part of India. This area was selected by Indian collaborators from Acharya N.G. Ranga Agricultural University (ANGRAU) in Hyderabad, Andhra Pradesh. Figure 1-1 illustrates the location of the study area. This 512 ha watershed was selected for analysis because of its relative proximity to ANGRAU and because it is illustrative of the common regional problem of groundwater decline, making farming systems increasingly vulnerable. There are 157 households with landholdings in Wargal; 198 borewells are found in Wargal.

Climate of Wargal

The annual average rainfall in Wargal is 780 mm; about 80% of rainfall is received from June-September from the southwest monsoon system. Average annual Potential evapotranspiration (PET) in Wargal is between 1600 and 2000 mm/year (UNEP, 1992). PET is the amount of water that would be evaporated and transpired from a landscape that had no soil moisture deficit. The year is divided into three seasons: kharif season is the rainy season and most important growing season from June-September, rabi is the season from October-February, summer is the very hot, dry season from March-May.

Groundwater System of Wargal

Groundwater in the Wargal study area occurs, based on field observations (CGWB, 2007) and the work of Marechal et al. (2006), under largely unconfined conditions in consolidated formations (fractured granite; transmissivity: 100 to 150 m^2/day; specific yield: 0.010 to 0.015). The study by Marechal et al. (2006), in a watershed nearby the Wargal area, characterizes the hydrogeology as being Archean granite overlain by a clayey-sandy regolith layer. This is consistent with the general hydrogeological characterization developed by Dewandel et al. (2006) for hard-rock aquifers in India. The fissured granite layer, 20-35 m thickness, is typically where borewell casings are screened for groundwater withdrawal; this layer also is responsible for much of the horizontal flow (Dewandel et al., 2006). The water table is 15-30 m below the ground surface, and there is very little interaction with surface water. The diagram of Figure 1-2 (adapted from Marechal et al., 2006) describes the aquifer system of Wargal.

There are sometimes increased water quality problems as groundwater levels become reduced; this is often to due naturally occurring arsenic and fluoride in the geology and soils of a region (Khan, 1994, concerning arsenic in Bangladesh; Subba Rao and Devadas, 2003, concerning fluoride in India). The concentrations of fluoride and arsenic in groundwater are sometimes greater deeper in an aquifer, and more water is withdrawn from deeper in the system as water levels decline. There have been anecdotal reports of some people in Wargal showing mild symptoms of fluoride contamination (Reddy, 2009), and the study of Subba Rao and Devadas (2003) in a district in western Andhra Pradesh documents a number of cases of fluoride-contaminated groundwater.

The Wargal watershed is located in the northwestern Andhra Pradesh district of Medak; groundwater resources for the Medak district (in 2005) were a total renewable groundwater volume of 813.19 Mm^3 and a net annual draft 704.07 Mm^3, leaving a balance of 109.12 Mm^3 of groundwater or a stage of ground water development of 87% (CGWB, 2007); these values were developed from large-region simple water balance estimates and limited data on borewell withdrawals. A decade of monitoring groundwater levels in borewells in Medak district (1996-2005) showed pre-monsoon groundwater decline of 1.1 to 5.2 m. and post-monsoon decline of 0.2 to 6.6 m during the 10 year period (CGWB, 2007). The monitoring consists of 26 wells being manually measured four times each year for depth to groundwater.

Artificial recharge of groundwater is an ancient and widespread practice in India. More than half a million artificial recharge structures (ponds and reservoirs from excavation and small dam construction) are scattered throughout the country (Sakthivadivel, 2007). There are six small reservoirs developed for groundwater recharge in Wargal. In-field water harvesting through tillage practices has received little attention relative to the groundwater recharge schemes outside of cropland areas. In-field water harvesting (or water harvesting tillage) research in India has been mostly concerned with residue management and runoff comparisons between conventionally tilled and no-till systems (Rao et al., 1998; Bhattacharyya et al., 2006). The groundwater crisis can be addressed at both the supply and demand sides through water harvesting tillage: decreasing the runoff of rainfall from cropland areas reduces required irrigation withdrawals and also increases recharge of groundwater as stored water percolates beyond plant root zones.

Conservation tillage is any tillage practice that reduces soil and water loss from a cropland area. Water harvesting tillage, a type of conservation tillage, describes the formation during primary cultivation of soil surface geometries that allow for potentially substantial surface storage of rainfall or applied water. Soil surface microtopography has a significant impact on infiltration (Darboux and Huang, 2005), and in agricultural areas is largely influenced by tillage management. Numerous demonstrations of crop yield and soil moisture improvements have been demonstrated in response to water harvesting tillage (Twomlow and Breneau, 2000; Wiyo, 2000; Guzha, 2004; Tesfahunegn and Wortmann, 2008). However, the hydrologic benefits of water harvesting tillage at large spatial and time scales have received comparatively little research. An objective of this research was to demonstrate the groundwater recharge responses to increases in rainfed croplands under water harvesting tillage and changes in crop selection and irrigation management. Additionally, the study produced estimates of long term groundwater decline under present management practices. This analysis was completed using an established water balance model: the Soil and Water Assessment Tool (SWAT), described by Arnold et al. (1998), Gassman et al. (2007), and Krysanova and Arnold (2008).

Goals of the Research

Agricultural water use makes up 80% of India's total freshwater withdrawals, and more than half of the irrigation requirements of India are met by groundwater (CGWB, 2002; Shah et al., 2003); therefore, irrigation from groundwater can be credited with significant responsibility for the food grain self-sufficiency achieved by India in the last three decades. Throughout Asia, irrigation from groundwater has become a major contributor to agricultural improvements in recent decades. The extensive survey of Shah et al. (2006) collected data from 2,629 well-owners from 278 villages in India, Pakistan, Nepal, and Bangladesh for the purpose of assessing the significance of irrigation from groundwater in the agricultural economies of South Asia. Their data prompted the finding that for most farmers, irrigation from groundwater "has become the fulcrum of their survival strategy" (Shah et al., 2006). Some investigators have suggested that the groundwater socio-ecology in Asia, and particularly in India, is at a critical point (Mukherji and Shah 2005; Shah et al., 2003). While from a resource-management perspective, groundwater depletion could be said to be self-regulating; meaning, as groundwater is depleted, extraction becomes more expensive and groundwater withdrawals are reduced. There is little evidence that this self-regulation is happening in South Asia (Shah et al., 2006), and if it does, there are still severe consequences for households that lose the ability to irrigate from groundwater sources.

The progression of groundwater use in agriculture has been organized into four stages (Shah et al., 2003): (1) expansion of borewell installations, (2) groundwater-based agrarian boom, (3) onset of groundwater depletion concerns, and (4) collapse of groundwater-based systems. Data from the Wargal study area (perceptions of farmers, numbers of failed borewells, and district-scale ground water level monitoring) suggest that the study area is in stage three of the four stages: onset of groundwater depletion concerns. Broadly, the goal of this research is to find the best agricultural management solutions for reducing groundwater pumping and increasing groundwater recharge. The hypotheses being tested:

Hypotheses

The following hypotheses were tested in this research:

- Current rice cropland extent and management practices are depleting groundwater supplies
- Tillage for water harvesting can significantly increase groundwater recharge in rainfed croplands
- There are combinations of tillage, crop selection, and irrigation that can improve groundwater recharge and reduce groundwater pumping while remaining sufficiently productive for household economies

Objectives

- Assess groundwater sustainability of agricultural management scenarios (selected combinations of crop selection, irrigation management, and tillage) at a watershed scale
- Evaluate improvements to a hydrologic model, Soil and Water Assessment Tool for simulating groundwater balance under various cropping systems

- Combine biophysical and social analyses to improve the relevance and likelihood of implementation of proposed agricultural management solutions to groundwater depletion

These objectives were designed to test the three hypotheses about rice cropland extent, tillage for water harvesting, and combinations of management alternatives.

Groundwater in India: Evidence for and Causes of Depletion

Wargal Regional Groundwater Monitoring

The groundwater of Wargal mandal was estimated at 98% stage of development in 2004, meaning that annual groundwater withdrawals were nearly equal to annual groundwater recharge (1018 ha-m consumed of 1040 ha-m recharged, CGWB, 2007). Recharge estimates were based on topographic, geologic, soils, and weather data. Withdrawals estimates are based on total number of wells in the district (115,718 total, mostly borewells) and average daily operation time and flow rate. India's Central Groundwater Board (CGWB) observed a 2 – 4 m decline in water level in 26 observation wells in Medak district during the 10 years from 1996 to 2005, suggesting an approximate annual decline of 20 cm (CGWB, 2007). This decade of monitoring and the water balance simulations of Chapter 4 give some evidence that the groundwater of Wargal mandal is actually beyond a 100% stage of development, meaning withdrawals are exceeding recharge.

Northwest India Large Region Groundwater Decline

A recent groundwater depletion study that has received much attention is the remote sensing analysis of Rodell et al. (2009). The study area was northwestern India, the states of Haryana, Punjab, and Rajasthan, which is distant from the study area being considered here. However, the analysis is illustrative of regional groundwater decline reports that are common in the literature. In this case, the nature of the observations required that the study area be very large. The NASA Gravity Recovery and Climate Experiment (GRACE) satellites were employed to measure changes in terrestrial water storage (TWS). The GRACE system is different from typical remote sensing systems in that it does not use any sensing of electromagnetic waves (thermal, visible, or microwave), rather it uses changes in distance between the pair of GRACE satellites as they orbit the earth to estimate TWS changes. The changes in distance result from accelerations of the satellites in response to changes in the gravity field of Earth. The gravity field is altered by terrestrial landscapes, biomass, buildings, and water. Information about topography, land use/land cover, vegetation, and surface water allows the effects of these to be accounted for, leaving groundwater to explain the remaining variation in gravity field. During the study period from August 2002 to October 2008, 109 km^3 of groundwater loss was estimated; that is the equivalent of about 4 cm each year over the three-state area. Rainfall was considered to be normal during the period.

Groundwater Balance and Agricultural Management

The groundwater balance is connected to the overall water balance at the land surface. In this project, where it is proposed that agricultural groundwater withdrawals are reducing groundwater storage volumes, a convincing connection should be shown between groundwater pumping and groundwater level decline. Before looking at the relevant regional and national data, it is helpful to consider the simple water balances:

In the unsaturated zone and at the soil surface:

$$\Delta SW = P + I - ET - RO - \Delta SS - DP + \Delta UF \qquad (1\text{-}1)$$

where ΔSW is change in soil water, P is precipitation, I is irrigation, ET is evapotranspiration, RO is runoff, ΔSS is a storage pool representing the increase or decrease in surface storage in small or large depressions, DP is deep percolation, ΔUF is the net change in subsurface flow into and from the system.

In the saturated zone (groundwater system):

$$\Delta S = R - I - CR + \Delta SF \qquad (1\text{-}2)$$

where ΔS is change in groundwater storage, R is recharge (approx. = DP), I is irrigation pumped from groundwater, CR is capillary rise, ΔSF is the net change in flow into and from the groundwater system.

The water balances are diagrammed in Figure 1-3. The diagram includes infiltration (Inf) as a water balance component in the unsaturated zone; Inf is an indirect flow, but it is the only component crossing the boundary at the surface. Inf can be expressed as: $Inf = P + I - RO - ET - \Delta SS$. In the analysis of Wargal watershed, the boundaries of both zones are assumed to be the boundaries of the study area.

All of the above quantities are manageable (except P) either directly or indirectly. If the goal is to improve or maintain S (groundwater storage), observing the diagram of Figure 1-3 indicates that irrigation and recharge remain as the manageable quantities in the groundwater balance, irrigation managed directly and recharge managed indirectly through management of SS, ET, and I. Irrigation and recharge appear in the surface water balance as I and DP. Therefore, the data presented about population, irrigated area, rice cropland, and others should be associated either with I or DP as these are the quantities at the surface that are directly influencing the groundwater balance. The widespread reports of groundwater decline in India suggest that it is safe to assume that changes in SF and CR are not responsible for the observed large regional groundwater decline. There are large regions of northwestern and peninsular India where groundwater depletion is well documented (Foster and Chilton, 2003), and if depletion in these regions was caused by excessive groundwater withdrawals from neighboring areas, that would just mean that there is even more greater groundwater decline in those neighboring regions.

Historical Data: Rice Cropland Extent, Groundwater Irrigated Area, Rainfall

This section presents evidence from the literature and from national and state-level data suggesting that rice cropland management and extent has resulted in the observed groundwater depletion in India. Indian groundwater depletion is generally attributed to the large observed increases in irrigation from groundwater that have occurred in India during the last 40 years (Rodell et al., 2009; Rao et al., 2001; Shah et al., 2003). Flooded rice is the dominant crop in India and is typically irrigated heavily to maintain ponded surface water in fields. From 1961 to 2001, the national harvested rice area of India increased from 35 to 45 Mha and average yields jumped from 1500 to 3100 kg/ha (FAOSTAT, 2010). Trends are similar, as shown in Figure 1-4, in the study area's state of Andhra Pradesh during this period. Rice exports are small relative to domestic consumption; therefore, the huge increases in rice production from 1961 to 2007 are largely in response to the increase in India's population. As expected, the trends in rice production and population increase are similar: from 1961 to 2007 rice production increased 277% and population increased 255% (FAOSTAT, 2010).

Yield increases in the aforementioned period (214%: 1961 to 2007) are partly the result of increases in irrigated area and improvements in irrigation management; plant variety and nutrient management improvements have also likely contributed to yield increases. Figure 1-5 shows a nearly fourfold increase in area irrigated from groundwater resources between 1961 and 1993; also shown is the steady increase in

India's population. To create this expansion in groundwater irrigated area, the number of mechanized wells and borewells in India increased from less than 1 million in 1960 to more than 26-28 million in 2002 (Mukherji and Shah, 2005).

These data and figures show clear correlations between population, rice production, and groundwater irrigation. It could be argued that without a time series of water balance data, the causes of groundwater depletion cannot be known. This is true; however, it can reasonably be inferred – from the observed increases in area irrigated from groundwater, borewell installations, rice area, and from the literature on water balances of rice systems – that irrigation withdrawals of groundwater are resulting in depletion of groundwater resources in India.

The other possible explanation for reduced quantity of groundwater resources – aside from management affecting recharge and/or groundwater withdrawal – is declining rainfall trends. As mentioned above in the discussion of groundwater and surface water balances, recharge and irrigation are the manageable quantities of the groundwater balance. Recharge could be altered in numerous ways by management at the surface that affects surface storage, runoff, deep percolation, and/or evapotranspiration. If it is assumed, due to the increases in rice croplands which reduce runoff and increase surface storage, that the changes over time would not decrease the potential recharge of a landscape, then groundwater depletion must result either from a reduction in water reaching the surface (rainfall) or an increase in groundwater pumping. Increased irrigation from groundwater of course increases water applied to the surface, but the partitioning of the water – generally about half the irrigation water leaves the system as evapotranspiration – means the net change in the groundwater balance would be negative. Therefore, it should be examined whether precipitation changes could explain the observed groundwater depletion.

Long term rainfall trends (annual rainfall depth data from Kothawale et al., 2008) are considered in Figures 1-6 and 1-7 for the regions of groundwater depletion mentioned above – 20 cm/year in Medak district, Andhra Pradesh (CGWB, 2007); 4 cm/year in Haryana, Punjab, and Rajasthan (Rodell et al., 2009). Small annual declines in total rainfall, if trends are assumed linear, suggest rainfall changes have little connection to groundwater depletion. Linear trends from 1960 were estimated to be: -1.66, -1.80, -0.98, and 0.22 mm/year in Punjab, East Rajasthan, Haryana, West Rajasthan, respectively. If a long term average annual decline in rainfall is 3 mm and if 25% of rainfall is assumed to contribute to groundwater recharge, then groundwater decline associated with rainfall reduction would be at most 0.75 mm. Additionally, if the linear trends in annual rainfall are considered for the more recent time periods associated with the studies mentioned, then the rainfall trends become positive: 1.37 mm/year in Telangana (Medak study, 1996 - 2005) and 33, 41, 6, and 26 mm/year for the states in the northwest (Rodell study, 2002 - 2008). The Medak and GRACE studies are just two examples of numerous reports of groundwater depletion in India, and in these two regions, based on the small increases in average annual rainfall totals during monitoring periods that demonstrated groundwater depletion, it seems unlikely that changes in rainfall are responsible for groundwater decline as rainfall increased during the study periods. This suggests that groundwater pumping for irrigation is indeed the more probable cause of the reported groundwater depletion.

Water Balance Simulation Methods and the Soil and Water Assessment Tool

Soil and Water Assessment Tool Overview

The Soil and Water Assessment Tool (SWAT), Arnold et al., 1998; Gassman et al., 2007; Krysanova and Arnold, 2008), supported by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA), was chosen for modeling the water balance of the Wargal watershed for the purposes of estimating the groundwater balance. The model was used to estimate groundwater recharge and to upscale irrigation withdrawals. The simplified groundwater balance, assuming no net lateral sub-surface flows, is recharge minus irrigation withdrawals. Hydrologic simulations have allowed the groundwater balance to be assessed under current and alternative farm management, and have increased the evidence for the connections between agricultural management and groundwater depletion.

SWAT is a continuous-time, process-based, distributed-parameter hydrologic model that is used to estimate water quantity and quality at the landscape scale. The model is open source and supported releases are freely distributed. Geographic Information System (GIS) interfaces are available for preparation of landscape data. Water balance equations are solved for hydrologic response units (HRUs) that are developed based on combinations of soil type, slope, and land use/management. Watershed boundaries and subbasins are delineated from topographic data. Rainfall partitioning into runoff and infiltration is a highly important process description of any hydrologic model. SWAT has the advantage of allowing for the choice of the runoff/infiltration representation using the Curve Number (CN; SCS 1972) or Green-Ampt Mein-Larson (GAML; Green and Ampt, 1911; Mein and Larson, 1973) methods. It is suggested that it is preferable here to use the GAML method for the purpose of evaluating water harvesting tillage for groundwater recharge increases, as this sub-daily time step method can respond to tillage management changes better than a daily-time method given the episodic (high-intensity) nature of rainfall in Wargal. Additionally, SWAT has been shown to perform well prior to calibration in numerous watersheds (Rosenthal et al., 1995; Bingner, 1996) making possible the simulation of ungauged or sparsely instrumented watersheds. However, calibration does generally yield substantial improvements in water balance predictions and was done in the study area using a time series of observed reservoir storage volumes.

Modifications have been made to SWAT code to include depression storage in the GAML infiltration routine for simulation of water harvesting tillage and rice croplands; see Chapter 3 for details. Literature values were used to parameterize tillage for maximum depression storage. To summarize, SWAT was chosen as the tool for hydrologic simulations based on:

- Physical basis for most process descriptions; spatial distribution of parameters
- Ability to simulate runoff and infiltration using GAML equations with sub-daily precipitation data
- Incorporated, adjustable weather generator for long term simulations
- Demonstrated performance in ungauged watersheds (Rosenthal et al., 1995; Bingner 1996)
- GIS interface allowing for fast development and input of spatial data
- Open source code allowing for process modification
- Included sensitivity and uncertainty tools
- Demonstrated effectiveness at predicting recharge from land/water/atmosphere interactions at the surface: history of using SWAT output (recharge) as input to groundwater models (Kim et al., 2008)

Summary of Water Balance Simulation Methods

The methods employed here for the use of simulated water balance experiments closely follow the hydrologic modeling protocol proposed by Engel et al. (2007) for the purpose of improving the acceptability of modeling outcomes, remove bias of model users, developers, and increases the repeatability of model application studies. Briefly, the procedure of the water balance experiments can be organized into six steps:

1. Collection and processing of landscape data. Spatial data inputs to SWAT include a digital elevation model (DEM) for topographic representation, a land-use/land-cover (LULC) dataset for land cover and management description, and a soil map detailing all required soil properties. A DEM of the study area having 2.2 meter resolution was prepared using CartoSat-IRSP5 remote sensing stereo images (purchased from National Remote Sensing Centre, Department of Space, Government of India); see Figure 1-8. PCI Geomatics Orthoengine was used for image processing and DEM extraction. SWAT was used to delineate the watershed boundary based on topography, specifically the raster-based flow direction grid that is developed from the DEM.

Two options were available for LULC mapping: (1) use only household survey data to create lumped LULC classes of arbitrary spatial distribution based on reported farm management practices or (2) use multispectral remote sensing (RS) images of CartoSat-IRSP6 and supervised classification based on training areas from household surveys. It was decided to combine these options by using household survey data to obtain the extent of the major cropping sequences and using those areas to adjust the unsupervised classification of an RS. Based on household surveys, the agricultural areas could be simplified to three cropping systems. Based on 2008/2009 surveys of households in the watershed (N = 114), the dominant annual three-crop rotations were: maize/potato/vegetable, cotton/sunflower/vegetable, and rice/rice/vegetable in seasons kharif/rabi/summer, respectively. Kharif season is from June to September, rabi season is from October to February, and summer season is from March to May. The extent of each crop in each rotation is presented in Table 1-1. Rice and vegetable croplands are the only irrigated areas. Rice cropland areas were clearly distinguishable on the RS image, so there is little expected uncertainty in their extent and spatial distribution. Without an extensive time-series of RS images and abundant groundtruth data, the rainfed crops of the watershed are remotely indistinguishable. However, the extent of each crop can be assumed to be reliable because it is based on household surveys; it is only the spatial distribution of these areas that is uncertain. It is argued that uncertainty in location of these rainfed cropland areas is tolerable given that there will be some interannual variability in spatial distribution of rainfed crops based on farmer decisions, and there are small differences in hydrology (assuming uniform tillage) between these rainfed crops. Rice cropland areas are more consistent in their extent and spatial distribution because of the labor required to establish level, bunded fields. It is arguably the rice areas that are of greatest hydrologic significance due to uniquely large irrigation, surface storage depth, evapotranspiration, and deep percolation.

Soil mapping was completed using soil data from 39 locations in the study area; sampling was done in 2 to 5 depth classes (to 1 meter maximum) at each point. Soil data includes saturated hydraulic conductivity (K_s), % sand/silt/clay, bulk density, and organic carbon. Two depth classes (0-28 cm and 28-94 cm) were extracted from the data for consistency at all locations. Weighted and harmonic means were used appropriately to aggregate data into the two uniform depth classes. Ordinary kriging using % clay in layer 1 of soil was used to interpolate point data to create a complete coverage. The choice of % clay was made over other soil properties because it showed the most spatial autocorrelation compared to that of the available properties. This was decided based on visual inspection of semivariograms (plot of semivariance in property value in response to distance between observation locations); generally, small semivariance at low lag distances and larger semivariance at high lag distances suggests spatial autocorrelation. Semivariance is a spatial statistics quantity that describes the variance of some value (call it % clay) and % clay at some distance apart (lag distance). Semivariance is lag distance dependent as seen in Figure 1-9. See Figure 1-9 for the semivariogram of % clay. The result of kriging from point data was a continuous spatial distribution of % clay content throughout the watershed; 31 unique values of clay content resulted. To simplify the soil map k-means clustering was used to group the 31 values of % clay into 6 groups; associated soil properties were aggregated into the correct clay content classes using a nearest neighbor technique.

SWAT requires a weather generator database for climate generation. Climate generation is required to allow for simulations to continue if there is a data gap or formatting error in weather input data; also, future scenario simulations require use of the weather generator database. The database can be adjusted to predict hydrologic outcomes of climate change scenarios. This database of 168 climate parameters was developed using 34 years of daily climate data (solar radiation, minimum and maximum temperatures, rainfall) and 16 years of hourly rainfall data. Data used to calculate the required climate parameters were provided by the International Crops Research

Institute for the Semi-arid Tropics (ICRISAT; Singh, 2009). This was the nearest (45 km distant) source of a long record of quality climate data, and inspection of annual average rainfall totals suggests there is little climate difference between ICRISAT and Wargal. Temperatures, relative humidity and rainfall were measured in Wargal for input to SWAT for calibration and validation periods. Weather generator database location was listed in the Wargal watershed as 17.76472 N, 78.62447 E and elevation of 600 m.

2. Design and installation of hydrologic/climate monitoring systems

Climate data for SWAT input and watershed runoff data for model calibration and validation are summarized in Table 1-2. Rainfall observations were collected manually and automatically. Automatic rainfall collection, using a tipping bucket gage that logged each 0.25 mm of rainfall, allowed for hourly precipitation data for GAML infiltration simulation in SWAT. Sub-daily data were generated from measured daily rainfall for wet days by HYETOS, a program for disaggregation of daily rainfall data to hourly data (Koutsoyiannis and Onof, 2001) for periods when hourly rainfall data were unavailable; there were 6 months in 2010 – due to maintenance problems with the automated rain gage – during which HYETOS was required to disaggregate daily rainfall observations into hourly data. HYETOS uses the Bartlett-Lewis pulse based method to generate storms from daily data based on 6 monthly parameters developed from a record of hourly data. Hourly data from nearby ICRISAT (Singh, 2009) were used to calculate the 6 Bartlett-Lewis parameters. Disaggregated rainfall will not match actual hourly data, but it was the best option available given the instrumentation challenges in the Wargal watershed. HYETOS disaggregated rainfall has been shown to closely match observations (Rodriguez-Iturbe et al., 1988; Koutsoyiannis and Onof, 2001). Manual daily rainfall was collected at 15 non-evaporating gages distributed throughout Wargal. Groundwater levels were monitored in 6 borewells and 3 open wells using an electronic depth sounder. One of the borewells was monitored continuously with a pressure transducer.

Six reservoirs are found in the Wargal study area; these are water-harvesting structures excavated long ago that serve to increase groundwater recharge. The largest of these reservoirs, Kothakunta, is found at the outlet of the watershed and creates a generally closed watershed, meaning there is rarely outflow other than percolation of the tanks. Observations of water in Kothakunta reservoir were the data used for SWAT calibration and evaluation. The area and depth of water in Kothakunta reservoir, at the outlet of the study area, was monitored using GPS waypoint data and a staff gage that was manually read weekly or more frequently during rainy periods. A GPS was used to weekly mark the perimeter of the flooded area of the reservoir by walking around the reservoir at the water line and recording waypoints. Topographic survey data were used to develop the depth to volume and area to volume relationships required to convert observations to storage volume. Increases in storage volume during a time interval are interpreted as the outflow of the study area as this reservoir stores all outflow. Only one reservoir was monitored as a “runoff” gauge due to limited personnel available for data collection. It was decided that one target for calibration was sufficient given the small size of the watershed; this is commonly done in hydrologic modeling. Also, recharge observations allowed an additional evaluation measure to further test the performance of SWAT.

Irrigation pumping could be not be sampled in a large number of fields, but 4 borewells were monitored with flowmeters to record irrigation pumping for a small sample of the most commonly irrigated crops: rice and vegetables. It is expected that for farmers with functional borewells there is little variability in irrigation depths for a given crop due to the management of irrigation that is generally dependent only on electricity supply. Chapter 4 details the irrigation management setup in SWAT and presents the irrigation observations used.

3. Setup and initialization of hydrologic model. SWAT setup consisted of input of formatted landscape data (soils and topography and land use) and weather data. Cropping system management was parameterized through tillage specification, planting dates, crop selection, and irrigation management. An initialization period of about a year and half (using some simulated and some measured weather data) was used to establish more suitable initial soil moisture and reservoir level conditions.

4. Model calibration and evaluation. This step provided quantitative information on the uncertainty of simulated water balance components at the watershed scale using observed reservoir storage volume at the outlet of the watershed as the calibration target. 13 of the most important parameters – based on expert knowledge and sensitivity analyses of SWAT in the literature – were adjusted to improve accuracy of prediction of outflow (Chapter 4). Based on the recommendations of Moriasi et al. (2007), the 3 quantitative statistics being used for model calibration and evaluation were the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR).

5. Water balance simulations of alternative cropping systems. This step completed the simulation experiments by estimating the resulting water balance components of cropland management combinations in Wargal. Alternative farm management scenarios were created by combining tillage, crop selection, and irrigation management options, based on accepted water conservation strategies and participation of community members; these alternative management options are detailed in Chapter 4. A 10-year simulation using generated weather data was used to develop water balance predictions for existing management and also for all alternative management options.

6. Evaluation of alternatives. Groundwater recharge, evapotranspiration (ET), surface runoff, and irrigation withdrawals were among the outputs used to select management strategy combinations of greatest potential for groundwater quantity improvement. Chapter 4 provides details on the comparison of management alternatives.

Hydrology in Ungauged Basins

The International Association of Hydrological Sciences (IAHS) has launched a decade-long program (2003-2012) called Predictions in Ungauged Basins, or PUB (Sivapalan et al., 2003). The central goal of this initiative is to reduce predictive uncertainty of hydrologic models by improving hydrologic process understanding, developing ways to generalize hydrology among similar watersheds, and increasing the available hydrologic and landscape data. This research contributes to the goals of PUB by improving a hydrologic model through increasing the physical basis of the infiltration routines with the addition of a parameter which can be expected to have much lower uncertainty and variability than the other soil properties important for infiltration prediction: effective hydraulic conductivity and wetting front suction. Also, the use of small surface reservoirs as runoff gages increases the evidence for this being an effective strategy for acquiring data for model calibration and evaluation in the absence of streamflow measurements.

Factors Influencing Groundwater Recharge: Literature Review

Of the roughly 35 million km^3 of freshwater on Earth, 69% is frozen in glaciers and permafrost, and of the remaining 31% of global freshwater resources 96% occurs as groundwater – the rest is divided between surface water and soil moisture (Shiklomanov, 2000). An important objective of this research is to understand how the groundwater balance can be managed through reductions in irrigation withdrawals and increases in recharge through tillage management. The following sections review a variety of literature on groundwater recharge to assess which factors have the greatest influence on recharge.

Groundwater recharge is primarily controlled by climate, topography, soil properties, land use/land cover, and geology (Rushton, 1988; Le Maitre et al., 1999; Delin et al., 2000; de Vries and Simmers, 2002; Lin et al., 2007). The following review of literature attempts to select the dominant factor(s) for a given climate/region. The strength of correlations between groundwater recharge and soil properties, topography, geology, and land use/ land cover (LULC) are compared, qualitatively, from a review of research on groundwater recharge estimation and prediction.

Rationale and Significance of a Groundwater Recharge Literature Review

The two main issues having management implications associated with groundwater recharge are groundwater contamination (quality) and groundwater depletion or overdraft (quantity) (Lerner et al., 1990). Groundwater is the main source of water for agricultural, municipal, and industrial uses in some parts of the world; therefore, the quantity and quality of groundwater is of great importance and is the focus of management efforts. Cities or villages that depend on groundwater for domestic supplies are vulnerable if groundwater supplies become of insufficient quantity or quality; water has to be imported or purified to meet domestic supplies. The same is true for farming systems and industries that depend on groundwater.

Groundwater can be managed by changing water fluxes at the land surface by altering soil properties (organic or mineral amendments), topography (water harvesting ponds, tillage), or LULC (impervious area, types of vegetation). Subsurface flows can also be altered by modifying geology through recharge and discharge structures that penetrate confining or slow-flowing formations; groundwater withdrawals for agricultural, municipal, or industrial supply do of course influence subsurface flows. It is sometimes desirable to increase groundwater recharge to meet increased withdrawal demands, and it is sometimes the goal to decrease groundwater quantity to prepare for construction or relieve waterlogging and/or salinity problems in croplands. Managing anything well requires information about the quantity of interest and the relevant processes; therefore, it is helpful to know which factors related to groundwater recharge are the most important to consider. To summarize, the objectives of this review are:

- Compare correlations of the four manageable factors – soil properties, topography, geology, LULC – to groundwater recharge
- Determine if there is consensus in the literature on the factor that dominates groundwater recharge (locally)
- Find methods of recharge measurement/estimation that are most regularly used

Land Surface Environmental Factors and Groundwater Recharge

With a focus on the four manageable, environmental factors being considered, three synthesis papers were selected to evaluate the prevalence of factors considered for groundwater recharge. Two of the reviews were selected to approach groundwater recharge from different perspectives. The first perspective is that of vulnerability assessment, contamination, and water quality (Gogu and Dassargues, 2000); the second perspective is that of recharge processes, estimation, and quantity (de Vries and Simmers, 2002). The third review covers an extensive range of study areas and summarizes recharge rates and controls among them. Qualitative comparisons are made of these reviews to examine the frequency of consideration of the four factors in the studies included in each review. Additionally, nine studies of groundwater recharge relationships to the three most manageable of the four factors (soils, topography, LULC) were sampled and reviewed for comparison. These papers (published in the last 10 years) were summarized and their methods and outcomes tabulated for comparison.

Groundwater quantity and quality are well connected because the same factors that make a groundwater system vulnerable to quality degradation can improve groundwater recharge or quantity; areas of greater groundwater recharge are the areas that are most vulnerable to contamination. Ten methods of vulnerability assessment are reviewed by Gogu and Dassargues (2000); references and variables included for vulnerability assessment are given in Table 1-3.

The outcome of a vulnerability analysis is a quantitative measure (often a map) of groundwater vulnerability to contamination; however, the measure of vulnerability is just a number – some type of index – that is relative to other vulnerabilities predicted with the same method. There is no absolute vulnerability quantification. The most thorough methods are the DRASTIC and SINTACS approaches which both use the following seven parameters for vulnerability classification: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity.

The review by de Vries and Simmers (2002) suggests climate, geology, topography, soil condition, and vegetation are the factors determining groundwater recharge. Geology control of recharge is illustrated by the case of recharge differences in Botswana between the Kalahari sands and the adjacent Precambrian hard-rock area. Rainfall in the two areas is similar (300 – 500 mm/year); tracer observations and modeling estimates show similar recharge in the Kalahari sands (1-10 mm) and hard-rock areas (10-30 mm). However, spatial distribution of recharge is very different between the two areas. The hard-rock area shows about 50% of recharge occurring through preferential flow from fractured rock, creating small (5-10 km^2) groundwater basins that often coincide with morphologic (read: topographic) depressions. Groundwater recharge in the Kalahari sands is more spatially uniform, having less variability of soil moisture in the vadose zone and little geologic control of recharge.

A very thorough review of 98 groundwater recharge studies reported in the literature was completed by Scanlon et al. (2006) focusing on recharge in arid and semi-arid regions. Their conclusions are summarized in the following three sentences. The chloride mass balance technique is the most widely used method for estimating recharge. LULC change is the factor most regularly controlling recharge: in Niger LULC changes resulted in recharge responses that greatly exceeded those resulting from climate variability, including severe droughts; in Australia, deforestation has resulted in recharge increases of 2 orders of magnitude, causing severe groundwater salinity problems due to the flushing of the large amounts of chlorides present in soils. The authors suggest that high sensitivity of groundwater recharge to LULC means that recharge can be managed in most cases by LULC changes.

Land use and land cover

Groundwater recharge in arid and semiarid regions is typically small relative to other water balance components. Rainfall distribution in these areas is characterized by marked wet and dry periods; the wet periods having storms of significant intensity. The result of these precipitation patterns is that groundwater recharge is largely episodic (de Vries and Simmers, 2002). Episodic recharge describes groundwater recharge events of low frequency and large relative contributions. This type of recharge is highly sensitive to topography and difficult to manage through vegetation changes (de Vries and Simmers, 2000; Zhang et al., 1999).

The conversion of native vegetation to annual cropping systems in southeastern Australia has increased groundwater recharge and caused salinity problems as a result of rising water tables. To assess the impact of agronomic practices (vegetation type) on groundwater recharge, Zhang et al. (1999) used a biophysically based water balance model (WAVES) at two sites in Australia to simulate water balance components in response to changes in crop rotation and type. Their simulations showed that perenializing croplands and growing crops having greater rooting depth did decrease occurrence of small recharge events and overall recharge. Vegetation management was able to reduce annual recharge amounts by elimination of fallows and increased root depths. At one location, simulating two different rotations, a change to a deeper rooting variety (0.5 m depth to 1.0 m depth) resulted in reduction in annual recharge of

50%. The main conclusion was the recommendation that fallows be replaced with vigorously vegetative crops to reduce recharge.

Water flows in the Dill Catchment, Germany were simulated to estimate sensitivity of flows to vegetation and soil property changes associated with vegetation changes (Huisman et al., 2004). Water flows considered were total runoff, actual evapotranspiration, surface runoff and ground water recharge; vegetation scenarios were pasture (perennial) and cropland (annual): cropland was a common rotation of summer barley, winter rape, and winter wheat. A quantity called distinction level was used to compare hydrologic responses to vegetation change. The distinction level helps compare the sensitivity of the simulated hydrologic fluxes to soil and vegetation parameter changes relative to the uncertainty in these fluxes due to parameter uncertainty. The results showed very little sensitivity of hydrologic fluxes to soil properties (saturated hydraulic conductivity, bulk density, available water content, depth of top soil layer). For the study area, groundwater recharge was little affected by changes from cropland to pasture because the opposite effects on runoff and evapotranspiration. Higher evapotranspiration and lower runoff amounts resulted from shifts of cropland to pasture (replacing 50% of cropland with pasture – runoff: 596.9 to 536.0 mm/yr; ET: 292.9 to 352.8 mm/yr).

Groundwater recharge and baseflow were estimated for the Upper Mississippi River basin (Arnold et al., 2000) using the Soil and Water Assessment Tool (SWAT) and two data analysis methods (recursive filter to separate baseflow from daily flow and hydrograph recession displacement to estimate groundwater recharge). Groundwater recharge, runoff, baseflow, and ET were most sensitive to (in order of decreasing sensitivity): Curve Number, soil available water capacity, evaporation compensation coefficient (adjusts the depth distribution of evapotranspiration from the soil). The greatest sensitivity to Curve Number is not surprising as this quantity contains considerable information about land use/land cover.

Topography

It has been shown by Delin et al. (2000) that even small differences in topography can substantially influence groundwater recharge. Their research site in the sand plains of central Minnesota was planted in maize under uniform tillage, eliminating most of the effects on recharge from land use and microtopography differences between sites. An upland and lowland site were selected, separated by 78 m of distance and 1.4 m of land surface elevation difference. Three methods for recharge estimation were used: well hydrograph analysis, unsaturated zone water balance, and chlorofluorocarbon tracer dating. Mean annual recharge at the site of lower elevation was greater than recharge at the site of higher elevation by 30% (estimated from hydrograph analysis), 60% (estimated from water balance), and 80% (estimated from chlorofluorocarbon dating). These results from a diversity of methods during a 4 year study suggest that small differences in topography (1.4 m) can be significant factors in estimation of groundwater.

The resolution of the representation of topography can significantly impact predictions of land surface processes (Schoorl et al., 2000). Digital elevation models (DEMs) of the same terrain using different resolutions can result in result in different predictions of landscape properties or processes. Computational and sensing costs currently preclude very high resolution DEMs, but the microtopographic relief that they represent does influence land surface hydrologic processes. The effect on hydrologic simulations of runoff in response to centimeter-scale representations of a landscape were considered by Martin et al. (2008); interpolated at resolutions of 0.75 cm, 10 cm, 25 cm, 50 cm, 75 cm and 100 cm for vegetated and bare surfaces of a 20 m x 10 m slope in British Columbia, Canada. Elevations were obtained from a ground-based laser scanner. Their results showed marked decreases in mean depression storage (MDS) for the landscape with increasing DEM grid size. From 0.75 cm resolution to 25 cm resolution, MDS decreases from 2.4 cm to 1 cm, and is negligible at resolutions above 25 cm. They demonstrate the infiltration/runoff partitioning changes in response to varying MDS, making clear the implications for groundwater recharge.

The strength of topography as a predictor of groundwater recharge was quantified by Bakhsh and Kanwar (2008) in their study of landscape attributes and their correlation to subsurface drainage clusters. Flow data from measurements of subsurface drainage (pipes below agricultural fields) was used to find the landscape attributes (soil type, elevation, slope, aspect, curvature, flow length, flow direction, and flow accumulation) that best explained flow variations. Thirty-six plots in a field each had their own drainage outlet and subsurface flow was measured from each plot. While subsurface flow was occurring laterally through drainage pipes, it was essentially deep drainage or potential groundwater recharge that was being intercepted. Stepwise discriminant analysis was used to select the attributes that made the biggest contribution to subsurface flow. Elevation and flow accumulation were both selected as the attributes that best explained the spatial variability of subsurface flows. Three soil types were classified for the site; saturated hydraulic conductivity was considerably different among them (35 – 100 mm/hour), but the analysis only selected topographic variables as having strong correlation with subsurface drainage flows.

Soil properties

Sensitivity analysis of groundwater recharge to numerous soil and vegetation parameters was completed using a simple one dimensional water balance with weather and vegetation information for England (Finch, 1998). One-at-a-time sensitivity analysis was used: all parameters being held at their mean values while the parameter of interest varies across its specified range. Numerous vegetation parameters were considered for three vegetation types, and mean annual recharge was estimated at 176.7, 290.5, and 96.4 mm for permanent short vegetation, annual short vegetation, and forest, respectively. Water balance simulations showed greater sensitivity of groundwater recharge to soil parameters (available water content, root zone depth) than to vegetation parameters (leaf area index, canopy height, growing season length). The simplified water balance model estimates runoff as 10% of rainfall if a rainfall event is greater than 5 mm; topography and a physically-based description of infiltration/runoff processes were ignored for the purposes of the study.

A method for estimating groundwater recharge in southern India was tested by Anuraga et al. (2006) using a soil-water-atmosphere-plant model able to describe land use and soil types. Soil data for the study area of Bethamangala subwatershed was simplified into two classes: one sandy loam (Type 1) and one clay (Type 2). Annually, average recharge for the soils was 212 and 99 mm for the sandy and clayey soils, respectively; this difference is claimed to be due to the higher evaporative losses from the clay soil as a result of its higher water holding capacity. Annual water balances for three cropping intensities were simulated. Type A: Finger millet, potato, and tomato are cropped during kharif, rabi, and summer seasons, respectively: total amount of irrigation is 410 mm/year. Type B: Finger millet is cropped during kharif season with supplemental irrigation of 150 mm/year. Type C: Finger millet is cropped during the kharif season without irrigation. Recharge for sandy and clayey soils, respectively, for cropping systems were 220 and 90 mm/year for system A, 232 and 124 mm/year for system B, and 184 and 84 mm/year for system C. This suggests that soil texture influence on recharge is strong.

A single-layer soil water balance model, developed by Eilers et al. (2007) was used to estimate groundwater recharge during a 36 year period in semi-arid northeast Nigeria. The model includes 11 soil and 13 vegetation parameters that are not spatially distributed. Simplicity and low data requirements of the model are touted as its strengths, and it is promoted for use in cropland areas for water management purposes. The simulated water balance was used to find sensitivity of groundwater recharge to model inputs and parameters. Total available water (TAW), followed by rooting depth and then by crop coefficient, was found to be the parameter with the greatest effect on simulated recharge. TAW depends both on soil properties and plant rooting depth. Near surface storage (NSS) depth was also shown to significantly influence recharge.

Quantifying Groundwater Recharge

Methods for quantifying groundwater recharge can be grouped into 3 categories: physical, tracer, and numerical modeling (Scanlon et al., 2002). These methods are used differently in surface-water based studies, unsaturated zone studies, and saturated zone studies. Table 1-4 summarizes the various methods for measuring and estimating groundwater recharge. In this study in the Wargal watershed, unsaturated zone water-balance modeling is used to estimate groundwater recharge using a distributed solution to the water balance equation at the surface and in the unsaturated zone. Deep drainage, water percolating below the root zone is assumed equivalent to groundwater recharge. This equivalency assumption is valid based on the limited surface-water/groundwater connections and the substantial depth to groundwater. Seepage meters, lysimetry, and tracers all only give point estimates, and sufficient point estimates to distribute groundwater recharge in the 500 ha study area would be too costly. The water-table fluctuation method would not be effective because of the amount of groundwater pumping and number of wells (190); it would not be possible to have a sufficient number of groundwater wells that were uninfluenced by groundwater pumping.

Discussion and Conclusions on Factors Influencing Groundwater Recharge

The studies considered in this review span a range of locations and climates, making it difficult to make a rigorous comparison of correlations (groundwater recharge to soil properties, topography, geology, LULC). This review can, however, suggest environmental factors having the greatest correlation to recharge in a certain region. Table 1-5 summarizes the papers reviewed in this section: giving their location, the factors considered, and the factor explaining most of the variability in groundwater recharge. The dominance of simulated water balances in experimental methods is not uncommon in groundwater recharge studies, and it affirms the use of water balance simulations in the Wargal study area. Measured water balances are difficult as determination of boundary conditions of a groundwater system generally requires vast instrumentation for measurement of surface and subsurface quantities (including descriptions of geology) both in the study area and in surrounding areas. Tracer mass balances seem to be the most effective way of estimating local recharge; seepage meters can also provide accurate point estimates of recharge. The prevalence in the literature of simulation tools for estimating sensitivity of groundwater recharge to environmental factors supports the use of SWAT in this analysis to estimate groundwater recharge under current and modified management.

This review and the extensive review by Scanlon et al. (2006) suggest that land use and land cover has the most control over recharge processes within a given climate. In 4 of the 9 studies tabulated above, a quantity related to LULC dominates groundwater recharge control. In 3 of the 9 studies, a topographic quantity was found to be most influential on groundwater recharge. Of the 6 studies that considered LULC there were 2 which find a soil property having a greater influence on recharge. For agricultural areas, the sensitivity of recharge to LULC suggests that cropping system changes can have significant effects on groundwater recharge.

Options for Managing Groundwater in Agricultural Systems

Recall the water balance discussion in the earlier section, "Groundwater Balance and Agricultural Management". Equation 1-1 described the water balance of the unsaturated zone and at the soil surface: $\Delta SW = P + I - ET - RO - \Delta SS - DP + \Delta UF$, where SW is soil water, P is precipitation, I is irrigation, ET is evapotranspiration, RO is runoff, ΔSS is a storage pool representing the increase or decrease in surface storage in small or large depressions, DP is deep percolation, ΔUF is the net change in subsurface flow into and from the system.

Equation 1-2 described the water balance in the saturated zone (groundwater system): $\Delta S = R - I - CR + \Delta SF$, where S is groundwater storage, R is recharge (approx. = DP), I is irrigation pumped from groundwater, CR is capillary rise, ΔSF is the net change in flow into and from the groundwater system. As discussed earlier, if the goal is to improve or maintain S (groundwater storage), then it is essentially irrigation and recharge that remain as the manageable quantities in the groundwater balance. These quantities appear in the surface water balance as I and DP. Decreasing irrigation pumping (I) could be done through a variety of possible management changes: providing supplemental rather than full irrigation, irrigating only at critical phenological times, changing crop planting date to increase effective rainfall, choosing crops with lower water requirements, or improving application technology. At the farm-scale, efforts to increase recharge (DP) include: excavating farm ponds, using zero or reduced tillage, mulching, and tillage for water harvesting (tied-ridging, contour bunding, and others). All these techniques can increase groundwater recharge by increasing surface water storage depth which allows for longer infiltration times of excess rainfall. The above review of groundwater recharge studies highlights the difficulties associated with measurement of groundwater recharge and the prevalence of water balance models for use in simulation of recharge.

Contributions of this Research

There are four major contributions that make this research significant. (1) The improvement of the GAML infiltration process description in SWAT to include surface storage depth as a time-varying head and as a storage term at the surface. This allows for evaluation of water harvesting tillage and enables flooded croplands (rice) to be simulated with the use of SWAT's land use update routines (lup.dat), which allow for dynamic cropland areas to represent management changes and intensive cropping sequences. This improved infiltration description has a stronger theoretical basis than the typical GAML formulation used in SWAT and similar hydrologic models, and sensitivity analyses (Chapter 3) have shown that infiltration predictions are sensitive (rank 2 of 5 parameters) to the parameter describing maximum depression storage in systems having non-negligible surface storage depth. (2) The use of lup.dat in SWAT for sequences of multiple crops in a single year, common in semi-arid and tropical ecosystems, and for implementing cropping system changes is unique in its application here. Typically this functionality is used for long term (decade-scale) and broad land use change; for example, conversion of unmanaged forests to annual croplands. Here, it is used for the first time (according to lead SWAT model developer: Arnold, 2010) to model these intensive cropping sequences. (3) The use of reservoir storage volumes for calibration and evaluation of model predictions in a small watershed with little convergent surface flow is an innovative strategy for data acquisition and model application in an ungauged basin (Chapter 4; Liebe et al., 2009). Small reservoirs for irrigation use and groundwater recharge are common in India and in some areas of Africa; this research demonstrates an effective, inexpensive way to use these surface water bodies to calibrate and evaluate hydrologic models in watersheds without records of streamflow. (4) This research quantifies the impact of rice croplands on the groundwater balance at the landscape scale in a typical semi-arid Indian watershed. In recent years there has been growing awareness, publicly and in the scientific literature, that groundwater depletion is becoming a problem in India (CGWB 2007; Rodell et al., 2009; Shah, 2007), but there is no information on the extent of irrigated croplands (largely rice) allowable for groundwater sustainability.

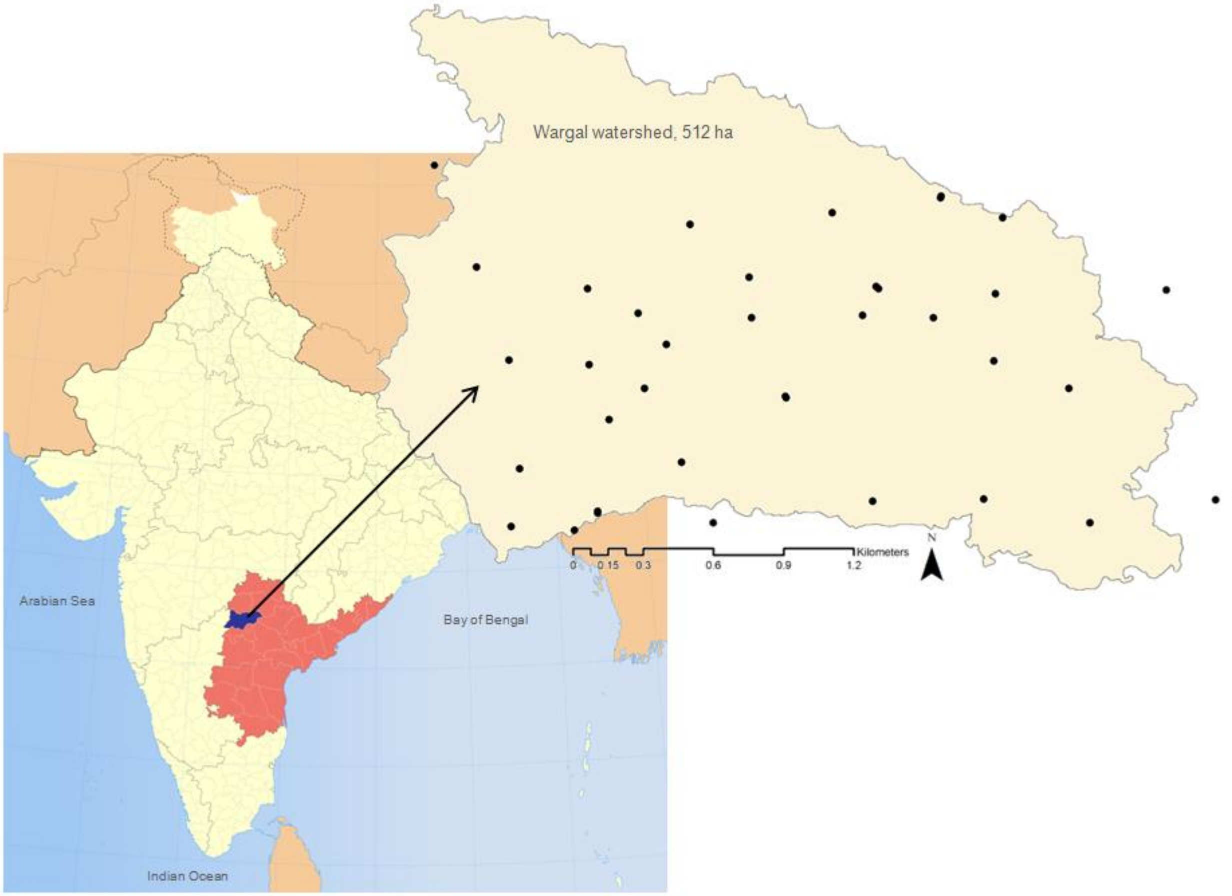

Figure 1-1. Study area location in Wargal mandal, eastern Medak district, northwestern Andhra Pradesh

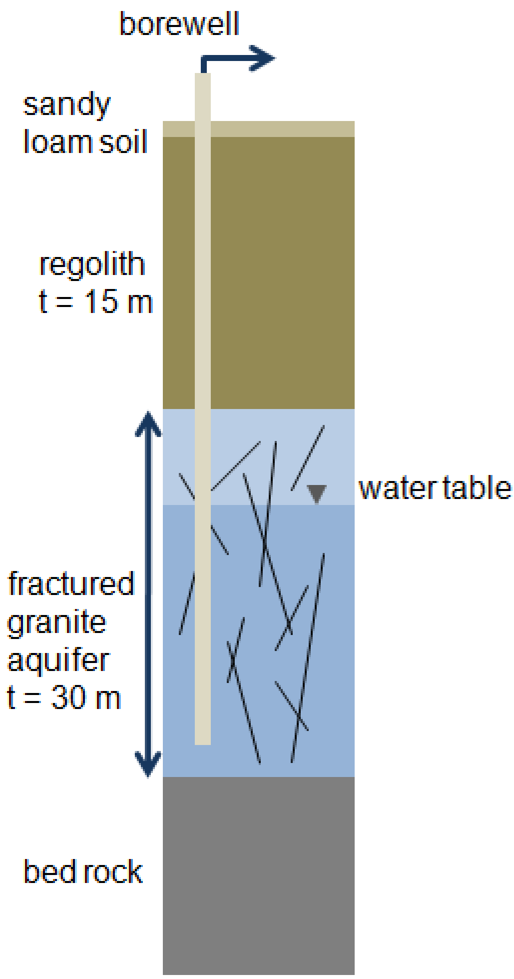

Figure 1-2. Groundwater system diagram of Wargal (adapted from Dewandel et al., 2006 and Marechal et al., 2006). t is layer thickness, values are approximate. Water table height fluctuates between 15 and 35 m below surface.

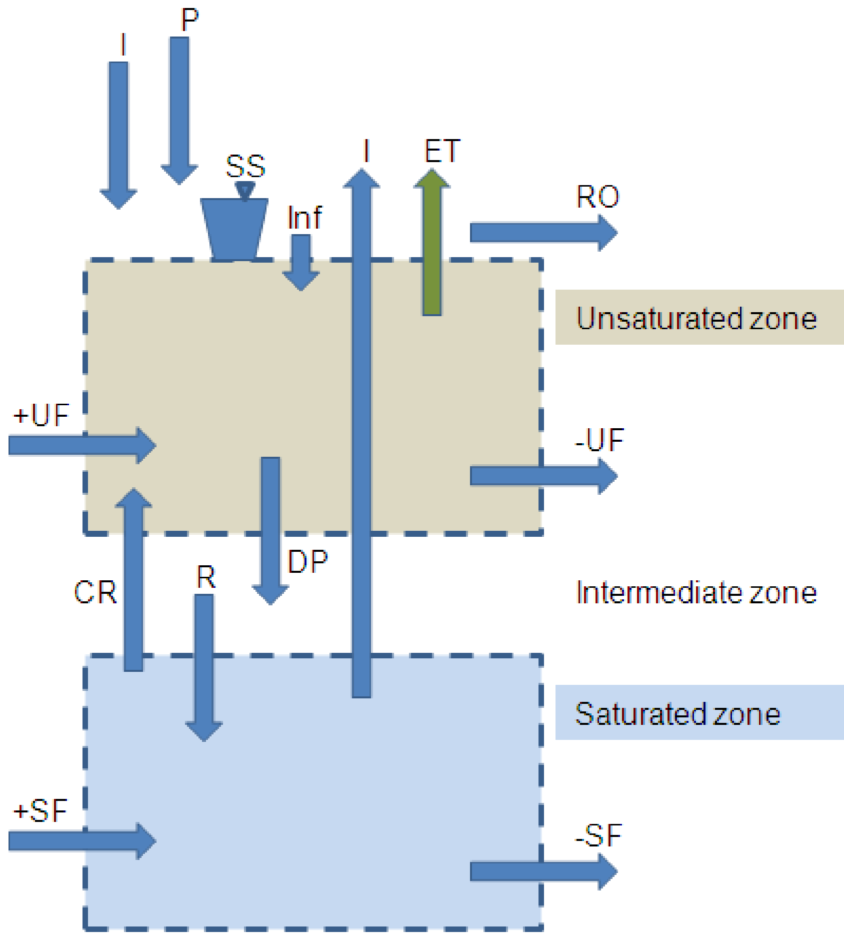

Figure 1-3. Water balance diagram showing connections between unsaturated and saturated zone water balances. I is irrigation, P is precipitation, SS is surface storage, Inf is infiltration, ET is evapotranspiration, RO is runoff, UF is unsaturated flow, CR is capillary rise, R is groundwater recharge, DP is deep percolation, SF is saturated flow.

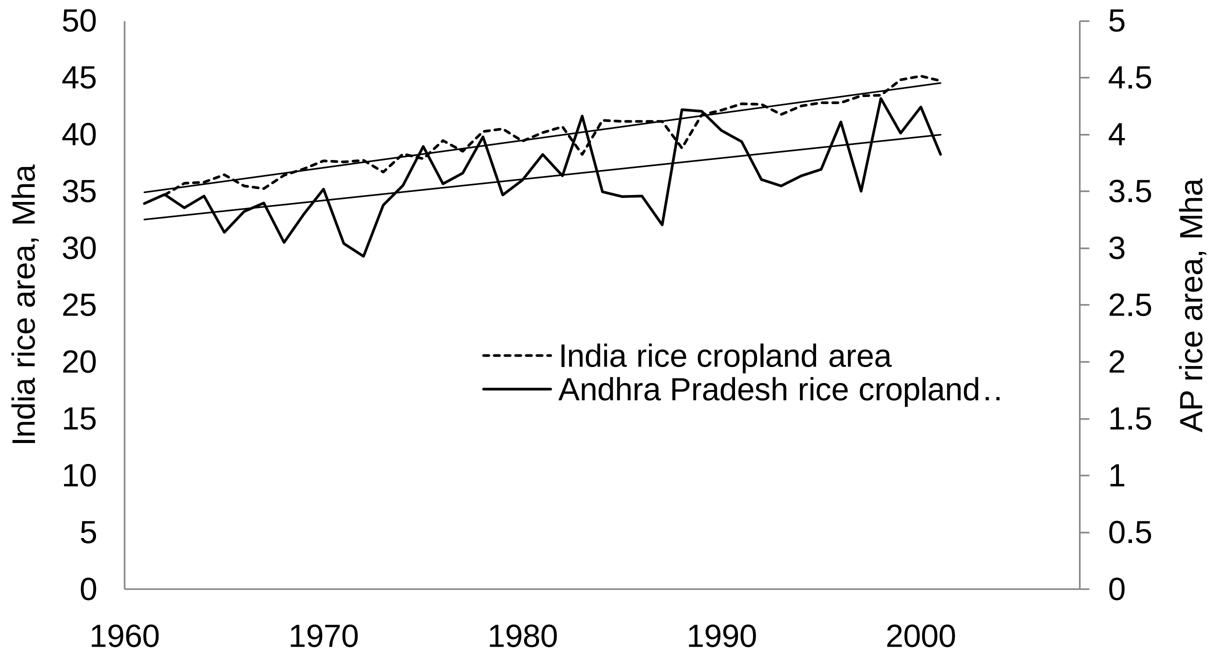

Figure 1-4. Total annual harvested areas of rice in India and Andhra Pradesh, 1961-2001

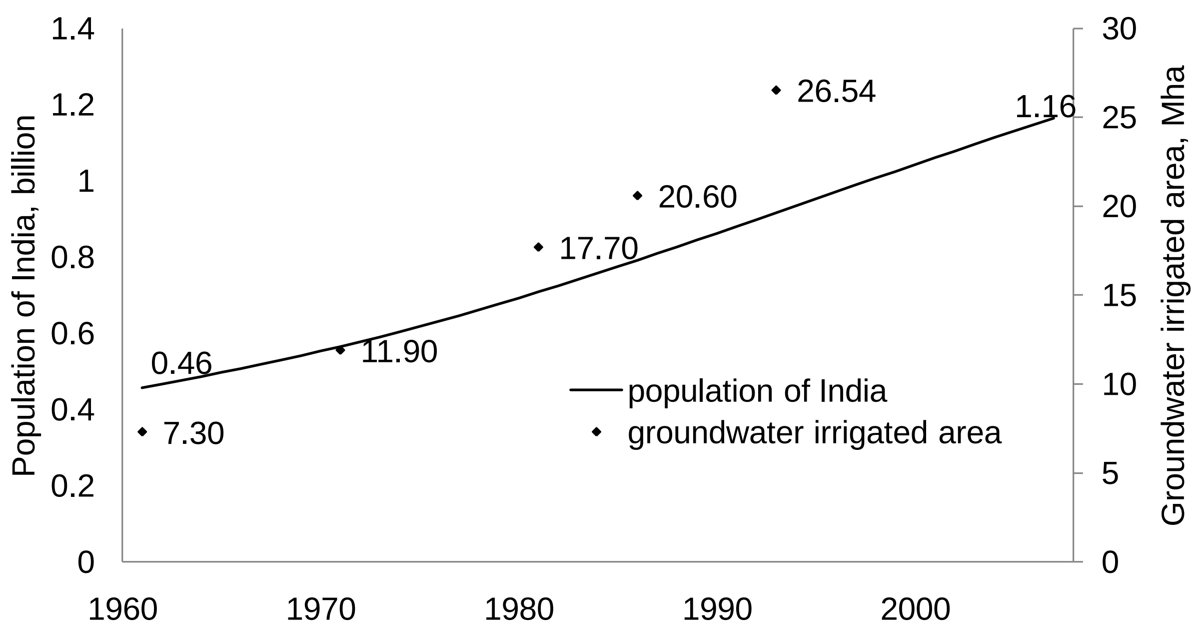

Figure 1-5. Area equipped for mechanized irrigation from groundwater source in India: 1961, 1971, 1981, 1986, 1993; population of India each year from 1961 to 2007.

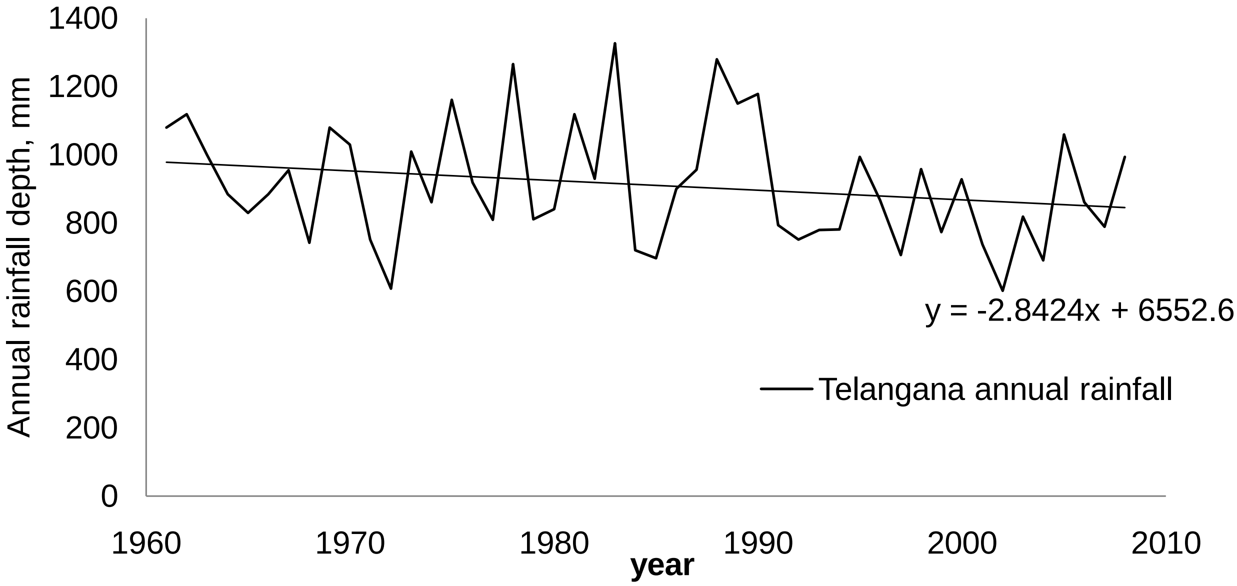

Figure 1-6. Annual rainfall in Telangana region (1960 – 2008): slight declining trend observed (about 3 mm/year reduction in annual rainfall if trend is assumed linear)

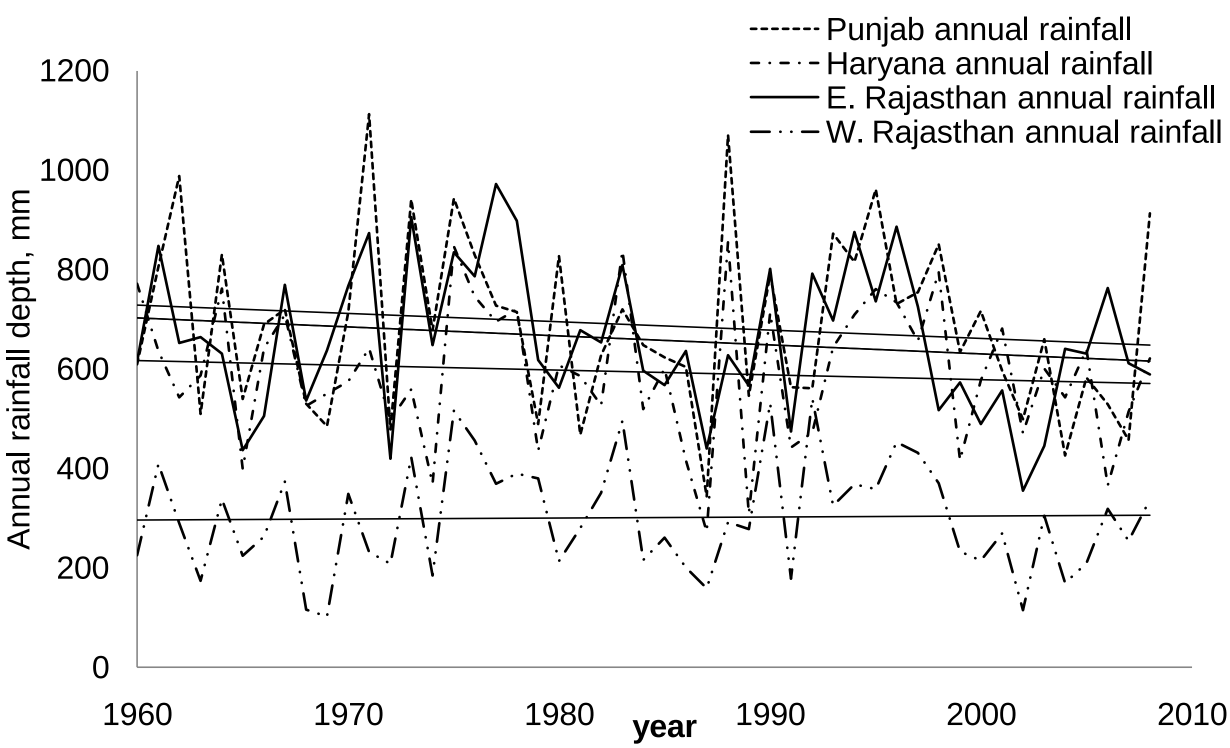

Figure 1-7. Annual rainfall trends (1960 – 2008) in the 3-state region of the GRACE study of Rodell et al., 2009

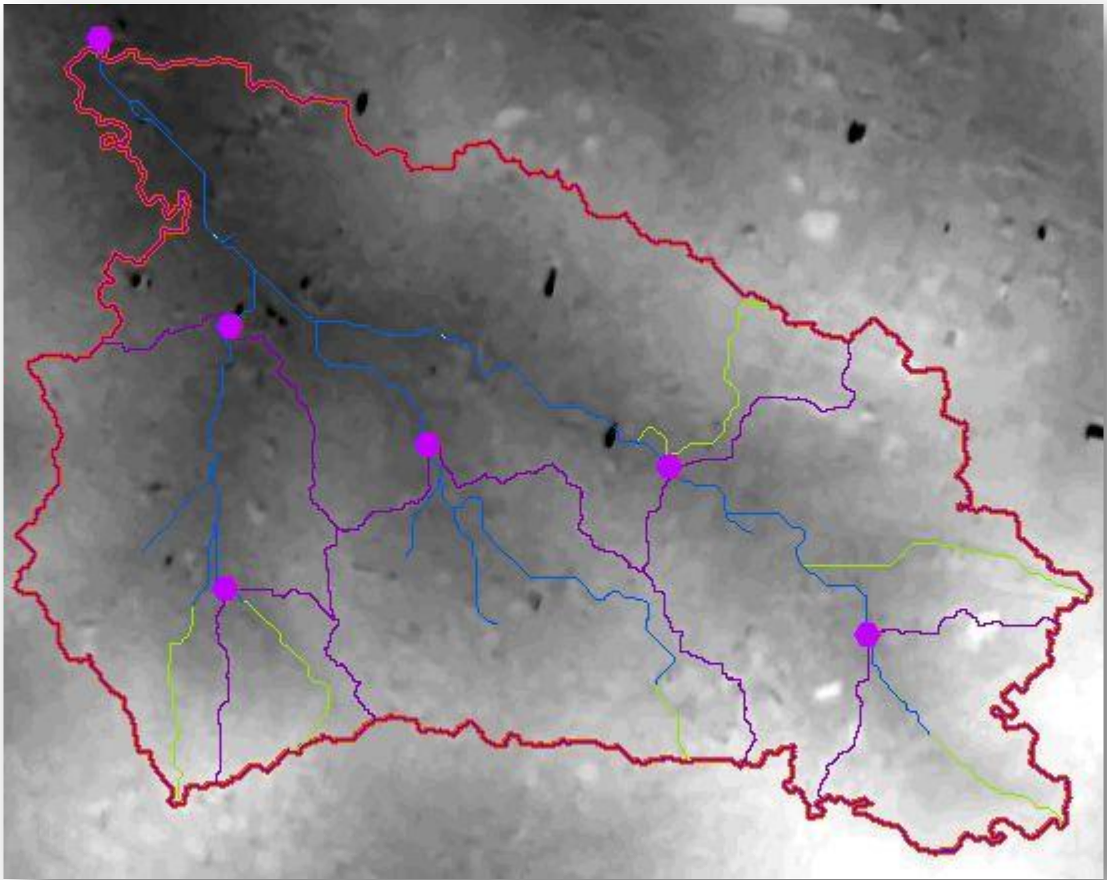

Figure 1-8. Watershed boundary, reservoir locations (large dots), and digital elevation model of Wargal watershed, 2.2 m resolution

Table 1-1. Areas (ha) of cropland for three-crop rotation in Wargal

	kharif ha		rabi ha		summer ha
maize	65.96	potato	40.96	beans	10.30
cotton	65.14	sunflower	23.36	beans	10.30
rice	92.63	rice	60.60	beans	10.30
range	288.41	range	387.21	range	481.23

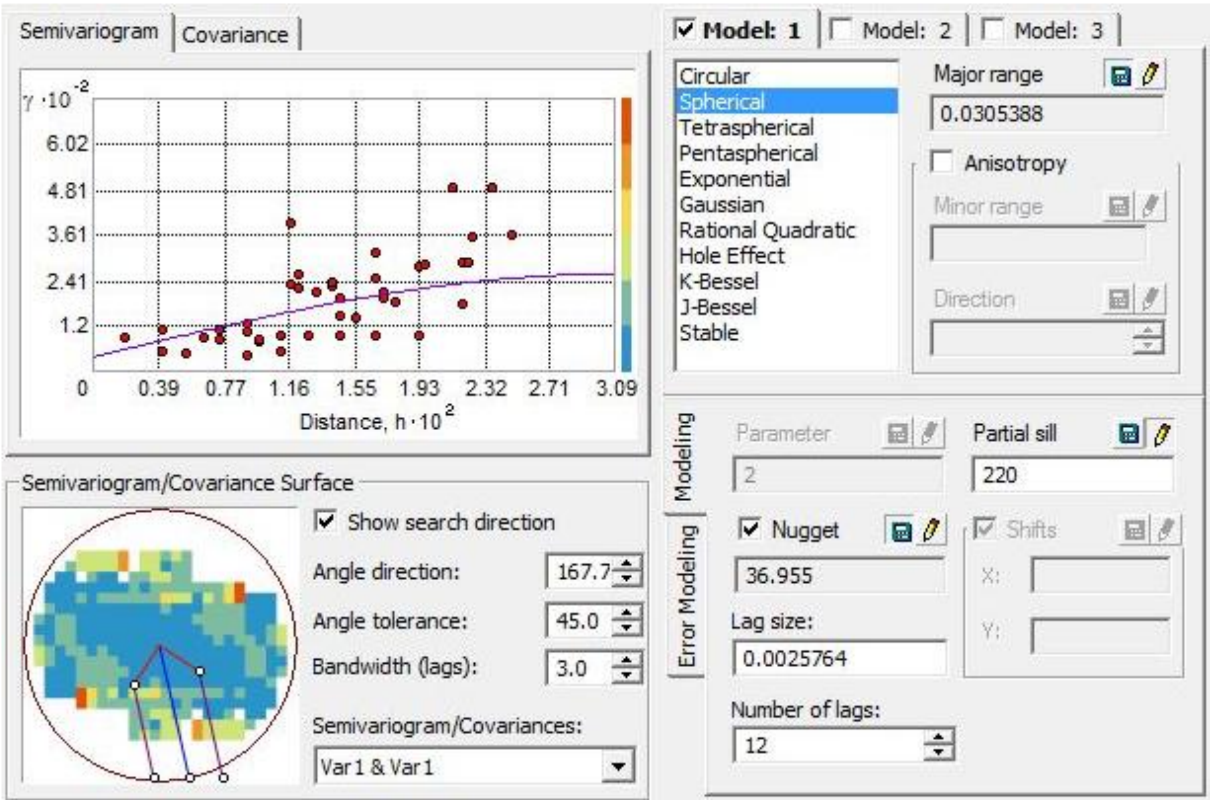

Figure 1-9. Variogram plot of % clay in layer 1 of Wargal soil: used to evaluate spatial autocorrelation of soil properties and for kriging to generate continuous map of soil data

Table 1-2. Climate and hydrologic monitoring systems: observation numbers, frequency, purpose

Observation	Collection method and number of observations	Frequency	Purpose
Rainfall	continuous, automated (1) and manual (15)	bi-weekly (continuous) and weekly (manual)	input for hydrology model
Weather Parameters (Solar radiation, wind speed, and temperature)	manual (1)	daily	input for hydrology model
Reservoir depth and area	staff gage: manual reading (1)	weekly (daily during rainy periods)	calibration of hydrology model
Drain flows to tanks	water level recorder in flumes: continuous, automated (2)	weekly	calibration of hydrology model
Groundwater levels	pressure transducer: continuous, automated (1) and sounder: manual (9)	bi-weekly (continuous) and weekly (manual)	calibration of hydrology model
Irrigation pumping	flowmeters on borewells: manual reading (4)	weekly	input for hydrology model

Table 1-3. Sources and factors included in analysis by Gogu and Dassargues; adapted from Gogu and Dassargues 2000

Reference and model name	Parameters			
	Topography	Soils	Geology	LULC
Albinet and Margat, 1970			•	
Goossens and Van Damme, 1987		•	•	
Carter and Palmer, 1987		•	•	
Foster 1987, GOD			•	
Aller et al., 1987, DRASTIC	•	•	•	
Navulur and Engel, SEEPAGE		•	•	
Civita, 1994, SINTACS	•	•	•	•
Van Stempvoort et al., 1993, AVI		•		
Civita and De Regibus, 1995, ISIS	•	•	•	•
Doerfliger and Zwahlen, 1997, EPIK	•	•	•	•

Table 1-4. Summary of methods for quantifying groundwater recharge

	Physical	Tracer	Numerical Modeling
Surface-water Based Studies	channel water budget, seepage meters	heat, isotopic	water balance simulation
Unsaturated Zone Studies	lysimetry, zero-flux plane, Darcy's law	applied, historical, environmental	water balance simulation
Saturated Zone Studies	water-table fluctuation, Darcy's law	historical, environmental	water balance simulation

Table 1-5. Summary of the 9 recharge studies highlighting dominant factors

Study area; Reference	Factors: *most important	Experimental methods
southern India; Anuraga et al., 2006	soil*, LULC (cropping system)	distributed simulation
Upper Mississippi River Basin; Arnold et al., 2000	soil, LULC*	distributed simulation
Nashua, Iowa; Bakhsh and Kanwar, 2008	soil, topography (elevation*, slope, aspect, curvature, flow length, flow direction, flow accumulation*)	drain flow measurement
Central Minnesota corn field, Delin et al., 2000	topography(elevation*), soil	simulation, tracers, well hydrographs
Wallingford, UK; Finch, 1998	soil, LULC (LAI*, stomatal resistance, rooting depth, AWC)	local simulation
northeast Nigeria; Eilers et al., 2007	soil (total available water*), LULC (rooting depth, Kc)	local simulation
Dill catchment, Germany; Huisman et al., 2004	soil, LULC (cropping system*)	distributed simulation
British Colombia, Canada; Martin et al., 2008	topography (DEM resolution*)	distributed simulation
Mallee, SE Australia; Zhang et al., 1999	LULC (rooting depth*, fallowing)	distributed simulation

CHAPTER 2
RAINFALL INTENSITY-DURATION-FREQUENCY RELATIONSHIPS FOR ANDHRA PRADESH, INDIA: CHANGING RAINFALL PATTERNS AND IMPLICATIONS FOR GROUNDWATER RECHARGE

Rainfall Characterization and Water Resource Management

The development and maintenance of rainfall intensity-duration-frequency (IDF) relationships is important for a variety of water-related design and management, including flood control, energy generation, water supply, agricultural drainage, and others. With growing competition for freshwater resources in much of the world, the role of updated IDF relationships for application in developing innovative water management strategies is becoming increasingly important. Improved characterization of rainfall, through updated IDF relationships, has been shown to improve water resource planning and management decisions (Karl et al., 1995; Angel and Huff, 1997; Guo, 2006). For example, a case study of Chicago urban drainage systems showed that drainage systems designed using updated IDF relationships, using shorter records of more recent data, performed significantly better than those developed from older rainfall records (Guo, 2006).

There is mounting evidence from global and regional studies that precipitation patterns are shifting toward more common higher intensity storms and fewer light and moderate events (Kunkel et al., 1999; Easterling et al., 2000; Trenberth et al., 2003; Goswami et al., 2006; Joshi and Rajeevan, 2006). These observed changes in rainfall characteristics suggest that IDF analyses be regularly updated to include more recent and shorter records of rainfall time series and exclude older, less-representative data. The analysis of Trenberth et al. (2003) notes that the Clausius–Clapeyron equation relating vapor pressure and temperature suggests a 7% increase in atmospheric water content for each ^{0}C increase in average annual temperature. As a result of low-level moisture convergence, local rainfall rates greatly exceed average regional or global evaporation rates; therefore, rainfall intensities could be expected to increase at a rate at least as large as 7% / ^{0}C. However, this differs from the accepted 1 – 2% / ^{0}C increase in total annual precipitation depths (IPCC, 2001). To reconcile the differences in these predictions, it follows that low and moderate intensity precipitation events will be less common, and precipitation would trend toward less frequent, higher intensity events (Trenberth et al., 2003). This argument is supported by global climate model predictions (the UKHI and CSIRO9 general circulation models; Hennessy et al. 1997) and by an investigation of rainfall records for the large region of central India (Goswami et al., 2006). Of course the spatial distribution of this change in precipitation character is uncertain, but it would mean greater risk of both dry spells and floods for some regions even though annual precipitation totals may increase slightly.

The recent rainfall character study (Goswami et al., 2006) of a large central Indian region used analyses of daily rainfall data from 1803 stations (1951-2000), and found significant increases in frequency and magnitude of high intensity rain events (>100 mm/day) and significant decreases in frequency of light and moderate events (>5 and <100 mm/day). The authors observed that these trends are more difficult to notice based on analyses from individual station data due to the large variability in daily data. The regional analysis, however, having much larger sample size due to the large number of stations, is better able to detect long term trends in rainfall intensity.

Groundwater Resources in India

Groundwater in India is a highly important resource for irrigation and household use, and its extensive use is resulting in widespread groundwater depletion (Chapter 1

“Introduction to Study Area”, Shah et al., 2003; CGWB, 2007; Rodell et al., 2009). There is general agreement that water scarcity in India is severe (Alcamo et al., 2000; Yang et al., 2003). Total (761 km^3) and agricultural (688 km^3) water withdrawals for India are the highest in the world, and nearly 90% of withdrawals are for agricultural use (AQUASTAT, 2010). More than half of the irrigation requirements of India are met from groundwater (CGWB, 2002; Shah et al., 2003), and the number of mechanized borewells in India has increased from less than 1 million in 1960 to more than 20 million in 2000 (Shah, 2007). Groundwater in India is a highly important resource for irrigation and household use, and its extensive use is resulting in widespread groundwater depletion (Shah et al., 2003; CGWB, 2007; Rodell et al., 2009).

A recent groundwater depletion study (Rodell et al., 2009) in the northwestern Indian states of Haryana, Punjab, and Rajasthan, is illustrative of common regional groundwater depletion problems in India. Using the Gravity Recovery and Climate Experiment (GRACE) satellites to measure changes in terrestrial water storage during the study period from August 2002 to October 2008, 109 km^3 of groundwater loss was estimated, or about 4 cm each year over the three-state area. In the southern state of Andhra Pradesh, the Central Groundwater Board (CGWB) of India observed a 2 – 4 m decline in groundwater levels in 26 observation wells in the Medak district during the 10 years from 1996 to 2005, suggesting an approximate annual decline of about 30 cm (CGWB, 2007).

Objectives: Precipitation Characterization and Groundwater in India

Considering the importance of groundwater resources in India, it is likely that if rainfall becomes characterized by more common events of high intensity, the result would be a higher fraction of rainfall contributing to runoff and a reduced fraction available for infiltration and groundwater recharge (de Vries and Simmers, 2002; Gujja et al., 2009; Gupta et al., 2010, Rangan et al., 2010). This may put the already reduced strained groundwater resources of India at even greater risk of depletion.

Several states in northwestern and peninsular India are experiencing groundwater depletion (CGWB, 2007, Rodell et al., 2009). In Andhra Pradesh, for example, depleted groundwater supply, resulting from irrigation withdrawal expansions, has severe consequences for farmers that have invested in borewell infrastructure. Farmers bear substantial costs of groundwater depletion: greater yield variability, costs of failed borewells, and the expenses to develop new borewells. Updated IDF relationships that reflect the changes toward more episodic rainfall in Andhra Pradesh serve to emphasize the importance of surface storage depth as a management option for increasing infiltration and groundwater recharge in agricultural areas

An area in northern Andhra Pradesh, in the Medak district is studied here as a case study to demonstrate the advantages of updated IDF relationships for a region in India that is facing acute water shortages. The objective of this study is to develop updated IDF relationships for Hyderabad, Andhra Pradesh, India. These updated rainfall descriptions are then used to demonstrate the changes in precipitation intensity and the need for regularly updated rainfall characterizations using recently available sub-daily rainfall records. The updated IDF relationships are compared to earlier analyses for the region, and the effects of changing rainfall character on groundwater resources in India are discussed. These IDF curves can be useful tools for numerous types of water resource management projects in Hyderabad (a major city in India) and the surrounding region. For example, in a small agricultural watershed near Hyderabad, the causes and solutions of groundwater depletion, a common regional problem, are being analyzed (Chapter 4), and these new IDF relationships are being used to improve predictions of infiltration (Chapter 3) and groundwater recharge.

Rainfall Characterization

Overview of IDF Analysis

Generally, the development of IDF curves follows four main steps. First, rainfall intensity data are organized into an annual maximum series. This is done for each duration of interest (1 hour, 4 hour, 8 hour, etc.) by finding the maximum rainfall intensity for the duration specified for each year. Second, a probability distribution is fitted to the annual maximum series using any choice of statistical techniques (maximum-likelihood, l-moments, or other). Third, the cumulative distribution function (CDF) chosen and parameterized in step two is used to calculate rainfall intensities from the frequencies (1/probability) desired (2 year, 5 year, 10 year, etc.) for each of the durations being considered. Fourth, the curves can be fitted to a parametric equation; this final step is optional and is useful if it is desirable to avoid using multiple CDFs for rainfall IDF prediction or if IDF curves are to be estimated for durations or frequencies not in the period of record. A common parametric equation form for IDF curves is (Bernard, 1932):

$$I_t^T = A1\frac{T^{A2}}{t^{A3}} \tag{2-1}$$

where I_t^T is the rainfall intensity of a combination of T (frequency or return period, years) and t (duration, hours) and empirically calculated constants A1, A2, and A3.

Limited IDF information is available for India. The study of Kothyari and Garde (1992), using rainfall data (1950-1980) from 80 recording gages grouped geographically based on rainfall characteristics, provided IDF curves for 5 large regions of India: northern, central, western, eastern, and southern. The Kothyari and Garde (1992) IDF relationships are the most current national IDF characterizations for India available in the literature, their IDF relationships will be used for comparison to those developed here. Their analysis found that the performance of Equation 2-1 (Bernard, 1932) could be improved by including some rainfall characteristic (Rchar) in the expression. Four rainfall properties were considered as candidates for inclusion in the equation: $\mathrm{I}_{\mathrm{t}}^{\mathrm{T}} = \mathrm{C1}\frac{\mathrm{T}^{\mathrm{C2}}}{\mathrm{t}^{\mathrm{C3}}}(\mathrm{Rchar})^{\mathrm{C4}}$, where I_t^T is the rainfall intensity of a combination of T (frequency or return period, years) and t (duration, hours), Rchar is some rainfall characteristic, and C1, C2, C3, and C4 are constants fitted to IDF data generated from the CDF which was fitted to observed data. Options considered for Rchar were mean annual rainfall (R), mean of the maximum monthly rainfall (Rmax), ratio (R/Rmax), and the 24-hr duration, two-year return period rainfall depth (R_{24}^2) were used. It was found by comparing multiple regression correlation coefficients that R_{24}^2 was most effective at improving IDF curve fit to observed data, giving the IDF equation of the form (Kothyari and Garde, 1992):

$$\mathrm{I}_{\mathrm{t}}^{\mathrm{T}} = \mathrm{C1}\frac{\mathrm{T}^{\mathrm{C2}}}{\mathrm{t}^{\mathrm{C3}}}(\mathrm{R}_{24}^{2})^{\mathrm{C4}} \tag{2-2}$$

Methods for Rainfall IDF Development for Andhra Pradesh

Two rainfall time series obtained (Singh, 2009) from recording gages at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) near Hyderabad, Andhra Pradesh, India were used to develop IDF relationships for this study. The first series consisted of 140,256 records of hourly rainfall (16 year period, 1993-2008); this data series was used for development of IDF relationships. The second rainfall time series consisted of 12,784 records of daily rainfall from (35 year period, 1974-2008); this data was used to analyze long term trends in occurrence of threshold-based high intensity rainfall events. Sub-daily rainfall records are important in rainfall IDF analyses for accurate determination of short duration (2, 4, 8 hour) storm intensities, and hourly rainfall records for India are sparse and are generally only available since the early 1990's (Jain et al., 2007). Average annual rainfall in Hyderabad is 880 mm, and 75% of that rainfall arrives during the rainy season from June to September called Kharif. The studies of Indian monsoon rainfall variability (May, 2004) and spatial coherence of tropical rainfall (Moron et al., 2007) suggest that the IDF relationships developed here, based on rainfall records from a recording station in Hyderabad are applicable for the Medak district.

Using the hourly rainfall data, annual maximum series (AMS) for all durations considered were developed by calculating a moving average intensity for each duration and then finding the maximum average intensity for each duration during a calendar year. This is step one of IDF curve development. The Weibull probability distribution was chosen based on graphical and log-likelihood value comparisons of fit to the AMS data of Weibull, Generalized Extreme Value, Gamma, and Log-Normal probability distributions. Maximum likelihood estimation of parameters for the Weibull CDF was completed independently for each of the five durations (1, 2, 4, 8, and 24 hour); see the resulting parameters α (Weibull scale parameter) and β (Weibull shape parameter) in Table 2-2 (this is step two). The two-parameter Weibull probability density and cumulative distribution functions are:

$$f(\mathrm{I}) = \alpha\beta^{-\alpha}\mathrm{I}^{\alpha-1}e^{-(\mathrm{I}/\beta)^{\alpha}} \qquad (2\text{-}3)$$

$$F(I) = 1 - e^{-(\frac{I}{\alpha})^{\beta}} \quad (2\text{-}4)$$

where f is probability, F is cumulative probability, I is rainfall intensity, α is Weibull scale parameter, and β is Weibull shape parameter. The five resulting CDFs were used to calculate rainfall intensity for the 5 durations at all the frequencies required; in this case 2, 5, 10, 15, 25, 50, 75, and 100 year return periods were considered (step 3). The IDF data were then fitted to a parametric equation of the form of Equation 2-2 for comparison to the Kothyari and Garde (1992) equation to examine the change in IDF relationships for the region in the last 3 decades.

Exploration of Trends in Occurrence of Rainfall Events of High and Low Intensity

Differences in IDF curves between those developed here and those developed using older rainfall records (Kothyari and Garde, 1992) can give evidence for a change in character of precipitation for the region near Hyderabad, India. However, trends in the total annual numbers of threshold-based high and low/moderate intensity rainfall events for single recording station can add to the available evidence for changing rainfall characteristics. Days were counted as high intensity (I) event days if $I \geq 50$ mm/day; low to moderate days were those having $5 < I < 50$ mm/day. These intensity classes are commonly used to group rainfall days into high and low/moderate classes (Angel and Huff, 1997; Goswami et al., 2006). For each calendar year, days in each class were summed. A longer record was used for this trend analysis than was used for IDF curve development because of the lack of hourly rainfall data availability and the decision to use a more recent, shorter record for IDF analysis. Hourly rainfall data give more reliable IDF relationships, especially for short durations, and most of the available hourly rainfall records in India begin in the early 1990's (Jain et al., 2007).

Results and Discussion: IDF Curves and Event Intensity Trends

Table 2-1 presents the 1, 2, 4, 8, and 24 hour annual maximum rainfall intensities for the 16 year record (1993-2008) from which IDF curves were developed. Annual and rainy season (kharif) rainfall totals and number of rain days are also presented. The IDF curves developed from the inversion of the fitted Weibull CDF at each duration, using the various probabilities (1/frequency) and solving for intensity, are plotted in Figure 2-1. These intensities were used to fit coefficients C1, C2, C3, and C4 to equation 3-2. Fitting was done separately for each duration and then also for all durations combined (see resulting constants in Table 2-2); coefficients were fitted using an automated iterative routine with the goal of minimizing the average root mean squared error (RMSE) between intensities from the CDF and those from Equation 2-2.

Using the coefficients of Kothyari and Garde (1992) listed in Table 2-2, the RMSE of rainfall intensities from IDF relationships developed using recent data (1993-2008) and those calculated from the original Kothyari and Garde formula (1950-1980 rainfall data) was 28.98 mm/hour. Mean difference (intensities from original Kothyari and Garde formula minus intensities from newly parameterized Weibull CDF) was -25.43 mm/hour (Table 3-4), and percent difference from the original 1992 formula was greater than 100% for many return period-duration combinations. This suggests significant increases in intensity of rainfall events during the last 3 decades for the region near Hyderabad, India.

Analyzing the daily rainfall data from Hyderabad (1974-2008), noticeable trends of increasing annual numbers of high intensity rainfall events ($I \geq 50$ mm/day) and decreasing numbers of low and moderate intensity events ($5 < I < 50$ mm/day) were observed (Figure 2-2). These trends have low to moderate statistical significance based on t-tests of the hypothesis of no trend; p-values of 0.27 and 0.082 for slopes of increasing trend of high intensity events and decreasing trend of low and moderate events, respectively. The non-parametric Mann-Kendall test of trend significance showed a significant ($\alpha = 0.05$) increasing trend for annual numbers of high intensity rainfall events, but no significant trend for annual numbers of low and moderate intensity events. The moderate strength of the trends is consistent with the observations of Goswami et al. (2006) that the high variability of single-gage records makes it difficult to observe trends of high statistical significance, but the directions of the trends are consistent with their analysis for all of central India.

Discussion: Precipitation Characterization and Groundwater in India

Changing rainfall characteristics generally have important impacts on the hydrology of a region. In semi-arid regions, like that of the Hyderabad region, the annual potential evapotranspiration is much greater than precipitation, runoff generation is generally Hortonian, and groundwater recharge in these regions depends largely on high intensity storms and the storage of excess rainfall in surface depressions (de Vries and Simmers, 2002). Channelized flow is highly seasonal, meaning most groundwater recharge results from areal infiltration and percolation of surface storage of excess rainfall. Higher intensity rainfall patterns lead to greater runoff and a lower proportion of rainfall being infiltrated and available for groundwater recharge. For the agricultural regions of semi-arid India, groundwater recharge is of major concern: groundwater depletion is common as a result of substantial irrigation withdrawals. Given the scarcity and seasonality of surface water resources in the region, increased rainfall variability makes irrigation from groundwater resources even more important. The evidence provided by this study suggests rainfall in peninsular India is becoming increasingly characterized by higher intensity events and fewer low and moderate intensity events. This result has a variety of management applications, but for agricultural areas dependent on groundwater, one application would be to increase investments in reservoirs, farm ponds, and water harvesting tillage to increase the infiltration of rainfall. The value of groundwater resources can be expected to increase when there is more variable rainfall.

Conclusions on Rainfall Intensity Trends and Groundwater Recharge

Rainfall IDF relationships are useful tools for various hydrologic analyses, and the updating and maintenance of these relationships is important for decision-making that requires information about the character of rainfall. The recent evidence of more common high-intensity rainfall events was extended in this study to illustrate IDF differences between old and new records and to recommend that IDF relationships be regularly updated using more recent rainfall records. The newly developed IDF relationship for the Hyderabad region of southern India, using the formula of Kothyari and Garde with updated parameters based on 1993-2008 rainfall data, including the 2 year, 24 hour rainfall of 103.2 mm, is $I_t^T = 7.11\frac{T^{0.253}}{t^{0.479}}(103.2)^{0.389}$. These new IDF curves show noticeably greater rainfall intensity patterns – on average 25 mm/hour or 123% greater for 1 to 24 hour durations – compared to the previously available rainfall characterization (Kothyari and Garde 1992) for the southern region of India. Based on this large IDF difference, it is recommended that IDF relationships be regularly updated to improve decisions and designs that utilize these relationships. These results are consistent with the growing consensus that precipitation patterns are shifting, especially in lower latitudes, toward higher intensity rainfall events and a decrease in moderate and low intensity rainfall (Owor et al. 2009; Pall et al. 2006; Trenberth et al. 2003; Allen and Ingram, 2002). Similar studies of changing IDF relationships using shorter, recent rainfall records in other regions of India and in other parts of the world could give increased evidence for changing rainfall characteristics.

Table 2-1. Annual maximum series rainfall intensity generated from hourly rainfall data from Hyderabad, Andhra Pradesh, India. Annual and Kharif season (June-September) total rainfall and rain days.

	Annual maximum series rainfall intensity, mm/hr					Rainfall totals, mm		Kharif
	1 hour	2 hour	4 hour	8 hour	24 hour	Annual	Kharif	rain days
1993	29.5	17.1	10.0	5.0	2.4	831	588	49
1994	34.8	23.4	14.1	8.9	6.0	848	550	62
1995	54.1	29.9	15.7	7.9	4.0	1266	747	54
1996	50.3	27.8	16.2	11.1	4.7	1063	911	64
1997	29.2	17.8	11.8	7.7	3.9	743	433	48
1998	34.1	21.2	12.0	7.9	2.8	1181	887	64
1999	30.0	16.6	8.7	4.4	1.9	580	455	63
2000	154.9	136.4	105.6	66.0	36.9	2016	1797	66
2001	37.4	20.7	10.5	6.4	2.6	688	514	53
2002	18.5	14.1	7.1	3.8	2.2	623	473	48
2003	50.6	41.2	25.4	12.8	4.3	926	789	66
2004	29.4	26.5	14.3	7.7	3.2	783	546	47
2005	46.7	32.3	18.3	9.3	4.4	1192	850	68
2006	33.8	24.6	17.2	11.9	4.6	889	636	75
2007	30.2	28.4	16.1	8.8	2.9	717	571	77
2008	44.0	25.8	15.6	9.9	7.0	1109	758	65

Table 2-2. Parameters for Weibull CDF: $F(I) = 1 - \exp(-(I/\alpha))^{\beta}$, where I is rainfall intensity, and parameters for IDF function: $I_t^T = C1 \frac{T^{C2}}{t^{C3}} (R_{24}^2)^{C4}$

Storm Duration	Weibull CDF parameters α, scale	β, shape	IDF function parameters C1	C2	C3	C4
1 hour	50.1056	1.6863	7.1068	0.4018	0.2259	0.7100
2 hour	35.2153	1.4214	7.1059	0.4303	0.2614	0.6885
4 hour	21.5984	1.2173	7.1035	0.4264	0.2976	0.6734
8 hour	12.6868	1.1703	7.1025	0.4113	0.3075	0.6686
24 hour	6.0630	1.0670	7.1022	0.4050	0.3318	0.6560
			fitted to all 5 durations			
			7.1052	0.2532	0.4786	0.3889
			Kothyari and Garde parameters			
			7.1000	0.2000	0.7100	0.3300

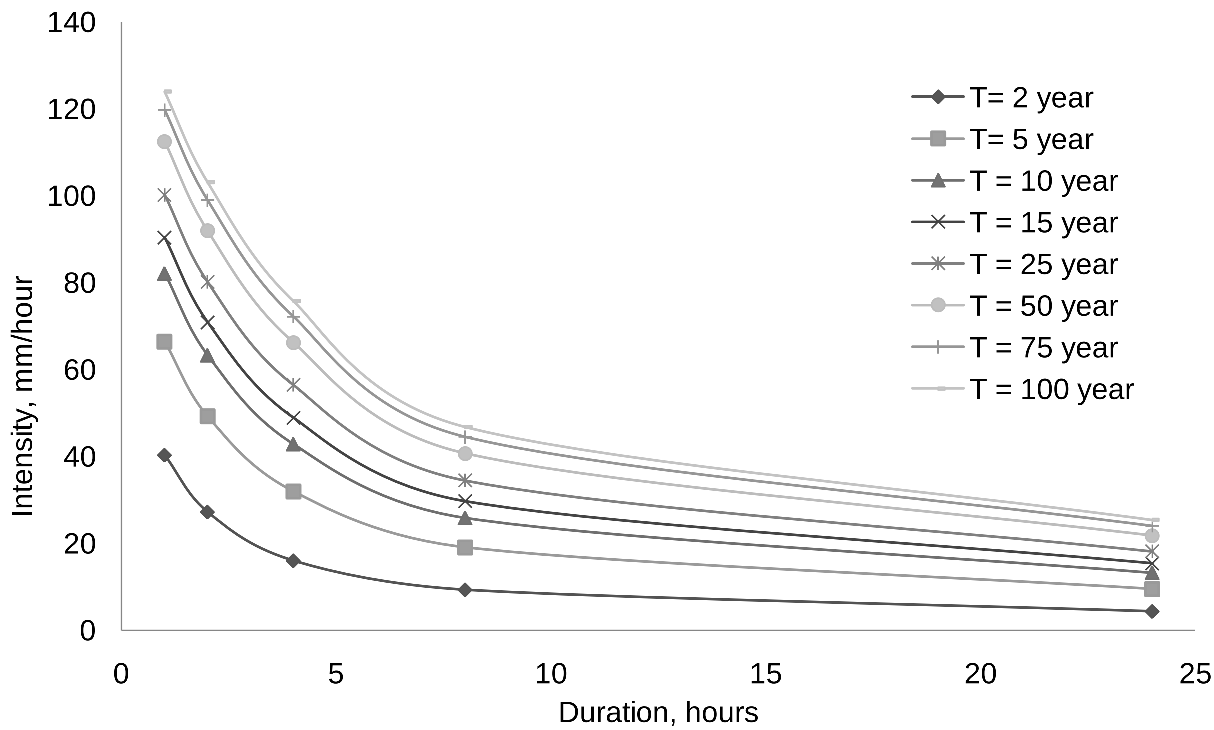

Figure 2-1. Intensity duration frequency curves for 1, 2, 4, 8, and 24 hour durations developed from hourly rainfall data from 1993 – 2008 from Hyderabad, India

Table 2-3. Rainfall intensity values from Weibull cumulative distribution functions (CDFs): hourly data 1993-2008 for Hyderabad

t (hours) duration	T, return period (years) 2	5	10	15	25	50	75	100
1	40.32	66.44	82.16	90.36	100.22	112.51	119.70	123.94
2	27.21	49.22	63.32	70.89	80.15	91.94	98.95	103.12
4	15.98	31.93	42.85	48.89	56.43	66.23	72.17	75.73
8	9.28	19.05	25.87	29.67	34.45	40.70	44.50	46.78
24	4.30	9.47	13.25	15.40	18.13	21.77	24.01	25.37

Table 2-4. Rainfall intensity (mm/hr) from Kothyari and Garde general formula fitted to recent intensity data (1993-2008) for Hyderabad[1]. RMSE calculated based on CDF intensities.

t (hours) duration	T, return period (years) 2	5	10	15	25	50	75	100
1	51.40	64.82	77.25	85.60	97.42	116.11	128.66	138.38
2	36.89	46.52	55.44	61.43	69.92	83.33	92.33	99.31
4	26.47	33.39	39.79	44.09	50.18	59.80	66.26	71.27
8	19.00	23.96	28.55	31.64	36.01	42.92	47.56	51.15
24	11.23	14.16	16.88	18.70	21.28	25.37	28.11	30.23
							RMSE	6.27

[1]: $I_t^T = 7.11 \frac{T^{0.253}}{t^{0.479}} (103.2)^{0.389}$

Table 2-5. Rainfall intensity (mm/hr) from Kothyari and Garde original formula fitted to older intensity data (1950-1980) for southern zone of India[1]. RMSE calculated based on CDF intensities.

t (hours) duration	T, return period (years) 2	5	10	15	25	50	75	100
1	37.67	45.24	51.97	56.36	62.43	71.71	77.77	82.37
2	23.03	27.66	31.77	34.46	38.16	43.84	47.54	50.35
4	14.08	16.91	19.42	21.06	23.33	26.80	29.06	30.78
8	8.61	10.34	11.87	12.88	14.26	16.38	17.77	18.82
24	3.94	4.74	5.44	5.90	6.54	7.51	8.14	8.63
							RMSE	28.98

[1]: $I_t^T = 7.1 \frac{T^{0.2}}{t^{0.71}} (103.2)^{0.33}$. RMSE

Table 2-6. Differences (mm/hour) in predicted rainfall intensity values between Kothyari and Garde IDF formula using 1992 parameters[1] and using updated parameters fitted from this study[2]

t (hours) duration	T, return period (years) 2	5	10	15	25	50	75	100
1	-13.73	-19.58	-25.28	-29.24	-35.00	-44.40	-50.89	-56.01
2	-13.86	-18.86	-23.67	-26.98	-31.75	-39.49	-44.79	-48.95
4	-12.40	-16.48	-20.37	-23.03	-26.85	-33.00	-37.20	-40.49
8	-10.39	-13.62	-16.68	-18.77	-21.75	-26.53	-29.79	-32.33
24	-7.28	-9.42	-11.44	-12.80	-14.75	-17.86	-19.96	-21.61
Mean Difference	-25.43							

[1]: $I_t^T = 7.1 \frac{T^{0.2}}{t^{0.71}} (103.2)^{0.33}$ and [2]: $I_t^T = 7.11 \frac{T^{0.253}}{t^{0.479}} (103.2)^{0.389}$

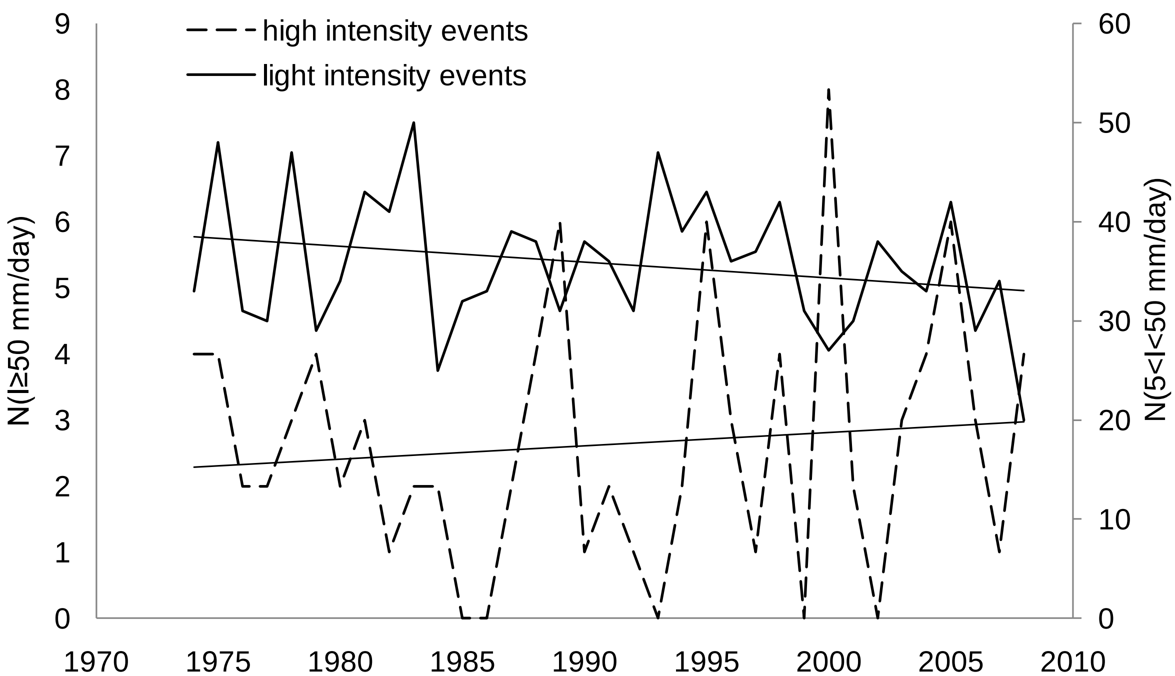

Figure 2-2. Annual counts of high (I ≥ 50 mm/day) and light intensity (5 < I < 50 mm/day) rainfall events (1974-2008)

CHAPTER 3
IMPORTANCE OF SURFACE STORAGE PONDING DEPTH FOR PREDICTING INFILTRATION AND RUNOFF IN WATER CONSERVATION TILLAGE SYSTEMS

Modeling Infiltration and Tillage: Implications for Groundwater Recharge

Infiltration, Surface Storage, and Changing Precipitation Character

Infiltration is the quantity of water that enters the soil at the intersection of the soil surface and the atmosphere. The rate of infiltration is controlled by the rate of water application (precipitation and irrigation), by the depth of surface water storage, and by the properties of the soil. In agricultural areas, tillage management arguably has the greatest influence on infiltration (Blevins et al., 1990; Knapen et al., 2008; Zhang et al., 2007). Its effects on infiltration result from greater surface roughness, which increases depression storage, and from lower bulk density, which increases hydraulic conductivity. Disruption of surface sealing and crusts through tillage also increases infiltration capacity of a soil. While there is extensive literature on tillage management effects on surface storage and roughness (Kamphorst et al., 2000; Planchon et al., 2002; Guzha, 2004), there has been comparatively little work done to quantify the importance of surface storage in simulation of infiltration and runoff. Excess rainfall (total precipitation minus interception, surface storage, and infiltration) is the amount of water available for direct runoff; this is generally greater than runoff, which is the amount of that converges into surface streamflow. For simplicity, excess rainfall is hereafter referred to as runoff (RO).

In semi-arid regions, potential evapotranspiration is much greater than precipitation; the ratio of precipitation to potential evapotranspiration for semi-arid zones is 0.20-0.50 (UNEP, 1992). Annual precipitation for semi-arid zones varies from 300-800 mm, in areas with summer rains and from 200-500 mm in areas with winter rains

(UNEP, 1992). Groundwater in semi-arid regions is an important resource for mitigation of droughts and dry spells (Shah et al., 2006). Channelized flow is uncommon and very seasonal, and groundwater recharge in these regions depends largely on high intensity storms and the areal infiltration and deep percolation of runoff stored in surface depressions (de Vries and Simmers, 2002).

One such semi-arid region is the Wargal agricultural watershed, Medak district, Andhra Pradesh, India, where groundwater depletion is a growing concern. More than 80% of annual rainfall (780 mm) in Wargal falls during the 4 months from June to September. Much of it is episodic, arriving in short, high-intensity events. There is growing consensus that precipitation patterns are shifting, especially in lower latitudes, toward more common higher intensity rainfall events and fewer moderate and low intensity rainfall events (Chapter 2; Owor et al., 2009; Pall et al., 2006; Trenberth et al., 2003; Allen and Ingram, 2002).

These trends toward increasingly episodic rainfall highlight the value of surface storage for management of infiltration and groundwater recharge and the potential importance of water harvesting tillage methods for dry spell mitigation. For an episodic rainfall pattern having high-intensity storms, daily time step models of infiltration and runoff can be expected to overestimate infiltration and thus underestimate runoff. The hourly or sub-hourly time step solutions of Green-Ampt have been shown to simulate infiltration better than the daily time step Curve Number (SCS, 1972) method under a variety of conditions (Rawls and Brakensiek, 1986; Wilcox et al., 1990; Stone and Sadler, 1991; Van Mullem, 1991). Curve Number infiltration has established guidelines for parameterization of tillage management; however, describing tillage for Green-Ampt infiltration is generally not considered.

Green-Ampt Infiltration and Depression Storage

The Green-Ampt infiltration model (Green and Ampt, 1911) can be described as an approximate, physically-based model developed from the application of Darcy's law. Water is assumed to infiltrate with a distinctly defined wetting front as illustrated in Figure 3-1. The development of the Green-Ampt equations is a direct application of Darcy's Law for deep homogeneous soils with uniform initial water content under constant, ponded infiltration,

$$q = K_s \frac{dH}{dz}, \tag{3-1}$$

where q is water flux [L/t], K_s is saturated hydraulic conductivity [L/t], and dH/dz is the hydraulic head gradient in the direction of flow [L/L]. Adding up heads in Figure 3-1 ($dH = h_p + L + \psi_f$), substituting infiltration rate q by dF/dt, where we call F cumulative infiltration ($F = (\theta_s – \theta_i)*L$), replacing K_s with K_{se} (effective hydraulic conductivity, accounting for air in the soil matrix of unsaturated soils), and substituting the soil moisture deficit, M, for $\theta_s – \theta_i$, Darcy's law then becomes:

$$\frac{dF}{dt} = K_{se}\left(\frac{h_p M}{F} + 1 + \frac{\psi_f M}{F}\right) \quad \text{or} \quad \frac{dF}{dt} = K_{se}\left(\frac{(h_p + \psi_f)M}{F} + 1\right). \tag{3-2}$$

Although in reality, $0 < h_p(t) < MDS$, in the classical use of derivation and use of the GAML equations, the ponding depth, h_p, is assumed negligible and is removed from the expressions in equation 3-2. Separation of variables and integration results in the familiar Green-Ampt infiltration equation:

$$F = K_{se}t + \psi_f M \ln\left(1 + \frac{F}{\psi_f M}\right). \tag{3-3}$$

Mein and Larson (1973), Chu (1978) and Skaggs and Khaleel (1982) improved the applicability of the Green-Ampt equation to allow for calculation under conditions of variable natural rainfall intensity (with periods of non-ponding and ponding conditions). The time to ponding, t_p, the cumulative infiltration at the time of ponding, F_p, and t'_p, the time to infiltrate Fp if ponding started from the beginning of the rainfall event, were introduced to allow for the following solution system. For $t < t_p$, f = i (rainfall intensity) and for $t = t_p$, f = i. Time to ponding can be calculated from $t_p = F_p/i$, where,

$$F_p = \frac{\psi_f M}{\frac{i}{K_{se}} - 1}. \tag{3-4}$$

Consideration of the ponding time adjustments finally result into,

$$F = K_{se}\left(t - t_p + t'_p\right) + \psi_f M \ln\left(1 + \frac{F}{\psi_f M}\right). \tag{3-5}$$

Using this form of the equation, h_p appears only in the surface water balance, calculated after runoff (RO) predicted by GAML, as

$$dRO = dR - dF - dh_p, \tag{3-6}$$

where dRO [L] is the increment of excess rainfall produced for an incremental rain, dR [L], dF [L] is the increment in cumulative infiltration for the same time step, and dh_p [L] is the change in surface storage depth for the same period. Equations 3-4, 3-5, and 3-6 will be called the “standard GAML solution” herein. This form of the Green-Ampt infiltration model now allows for infiltration to be simulated before and after ponding and if ponding ends and begins again. The MDS=0 solution, shown in the results to illustrate tillage and MDS importance, represents a negligible h_p both as a head and in a surface water balance. This solution form (MDS=0) is used to predict infiltration and runoff in a variety of field-scale and landscape-scale hydrologic models, Soil and Water

Assessment Tool (SWAT, Arnold et al., 1998; Gassman et al., 2007; Krysanova and Arnold, 2008) is one example.

It is proposed here that for agricultural systems under some form of water harvesting tillage, surface storage h_p, should be included as a time varying head ($0 < h_p(t) < MDS$) in the GAML equations in addition to the water balance at the surface (eq. 3-6). To simplify the handling of the time-dependent boundary condition in equation (3-2) we can assume that h_p is constant within each time step but changed for each time step (h_{p_i}). This simplification is acceptable in water harvesting tillage systems where dh_p for each dt is small relative to the total MDS if the time step is kept sufficiently small. This allows integration of equation (2) to yield,

$$F = K_{se}\left(t - t_p + t_p'\right) + (\psi_f + h_{p_i})M \ln\left(1 + \frac{F}{(\psi_f + h_{p_i})M}\right). \tag{3-7}$$

Equations 3-4, 3-6, and 3-7, solved concurrently for each time step will here be called the “complete GAML solution”. The proposed use of the complete GAML solution for water conservation tillage systems against the standard formulation is examined by repeating local and global sensitivity analyses with both forms of the GAML equations: with h_p only included in surface water balance for the conventional Green-Ampt method (standard GAML) and with h_p as a time-varying head in the GAML equation and also in the surface water balance (complete GAML). Sensitivity analyses were used to measure the strength of influence of h_p on infiltration predictions and to compare GAML infiltration sensitivity to all the remaining parameters.

Groundwater Recharge and Tillage Management: Modeling Implications

In this chapter, the focus is on improving the performance of infiltration predictions from the GAML equations through the addition of the typically neglected surface storage depth term, h_p; the importance of all five GAML parameters under conventional and tied-ridge tillage is compared. Conventional tillage describes disking, harrowing, moldboard plowing, or chisel plowing with no consistent orientation to elevation contours. Water harvesting tillage is a type of conservation tillage characterized by significant increases in microrelief or depression storage through the creation of surface geometries allowing for substantial water storage (i.e. tied-ridge tillage, pit tillage, contour bunding). Essentially, small basins are formed in croplands which can store excess rainfall and increase infiltration. The agronomic benefits of water harvesting tillage are generally realized in the form of increased crop yields resulting from increased plant available water (Twomlow and Breneau, 2000; Wiyo, 2000; Guzha, 2004; Tesfahunegn and Wortmann, 2008). In addition, increased infiltration can result in the potential hydrologic benefit of increased groundwater recharge (Foster and Chilton, 2003), an important benefit in many intensive agricultural areas of the world where aquifer levels are decreasing (Konikow and Kendy, 2005).

Rainfed agricultural systems, especially those in resource-poor and generally ungauged watersheds, are increasingly using water harvesting tillage to increase infiltration depths (Twomlow and Breneau, 2000; Wiyo et al., 2000; Tesfahunegn and Wortmann, 2008; Derib et al., 2009; Araya and Stroosnijder, 2010), and it may be in these systems, especially in the tropical regions having vulnerable soils, that alternative tillage management is the most economical means of increasing production (Rockström, 2001). Also, irrigated rice croplands, having substantial and well-identified surface storage depths, are extensive in many typically ungauged watersheds of Southeast Asia. Including surface storage depth in models using GAML-predicted infiltration is suggested as a possible means of improving model process descriptions for predictions in ungauged basins (i.e. PUB project, see Sivapalan et al., 2003).

In addition to the growing use of water harvesting tillage in rainfed systems, there is evidence in the scientific literature and in recent agricultural applications that there is renewed interest in water harvesting tillage even in humid, irrigated areas (Truman and Nuti, 2009 and 2010). In Mississippi, USA, for example, water harvesting tillage in the form of furrow diking (synonymous with tied-ridging) has been approved for cost sharing under the state's EQIP (Environmental Quality Incentives Program); for growers implementing furrow diking, half of the costs are paid by the state. In an analysis of the hydrology and economics of water harvesting tillage for irrigated cotton in Georgia, USA, it was found that a grower would recover investment costs for furrow diking tillage after the first 16 ha-mm of irrigation water savings. This was based on a cost of $1.17 / ha-mm to pump irrigation water and $18.50 / ha for implementing furrow diking (Truman and Nuti, 2009). Additionally, furrow diking resulted in a 2.6 times reduction in soil loss and 25% lower runoff compared to conventional tillage.

There are numerous process-based hydrology and water quality models using GAML infiltration with fixed or negligible MDS used in a surface water balance and assuming negligible h_p in GAML equations (MDS=0 or standard GAML solution form): SWMM (Storm Water Management Model; Huber and Dickinson, 1992), PRZM (Pesticide Root Zone Model; Carsel et al., 1998), WEPP (Water Erosion Prediction Project; Laflen et al., 1997), SWAT (Soil and Water Assessment Tool; Arnold et al., 1998), VFSMOD (Vegetative Filter Strip Modeling System, Muñoz-Carpena et al., 1999), WaSiM-ETH (Water Flow and Balance Simulation Model; Schulla and Jasper, 2000), and others. It is argued here that using the complete GAML form in models using the Green-Ampt method for infiltration prediction, there is no real loss of model parsimony. If MDS values for various tillage management can be assumed to have less uncertainty than other infiltration parameters, a reasonable assumption given the simplicity of measurement, the lower range of values, and the strength of literature values of MDS (Kamphorst et al., 2000; Planchon et al., 2002; Jones and Baumhardt, 2003; Guzha, 2004), then there may be a reduction in model equifinality concerns, meaning that a model user may have a better chance of getting the right answer for the right reasons (Beven, 2006; Gupta et al., 2008; Hughes, 2010).

Parameter estimation completed during GAML model calibration to match observed data can produce models of similar performance regardless of the solution form being used. For example in a watershed having extensive areas under water harvesting tillage, even if the MDS=0 GAML solution is used, streamflow could still be predicted well after calibration by increasing the values for K_{se} and/or ψ_f to achieve the same runoff reductions that actually result from the MDS of the areas under water harvesting tillage. The use of additional measured input factors (as opposed to simply using calibration procedures) is suggested as a way to avoid this problem (Ritter et al., 2003).

Here it is proposed that including h_p (and MDS) in the GAML equations and in a surface water balance would provide more certain predictions of infiltration and runoff, compared to MDS=0 and standard GAML solutions, for evaluating hydrologic effects of water harvesting tillage. The objectives of this chapter were to evaluate the importance of surface storage depth for Green-Ampt predicted infiltration in agricultural systems under conventional and water harvesting tillage, and to test the proposal that for systems with water harvesting tillage the surface storage depth could be used to improve the process description of GAML infiltration.

Methods for Analyzing the Importance of Surface Storage Depth

Site Description

The study area is a 512 ha watershed, called Wargal, in a rural, agricultural region of northwestern Andhra Pradesh, India (Figure 1-1). Soils in the area are mostly sandy loam and sandy clay loam with some small areas of clay loam and sandy clay (Soil Survey Staff, 1999). Rice, maize, cotton, potato, and sunflower are the most commonly grown crops. Conventional tillage, the typical practice in the area, is either moldboard or chisel plough drawn by animals and sometimes tractors. Tied-ridge tillage, also called furrow diking, basin tillage, or reservoir tillage, is the practice of creating earthen ridges perpendicular to direction of primary tillage (Figure 3-2). Tied-ridging was selected as the example of water harvesting tillage because it is sometimes used for potato and other vegetable crops planted late in the rainy season, and equipment is commercially available for mechanization. The ridges and ties can be created with hand tools or with a variety of animal-drawn or tractor-drawn implements. Typically, furrow spacing is 75 to 100 cm with ties every 2 to 6 meters (Jones and Baumhardt, 2003). Ridge and tie heights are approximately 20 cm. Analysis of the surface geometry suggests a maximum depression storage of 100 mm. Profile measurements of tied-ridge tilled systems show 50 to 60 mm maximum depression storage (Jones and Clark, 1987).

Groundwater depletion is a growing concern in the study region as a result of substantial rice cropland areas, high irrigation withdrawals, density of borewells, and unmetered electrical supply. This is a common scenario in much of India (Rodell et al., 2009). The broad goal of work in the Wargal watershed is to evaluate combinations of agricultural management options for improving groundwater recharge and reducing irrigation withdrawals. These evaluations are being made using a simulated water balance from the semi-distributed hydrology model, SWAT (Arnold et al., 1998; Gassman et al., 2007; Krysanova and Arnold, 2008). One of the management options being investigated for increasing groundwater recharge is to expand the extent of cropland areas under water harvesting tillage. It is expected that the infiltration increases from water harvesting tillage would result in groundwater recharge improvements.

Local Sensitivity Analysis

A simple, local sensitivity analysis (LSA), changing one parameter at a time, was completed to find the changes in runoff (RO) and infiltration (F) depths obtained for a 4-hour design storm of 2-year return period in the Wargal area; results from all 3 GAML solution forms were compared (MDS=0, standard, and complete). Percent changes in F and RO were calculated based on the difference in RO and F from solutions using mean MDS for each tillage treatment, conventional (CT) and tied-ridge (TR). Here, only MDS was varied from its minimum, mean, and maximum values. The purpose of the local sensitivity analysis was to give a simple, easily interpretable measure of MDS importance in GAML solutions.

Global Sensitivity Analysis

A global analysis of sensitivity (GSA) was included here to provide a more complete examination of the importance of MDS in the context of all the GAML parameters. Additional summaries of GSA methods (Saltelli et al., 2000; Saltelli, 2005;

Saltelli et al., 2008) and recent applications to hydro-ecological models (Muñoz-Carpena et al., 2007; 2010; Muñoz-Carpena and Muller, 2009; Fox et al., 2010; Chu-Agor et al., 2011) are available.

For a given model input factor X_i, the first-order variance-based global sensitivity index S_i gives the ratio of the output variance if the true value of the input was known to the total output variance (Y). Formally, a first-order S_i is defined as $S_i = V[\ E(Y|X_i)\ ] / V(Y)$, where X_i is a parameter or input of a model, Y is the output of interest, E is expected value, and V is variance. If a model if perfectly additive, meaning there are no parameter interactions, then the sum of all S_i's equals 1. This in practice represents a quantitative measure of how much of the total output variance is explained by the variation of the single parameter X_i alone (direct effect). First order indexes are used to select the input factor(s) of the model that would result in the greatest reduction in variance, V(Y), if the true value of the factor was known; hence they are typically used to prioritize the importance of model inputs (Saltelli, 2005).

Total-effect global sensitivity indexes, S_{Ti} are calculated to account for the presence of interactions (higher order effects). S_{Ti} gives the ratio of – the expected amount of variance that would remain if all other input factors were known (fixed) and only the input factor of interest was varied over its range – to the total output variance (Y), i.e. $S_{Ti} = E[\ V(Y|X_{-i})\ ] / V(Y)$, and are computed similarly to first-order S_i. They are generally used to fix a factor having little influence on V(Y) or to exclude unimportant input factors during model development (Saltelli, 2005). If a model is non-additive, meaning there are parameter interactions, then the sum of all S_{Ti} is greater than 1.

A program was developed in Matlab (Mathworks Inc., Natick, MA) for Green-Ampt infiltration of unsteady rainfall and was used to read in rainfall intensities, GAML parameters, and solve for cumulative infiltration (F), surface runoff (RO), surface storage (h_{pi}), and f (infiltration rate). Equation 7, an implicit function in terms of F, was solved for F using a combination of bisection, secant, and inverse quadratic interpolation methods (fzero routine in Matlab). h_{pi} was calculated at each time step *i* based on rainfall intensity, infiltration rate, previous time step h_{p-1}, and MDS. Variance-based first-order sensitivity indexes (S_i) were obtained for all the GAML parameters for various storm durations and return periods using the extended Fourier amplitude sensitivity test (FAST) (Saltelli et al., 1999). These were computed for target outputs total storm RO and F using the GAML Matlab program linked to the sensitivity and uncertainty analysis package SimLab 2.2 (Saltelli, 2005) that was used to sample input parameter sets and for post-processing of outputs to generate sensitivity indexes. Parameter sets of size 5000 were generated from the ranges and probability distributions selected for all five Green-Ampt parameters.

Parameters for Green-Ampt Infiltration Sensitivity Analysis

The first step in a good sensitivity analysis is a clear understanding of the objective; here, the first objective of the sensitivity analysis was to rank the relative importance of surface storage depth against all other model input factors for two tillage strategies: conventional (CT) and tied-ridge (TR). The second step is to develop ranges and probability distributions for all parameters of the model being used. Table 3-1 displays parameter values needed to use the Green-Ampt model for unsteady rainfall at the Wargal site. Ranges of the Green-Ampt parameters for the study area were based on observations and estimations from literature values; probability distributions were assigned to each of the parameters based on the range and values found.

Laboratory measurements of saturated hydraulic conductivity were performed on undisturbed soil cores collected from the experimental site (Figure 1-1) by partners at Acharya N. G. Ranga Agricultural University (ANGRAU) in variable depth increments from 0 – 1 m (136 samples from N = 37 locations); there were typically samples from 4 soil layers at each location. Values of saturated hydraulic conductivity (K_s) ranged from 0.131 to 165 mm/hr, based on constant head permeameter K_s measurements. For use in Green-Ampt, K_s values only in the top soil layer (0 – 30 cm) were used; the geometric mean K_s in this layer was 31.8 mm/hour. Hydraulic conductivity (K) of soil is dependent on water content; generally a drier soil has a lower K than a wetter soil. The effective hydraulic conductivity (K_{se}) in the Green-Ampt equation accounts for this air entrapment making $K_{se} < K_s$. The recommendation of Bouwer (1966) is to approximate K_{se} using $K_{se} = 0.5*K_s$; this approximation was used here in the absence of field measurements of K_{se}. A log-normal probability distribution was fitted to the K_{se} data; Weibull, log-normal, and Generalized Extreme Value (GEV) distributions were compared graphically. The GEV distribution fit the data most closely, but the log-normal distribution, also a good fit, was selected because it is what is typically used for K_s distribution (Carsel and Parish, 1988; Meyer et al., 1997) and the GEV distribution is unavailable in the SimLab (Saltelli, 2005) sensitivity/uncertainty analysis package that was used here.

There were no observations of average wetting front suction average (ψ_f) values for soils in Wargal watershed. The soil properties tables of Rawls et al. (1983) were used to estimate ψ_f based on observed soil texture data. The soil texture used here was sandy loam; it was one of the two dominant textures based on observations and measured K_s values were more consistent with those associated with sandy loam than with sandy clay loam. Soil texture analysis for the experiment site was made using the Bouycous Hydrometer method (Kalra and Maynard, 1991). Without additional data for determination of a probability distribution, the distribution of ψ_f was assumed uniform with parameters given in Table 3-1.

The initial volumetric water content (θ_i) and saturated volumetric water content (θ_s) were obtained like ψ_f using tabular data for sandy loam soil (Rawls et al., 1983; Fangmeier et al., 2005). Spatial variability is typically high for these parameters and temporal variability is high for θ_i. Literature values based on soil texture were the best estimates available for the study area.

The maximum surface storage depth (MDS) represents the maximum depth of surface storage of water over an area. It is the equivalent depth of water stored on the surface of the entire area if it was covered with an equal depth of water everywhere. There is not sufficient data in the literature to recommend changes in the other parameters for different tillage. Tillage is expected to influence infiltration through soil surface geometry changes, not through changes in soil structure. MDS is changed because significant differences in this parameter have been found for different kinds of tillage (Table 3-1). Based on a summary of literature values, MDS will be given a mean value of 5 mm for conventional tillage. With no data about distribution of MDS measurements, distribution will be assumed uniform: minimum and maximum MDS of 0 and 10 mm, respectively, for conventional tillage. MDS for tied-ridging will be assigned a mean of 32.5 based on the assumed uniform distribution and using the minimum value of Guzha et al. (2004) of 15 mm depression storage and a maximum value of 50 mm based on a conservative assessment of surface geometry and the work of Jones and Clark (1987).

Development and Selection of Design Storms for the Analysis

Hourly data of rainfall from 1993-2008 (16 years; Singh, 2009) from recording gages at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) near Hyderabad, Andhra Pradesh, India (20 km from study area) were used to generate rainfall intensity-duration-frequency (IDF) curves that were used for synthetic storm generation of design storms. IDF relationships were developed by fitting a probability distribution function to the annual maximum series rainfall intensity data (separately for selected durations: 2, 4, 8, and 24 hours). Parameters for distribution functions were estimated using maximum likelihood estimation. Three distribution functions commonly used for rainfall IDF representation, Gumbel, Gamma, and Weibull (Koutsoyiannis et al., 1998; Mohymont et al., 2004), were compared graphically with the empirical cumulative distribution functions (CDF) of annual maximum series rainfall for the selected durations.

Results and discussion of GAML Infiltration Sensitivity Analyses

Representative Design Storm for the Analysis

Plotting the Gumbel, Gamma, and Weibull CDF with the empirical CDF of 4-hour rainfall annual maximums showed similar fit to the data for Weibull and Gamma distributions (Figure 3-3). The Weibull distribution function was selected to be used here based on simplicity of form and frequency of use in the literature (Wilks, 1989; D. Koutsoyiannis et al., 1998; Madsen et al., 2009). The 16 year hourly rainfall record could be considered too brief for prediction of intensities and durations of low frequency storms (75 and 100 years; Table 3-2), but the unusually heavy rainfall events of August 2000 (92-year daily high rainfall for Hyderabad; Geological Survey of India, 2001) result in rainfall IDF relationships that can be considered reliable for low frequency storms. As only 2, 5, and 10 year storms of 4 hour duration were used here, this record was deemed adequate for generating design storms of those frequencies.

In the 16 year period of record, there were seventy 4-hour storms, thirty-three 6-hour storms, and nine 8-hour storms; these were analyzed to determine storm type for the area using mass distribution curves. Analyses of rainfall mass distribution curves suggest storms should be described as Type II (SCS, 1986), meaning total depths of rainfall before and after half of the storm duration are about equal, and peak rainfall intensity occurs at half the storm duration; this is sometimes referred to as an intermediate storm. The low number of long duration storms for the record period (nine 8-hour storms) is evidence of the episodic nature of rainfall in the region; storms are typically short and of high intensity. Therefore, it was decided to consider 4-hour storms for this analysis given that storms of this duration are much more common than 8-hour or 24-hour storms). The rainfall intensity-duration-frequency (IDF) data used to develop design storms are presented in Table 3-2. The rainfall intensity data for 4-hour design storms of the three return periods (2, 5, 10-year return period) that were used for this analysis are presented in Table 3-3.

Tillage and MDS: GAML solution form

The differences in infiltration and runoff depths between the standard and complete GAML solutions are demonstrated in Figure 3-4. For the MDS range of conventional tillage (CT; 0-10 mm), there are small differences in predicted RO and F. On average across the MDS range for CT, using the complete GAML form, predicted F was 1.2% greater and predicted RO was 2.5% lower than the F and RO predicted using the standard GAML form. These differences increase substantially for the MDS range of tied-ridge tillage (TR; 15-50 mm). On average across the MDS range for TR, using the complete GAML form, predicted F was 5.8% greater and predicted RO was 40.8% lower than the F and RO predicted using the standard GAML form. This shows that the solution form should be considered for GAML predictions in agricultural areas with significant MDS (> 15 mm). Also, Figure 3-4 demonstrates the importance of the MDS parameter for describing tillage, for either GAML solution form. The global sensitivity analysis was required to make quantitative comparisons between the importance of MDS and the other 4 GAML parameters.

Local sensitivity analysis

Results of the local sensitivity analysis (LSA; Table 3-4 and Figure 3-5) illustrate substantial infiltration and runoff depth differences between CT and TR tillage treatments, meaning that MDS can be an important parameter for improving descriptions of tillage management. Under the complete GAML solution with mean MDS values of 32.5 mm and 5.0 mm for tied-ridge (TR) and conventional tillage (CT), respectively, total runoff depth was 65% lower for TR than for CT, and predicted total storm infiltration was 31% greater for TR than for CT. Differences in RO and F within tillage treatments and between solution forms show that the manner in which h_p is included in GAML solutions is important for tillage treatments with significant MDS (> 15 mm). For TR with mean MDS using the complete GAML solution form, predicted RO decreased by 31% and F increased by 6% compared to the standard GAML form. GAML solution form is less important in conventionally tilled areas with low MDS (< 10 mm): for CT with mean MDS and the complete GAML solution form, predicted RO decreased by 3% and F increased by 6% compared to the standard GAML form.

Global Sensitivity Analysis

The first-order sensitivity indices (S_i) for each of the GAML parameters for both tillage treatments and both GAML solution forms are reported in Table 3-5 and Figure 3-6. Design storms of 4-hour duration (T = 2, 5, and 10 years) were used. The S_i of Table 3-5 show that for a tied-ridged system, MDS is the second most important parameter for GAML-predicted infiltration, meaning that for tillage with non-negligible surface storage, the parameter MDS is shown to explain more output variability in F and RO than all other parameters except K_{se}; parameters ranked by importance are: K_{se}, MDS, ψ_f, θ_s, θ_i. Of the five GAML parameters, K_{se} and MDS are the two parameters that are the least likely candidates for elimination from the solution or for fixing at a constant value for uncertainty analysis. Also, differences in S_i of MDS between the two forms of GAML solutions gives more evidence that it does matter how h_p is included in the GAML equations, as indicated by the percent differences in MDS S_i between complete and standard GAML solutions (Table 3-5). Under tied-ridging, using the standard GAML solution form resulted in decreases in the S_i for MDS of around 23%, making it of importance comparable to ψ_f, but MDS remained the second most important parameter using the standard GAML form. For a conventionally tilled system, sensitivity of infiltration to MDS is expectedly smaller but is still significant and is greater than that of θs; parameters ranked by importance are: K_{se}, ψ_f, θ_s, MDS, θ_i. There were significant changes in MDS S_i between solution forms for simulations using CT, but the lower overall S_i of MDS compared to those under TR, mean that the manner in which H is included in the GAML solution is of little importance for conventionally tilled systems.

Plotting S_i for the GAML parameters, Figure 3-6 illustrates the strength of influence of parameters on the variability of the outputs of interest (RO and F). Given the parameter ranges and distributions for sandy loam soils and tillage systems typical of this study area, it is evident that MDS becomes a significantly more important parameter if there is tillage having surface storage ranging from 15-50 mm. However, in systems having less surface storage (0-10 mm), MDS is one of the least important parameters. Figure 3-6 suggests that in studies of infiltration and runoff in conventionally tilled agricultural systems, most efforts should be directed toward improving estimates of K_{se} and ψ_f. It also suggests that in systems employing some type of tillage to reduce runoff, most efforts should be directed toward improving estimates of K_{se} and MDS. The sum of all S_i was about 0.98, meaning that the model is almost perfectly additive; therefore, any refinement to a parameter will result in direct reductions in output uncertainty.

Conclusions on the Importance of Surface Storage Depth for Tillage Parameterization

One outcome of sensitivity analysis is to guide investigators about which uncertain input factors contribute the most to the model output uncertainty. This study shows that K_{se} and MDS are the most important factors controlling total infiltration (F) and runoff (RO) in systems having tillage with significant depression storage. As a result, the most attention and resources spent on parameterization of GAML-predicted infiltration should focus on the parameters to which infiltration is most sensitive.

Substantial differences in predicted runoff and infiltration depths between conventional (CT) and tied-ridge tilled (TR) systems were observed; therefore, MDS was shown to be a useful parameter for describing water harvesting tillage. The results demonstrated here show small differences in F and RO for CT between the two solution forms, standard and complete, suggesting that the typical simplification of GAML to the standard form is an adequate solution for GAML predictions under conventionally tilled systems. However, the marked differences in first order variance-based global sensitivity indexes S_i for F and RO depths between the two solutions for TR suggest that h_p should be included both in the water balance and in the Green-Ampt equations.

The main advantage of the complete GAML solution over the MDS=0 and standard GAML solutions is that it represents a simple way to describe water-harvesting tillage (using the MDS parameter and the accompanying time-varying h_p) and to reduce the uncertainty of infiltration and runoff predictions. Thus, hydrologic models equipped with the complete GAML solution could become useful tools for estimating the landscape-scale impacts of water-harvesting tillage (of different MDS and areal extent) on infiltration, evapotranspiration, and groundwater recharge.

Based on the predicted infiltration increases from water harvesting tillage and also on the growing evidence of changing precipitation character, it could be expected that surface storage of excess rainfall will become an increasingly important management concern in agricultural areas and that there may be an increase in extent of agricultural systems having some form of water harvesting tillage, including tied-ridging, contour bunding, or pit tillage. Therefore, the advantages of the complete GAML solution demonstrated here could provide improved predictions of infiltration and runoff for field and landscape-scale hydrologic models employing standard or MDS=0 GAML solutions.

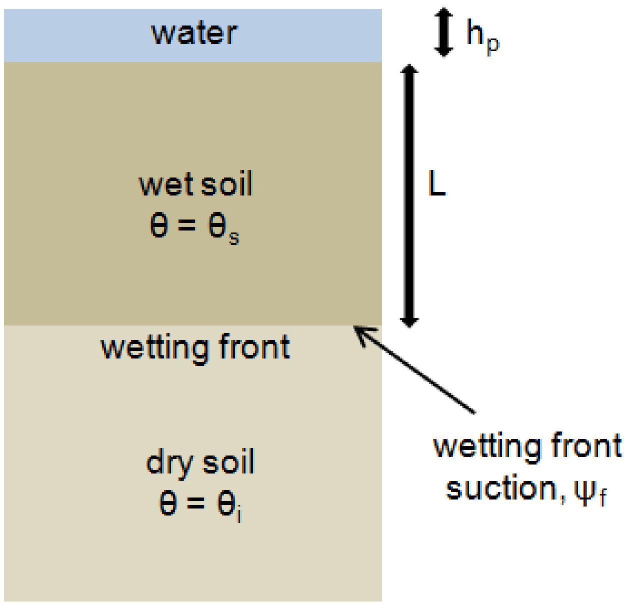

Figure 3-1. Illustration of infiltration modeled by Green-Ampt equation. θ, θ_s, θ_i, are volumetric water content, saturated and initial, respectively, h_p is depth of water ponded at the surface, L is distance from surface to the wetting front, ψ_f is wetting front suction.

Figure 3-2. Typical furrowed field beside tied-ridged field following rain event (image from Jones and Baumhardt 2003)

Table 3-1. Parameter values needed for Green-Ampt model: minimum, maximum, mean values and estimated probability distributions. Initial water content (θ_i), saturated water content (θ_s), effective hydraulic conductivity (K_{se}), wetting front suction (ψ_f), and maximum depression storage depth (MDS) for conventional tillage (CT) and tied-ridge tillage (TR).

Parameter	Min	Max	Mean	Units	Distribution
θi [1]	0.1	0.2	0.1	mm/mm	uniform
θs [1]	0.4	0.6	0.5	mm/mm	uniform
ψf [1]	26.7	194.0	110.4	mm	uniform
Ke [2]	1.1	44.1	15.9	mm/hr	log-normal (μ = 2.23, σ = 1.03)
MDS (CT) [3]	0.0	10.0	5.0	mm	uniform
MDS (TR) [4]	15.0	50.0	32.5	mm	uniform

[1] Rawls et al., 1983; Fangmeier et al., 2005
[2] laboratory analysis of local soils in Wargal study area
[3] Kamphorst et al., 2000; Planchon et al., 2002; Guzha et al., 2004
[4] Guzha et al., 2004; Jones and Clark, 1987

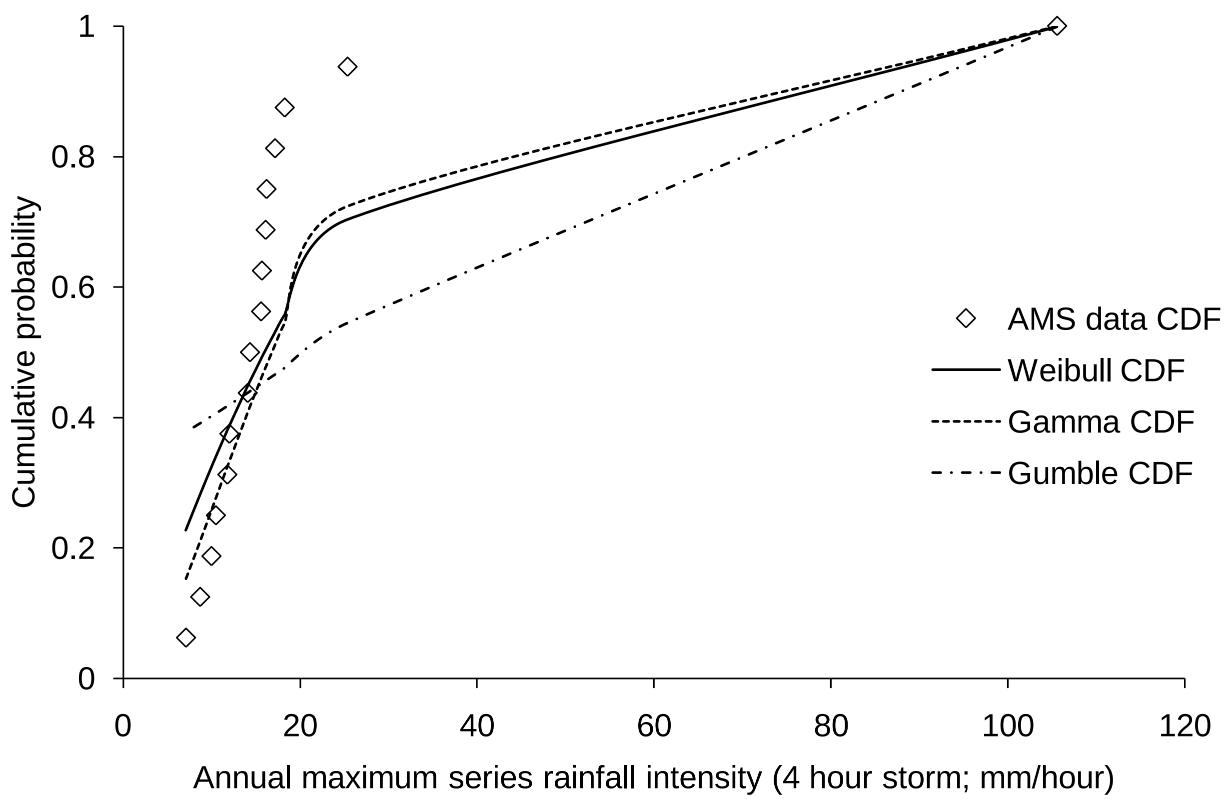

Figure 3-3. Empirical CDF for annual maximum series (AMS) rainfall intensity for 4 hour storms; Weibull, Gamma, and Gumbel CDF fitted to AMS data using maximum likelihood parameter estimation.

Table 3-2. IDF data (1993 – 2008 hourly rainfall), Weibull distribution used, values in the table are rainfall intensities in mm/hour

Duration	T, return period (years)							
t,(hours)	2	5	10	15	25	50	75	100
1	42.3	62.4	73.6	79.3	85.9	94.0	98.3	101.3
2	29.0	45.8	55.5	60.6	66.6	74.0	78.0	80.8
4	17.3	29.3	36.8	40.7	45.4	51.4	54.7	56.9
8	10.0	17.3	21.9	24.3	27.2	30.9	32.9	34.3
24	4.7	8.6	11.2	12.6	14.2	16.4	17.6	18.5

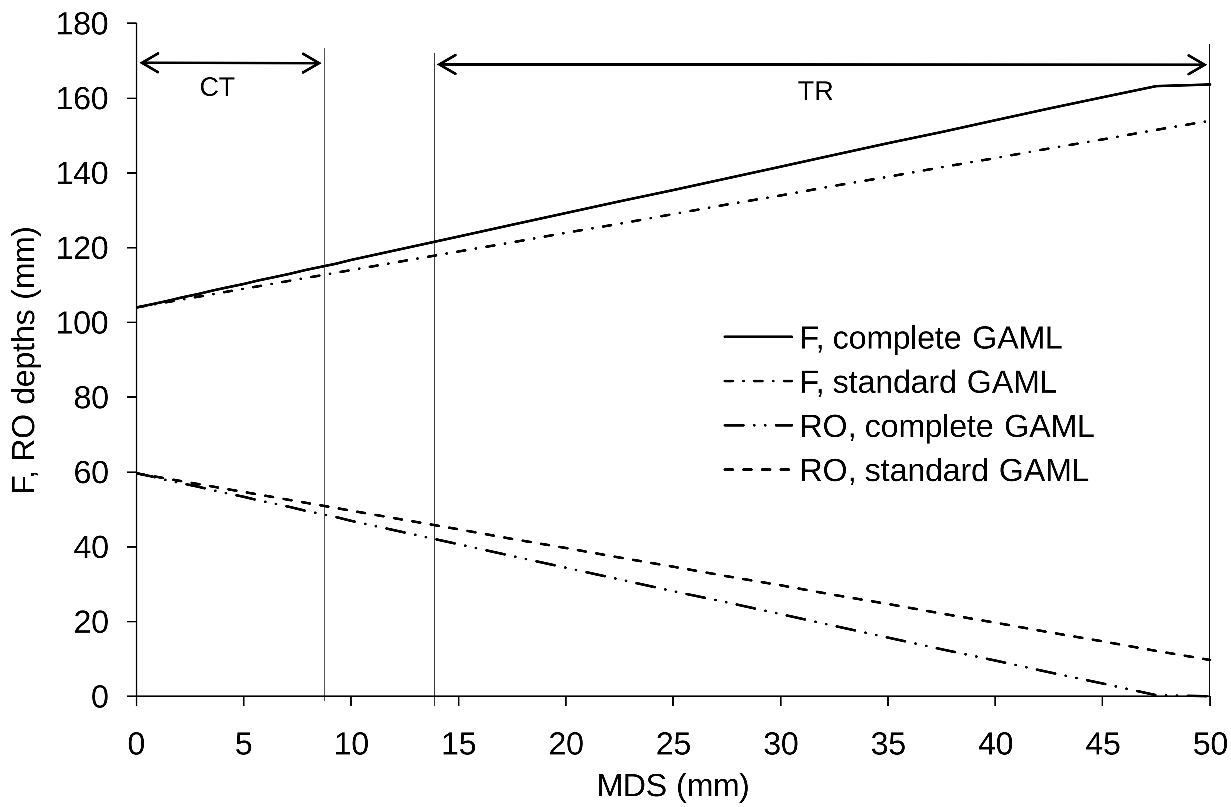

Figure 3-4. Infiltration (F) and runoff (RO) for a 4-hour 2 year design storm; complete and standard GAML solutions

Table 3-3. 4-hour design storms of 2, 5, 10-year return period used for rainfall input in GAML sensitivity analysis; 20 min time step

Duration hours	Design storm intensity, mm/hr 2 year	5 year	10 year
0.00	0.0	0.0	0.0
0.33	24.8	29.8	34.2
0.67	27.2	32.7	37.6
1.00	30.5	36.7	42.2
1.33	35.5	42.6	49.0
1.67	43.7	52.6	60.4
2.00	62.6	75.3	86.5
2.33	89.6	107.7	123.8
2.67	50.8	61.0	70.1
3.00	39.0	46.8	53.8
3.33	32.7	39.3	45.2
3.67	28.7	34.5	39.7
4.00	25.9	31.1	35.8

Table 3-4. GAML predicted runoff (RO) and infiltration (F) depths of conventional (CT) and tied-ridge (TR) tillage for 2 year, 4-hour storm; standard and complete GAML solutions. Min, mean, and max MDS were 0, 5, 10 mm for CT and 15, 32.5, 50 mm for TR.

			Runoff			Infiltration
			Complete GAML solution			
MDS	TR	CT	MDS = 0	TR	CT	MDS = 0
Min	40.7	59.7	59.7	123.0	104.0	104.0
Mean	18.9	53.3	59.7	144.8	110.3	104.0
Max	0.0	47.0	59.7	163.7	116.7	104.0
			Runoff			Infiltration
			Standard GAML solution			
MDS	TR	CT	MDS = 0	TR	CT	MDS = 0
Min	44.7	59.7	59.7	119.0	104.0	104.0
Mean	27.2	54.7	59.7	136.5	109.0	104.0
Max	9.7	49.7	59.7	154.0	114.0	104.0

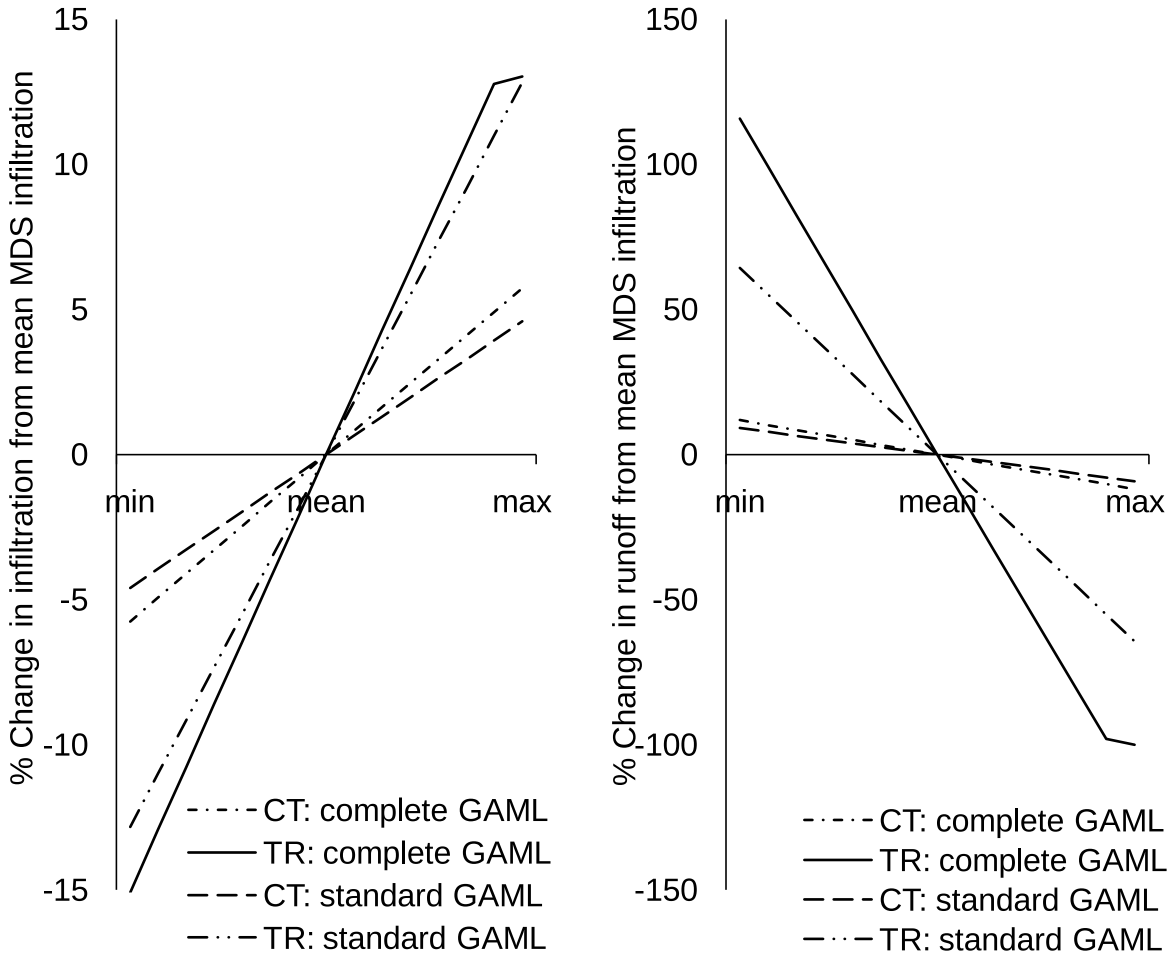

Figure 3-5. Infiltration and runoff % changes from mean MDS values for 2 year, 4-hour storm for both GAML solution types; min, mean, max are values of MDS for conventional (CT: 0, 5, 10 mm) and tied-ridge (TR: 15, 32.5, 50 mm) tillage.

Table 3-5. First order sensitivity indexes (S_i) for output F of the 5 GAML parameters for tied-ridge (TR) and conventional tillage (CT) for both GAML solution forms, complete and standard.

Tillage type	S_i of GAML parameters						
solution form	K_{se}	ψ_f	θ_s	θ_i	MDS	storm t, T	%change
TR	0.8210	0.0343	0.0117	0.0069	0.1105	4 hour, 2 year	
complete	0.8384	0.0358	0.0115	0.0062	0.0891	4 hour, 5 year	
GAML	0.8425	0.0375	0.0131	0.0062	0.0815	4 hour, 10 year	
TR	0.8273	0.0578	0.0099	0.0053	0.0858	4 hour, 2 year	28.8%
standard	0.8378	0.0571	0.0091	0.0048	0.0685	4 hour, 5 year	30.1%
GAML	0.8390	0.0588	0.0106	0.0049	0.0623	4 hour, 10 year	30.8%
CT	0.8982	0.0588	0.0115	0.0063	0.0115	4 hour, 2 year	
complete	0.8951	0.0573	0.0106	0.0055	0.0089	4 hour, 5 year	
GAML	0.8925	0.0581	0.0118	0.0054	0.0081	4 hour, 10 year	
CT	0.8965	0.0641	0.0110	0.0060	0.0079	4 hour, 2 year	45.6%
Standard	0.8934	0.0620	0.0101	0.0053	0.0059	4 hour, 5 year	50.8%
GAML	0.8905	0.0627	0.0113	0.0052	0.0054	4 hour, 10 year	50.0%

[1] % change in MDS S_i is the increase in MDS S_i when changing from standard to complete GAML solution form

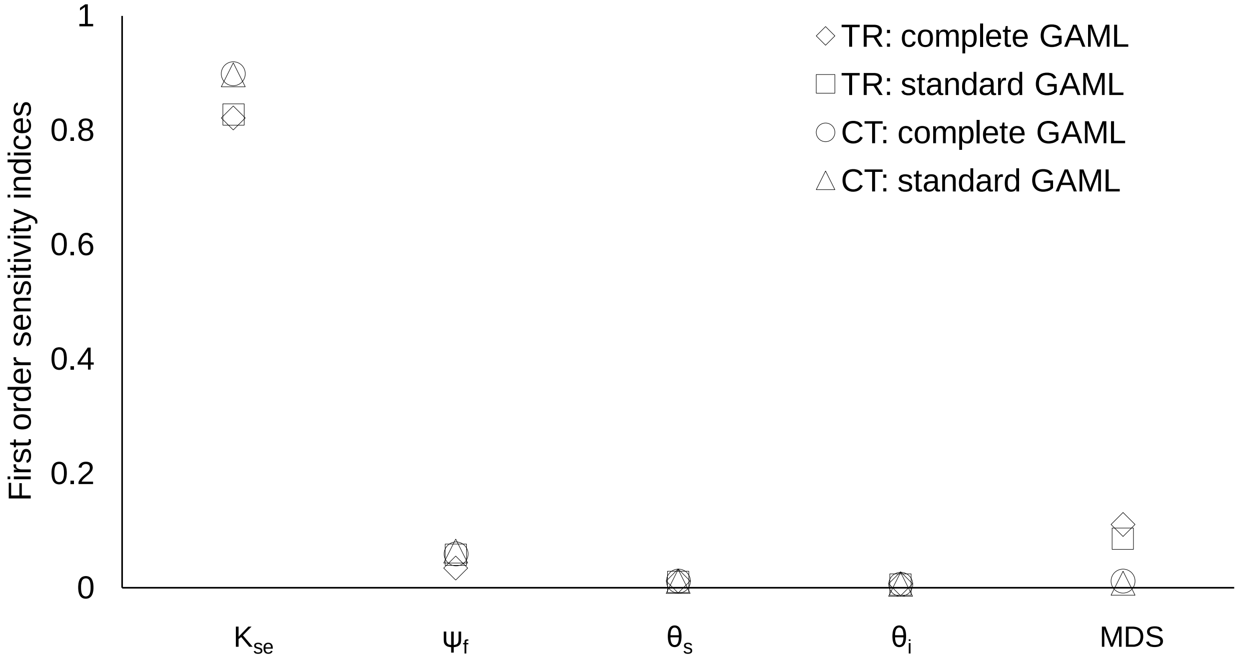

Figure 3-6. Total effect sensitivity indices (outputs are F and RO; their sensitivities to each parameter are equal) for Green-Ampt parameters for tied-ridge and conventional tillage for 4 hour design storm of 2 year return period.

CHAPTER 4
EVALUATION OF AGRICULTURAL MANAGEMENT ALTERNATIVES FOR SUSTAINABLE GROUNDWATER IN INDIA: SIMULATED WATER BALANCE RESULTS

Overview of Water Balance Simulation

Groundwater Management in India

There are 170 Mha of cultivated land in India – more than half the total land area of 328 Mha (FAOSTAT, 2010). Irrigated areas are 45% (77 Mha) of total cultivated area (AQUASTAT, 2010), and more than half of the irrigation requirements are from groundwater resources (CGWB, 2002; Shah et al., 2003). Total groundwater withdrawals of 251 billion km^3 are the highest of any nation (AQUASTAT, 2010). The harvested area of rice croplands in India (44 Mha) and the irrigation diversions for rice areas are greater than those of all other crops, and rice production at the national scale is the most valuable agricultural activity – valued at $30 billion/year (FAOSTAT, 2010). Field-scale water balance experiments in the Wargal study area have shown a groundwater balance of about -690 mm (1235 mm or irrigation; 542 mm of return flow recharge) for a rainy-season rice cropping system (Reddy, 2009). All these data should lead to the conclusion: rice cropland areas in India are extensive, highly important economically, have large consumptive water use, and depend heavily on groundwater resources.

For farming households, which make up about half of the population of India (FAOSTAT, 2010; 2009 population of India), groundwater depletion is concerning because it is expensive and increases vulnerability. A study of the costs of groundwater depletion in Andhra Pradesh has shown that increasing groundwater recharge is the most economical way to manage groundwater depletion (Reddy, 2005). The water balance simulations of this research in the Wargal watershed have served to quantify the impacts on the groundwater balance of recharge structures (small reservoirs), current farm management practices, and alternative farm management options. The costs of groundwater depletion refer to capital losses resulting from borewell infrastructure being ineffective due to lower groundwater levels, new required investments to deepen borewells and lower pumps, higher energy costs for groundwater withdrawal, and the indirect costs of lower net incomes from reduced areas of flooded rice croplands. It was shown in the study by Reddy (2005) of three villages in northern Andhra Pradesh that groundwater depletion costs are most damaging to farmers with smaller land holdings, and disparities in groundwater access and control generally develop – those having larger land holdings are able to adapt to groundwater depletion and retain access to groundwater resources.

The options for managing groundwater depletion are numerous, but they can be simplified into the following categories: increasing surface storage and infiltration of excess rainfall (to increase groundwater recharge), reducing groundwater withdrawals, and decreasing evapotranspiration (ET) in rainfed and irrigated croplands. This is explained in the conceptual model and discussion of surface and groundwater balances in Chapter 1. The simulated water balance experiments presented in this chapter serve to examine some of the possible agricultural management options for groundwater sustainability; the best options for groundwater sustainability are evaluated based on predictions of groundwater recharge and withdrawals, ET, and estimated household incomes.

Goals of Simulated Water Balance Experiments

In consideration of the significance of groundwater resources in India, there are three hypotheses being tested in this chapter by simulating the water balance of the Wargal watershed: (1) current rice cropland extent and management practices are depleting groundwater supplies, (2) tillage for water harvesting can significantly increase groundwater recharge in rainfed croplands, and (3) there are combinations of tillage, crop selection, and irrigation that can improve groundwater recharge and reduce groundwater withdrawals. The objectives of the simulation experiments:

- Assess groundwater sustainability of agricultural management practices (crop selection, irrigation management, tillage) at a watershed scale – quantify the groundwater balance (recharge – irrigation pumping) under current and alternative agricultural management
- Evaluate improvements to the Green-Ampt infiltration routines of a hydrologic model (Soil and Water Assessment Tool – SWAT; Arnold et al., 1998; Krysanova and Arnold, 2008) for simulating groundwater balance under various cropping systems

Water Balance Simulation Methods

SWAT Preparation

Preparing SWAT for hydrologic simulations required spatial datasets for soils, topography, climate, and LULC as described in Chapter 1: "Summary of Water Balance Simulation Methods." Detailed management of agricultural areas was described using planting dates, harvest dates, and irrigation information based on data from the Wargal area. Code modifications were made (Appendix A) to accommodate a surface storage depth for parameterization of water harvesting tillage. Agricultural management alternatives were prepared by developing text files to change cropland areas, irrigation depths, and tillage-induced MDS.

Describing agricultural management

Dates for planting and harvesting were those typical of kharif (June-September, rainy season), rabi (October-February), and summer seasons (March-May). Flowmeters on borewells were used to estimate daily irrigation applications for rice in kharif (N = 6, where N is the number of seasonal flowmeter records) and rabi (N = 5) seasons and for vegetables in summer (N = 4). Flow volumes were monitored by research partners from ANGRAU, measured field sizes allowed for conversion to application depth. Based on flowmeter data, daily irrigation applications in kharif and rabi seasons for rice were 8 mm/day and were 4 mm/day for vegetables in summer season. Modeling cropping system sequences (in kharif, rabi, and summer) required adjusting cropland areas dynamically 3 times each year. This was accomplished in SWAT using a lup.dat (land-use update) file and 3 text files which described changing cropland areas that were read-in by SWAT at specified dates each year. The seasonal cropland area files and lup.dat were also used for describing changed cropland areas for alternative management options.

To compare the water balance results of alternative agricultural management, existing management and 25 alternative management scenarios were simulated (Table 4-1) both for observed weather data (2009-2010) and for a 10-year simulation using generated weather data (2000-2009) from WXGEN (Sharpley and Williams, 1990) included in SWAT. WXGEN weather data were generated based on a database of 168 climate parameters for the Wargal watershed. Simulations were completed for both measured and generated weather data because the years of 2009 and 2010, for which there are observations of weather data, are not necessarily good representations of average annual rainfall. In 2009, annual rainfall was 667 mm (about 110 mm below normal); in 2010, annual rainfall was 1022 mm (about 240 mm above normal). The use of simulated weather data also resulted in some dry and some wet years, but the average annual rainfall during the 10 years (792 mm) was very close to the long term average in Wargal of 780 mm. Most of the results presented are from the 2000-2009 generated weather dataset because it was decided that the rainfall data of the generated dataset better represented average conditions. The trends in results were nearly identical for both weather datasets.

SWAT process modifications

To test the significance of tillage management for increasing groundwater recharge the GAML infiltration routines of SWAT were modified to allow for parameterization of tillage using a maximum depression storage (MDS) value – see Chapter 3 “Green-Ampt Infiltration and Depression Storage” and Equation 3-2. In order for the modified infiltration routine to work properly, 22 subroutines of SWAT required alterations (Appendix A). The subroutines requiring the most extensive changes were those for GAML infiltration (surqgreenampt.f), actual evapotranspiration (etact.f), irrigation from aquifer (irrsub.f), and tillage description (newtillmix.f and readtill.f). The infiltration routine was altered to allow for accumulation of surface storage of excess rainfall which created a time-varying head that influenced infiltration rates (Chapter 3). After modifications, surface storage accumulated up to the MDS value; additional excess rainfall became surface runoff. ET routine changes were made in order for stored surface water in cropland areas to be evaporated; evaporation rates were dependent on leaf area index as modeled by SWAT. The irrigation routine was changed so that irrigation applications could be stored on the surface if they were in excess of infiltration rates and there was a non-zero MDS value. The tillage description routines were changed to add the MDS parameter to the till.dat tillage database and to create the correct MDS in an area after a tillage operation with non-zero MDS was completed. These changes have allowed for ponded rice to be simulated more accurately and in combination with dynamically varying cropland areas; this was not possible with previous releases of SWAT.

SWAT Calibration and Evaluation

Model calibration is the estimation of parameters of model to improve its predictions of observed data. Model evaluation is the quantitative assessment of the performance of a model in predicting observations which were not used for model development or parameter estimation (calibration). The target for SWAT calibration and evaluation was a time series of 50 reservoir volumes from 3/19/2010 to 12/3/2010 (Figure 4-1); this was the best available runoff gauge given that there is limited channelized flow in the watershed. The reservoir at the outlet of the Wargal watershed creates a generally closed watershed, and the volume of water stored in this reservoir was considered a good substitute for streamflow data which are typically used to calibrate and evaluate hydrologic models. This time series of reservoir volumes begins in a dry portion of the year and extends beyond the rainy kharif season. As discussed in Chapter 1, these observations were obtained from GPS waypoint data and tank level gage data to measure flooded area and depth of water, respectively.

The 13 most important parameters of SWAT were varied across a specified range based on field data and literature values. Varying these 13 parameters required re-writing 838 text files for input to SWAT; therefore, automated calibration software was required. SWAT-CUP3 (Abbaspour, 2008), a program developed by the systems analysis and modeling group of Eawag (Swiss Federal Institute of Aquatic Science and

Technology), was used for SWAT calibration, evaluation, and sensitivity and uncertainty analysis. Generalized likelihood uncertainty estimation (GLUE) was implemented (Beven and Binley, 1992) in SWAT-CUP3. GLUE requires few assumptions about parameter distributions and is a simple model-independent method for parameter estimation. GLUE allows for the non-uniqueness of model realizations, meaning that numerous parameter sets can result in a model having similar performance. Model uncertainty comes only from parameter uncertainty under GLUE methodology. There is flexibility in the choice of performance measure or objective function. Here the Nash-Sutcliffe efficiency (NSE) was used; it is one of the 3 quantitative model evaluation techniques recommended in the model evaluation guidelines work of Moriasi et al. (2007). NSE is expressed by:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs}-Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs}-Y^{mean}\right)^2}\right] \qquad (4\text{-}1)$$

where Y_i^{obs} is the i-th observation for the output of interest, Y_i^{sim} is i-th simulated value, and Y^{mean} is the mean of all the observations used (n total observations). The range of NSE is - ∞ to the optimal value of 1. NSE > 0.5 is said to describe satisfactory model performance (Moriasi et al., 2007).

Model evaluation was by graphical comparison, NSE, percent bias (PBIAS), and the root mean squared error (RMSE) observations standard deviation ratio (RSR) were the 4 methods used to evaluate model performance, following the recommendations of Moriasi et al. (2007). PBIAS and RSR are expressed by:

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs}-Y_i^{sim}\right)}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right] \qquad (4\text{-}2)$$

$$\text{RSR} = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{mean})^2}} \tag{4-3}$$

NSE > 0.5, RSR < 0.70, and PBIAS < |25%| can be said to describe satisfactory model performance (Moriasi et al., 2007) for monthly data of streamflow. These guidelines should of course be adjusted based on prediction variable (sediment, phosphorus, or others), observation time step, and measurement uncertainty (Moriasi et al., 2007). These guidelines are generally more stringent for streamflow predictions than for other variables (water quality) and model performance is usually worse as observation time step is reduced (Engel et al., 2007; Yuan et al., 2001); that is, model performance on a monthly basis can be expected to be greater than that on a weekly or daily basis. The average observation time step of the reservoir volumes used for model calibration and evaluation in the Wargal watershed was 5 days (range of 1 to 28 days).

There was one year of reservoir volumes available for use for model calibration and evaluation; therefore, some strategy was required to be able to use all the data for both model evaluation and calibration. K-fold cross-validation is one strategy that allows all the data to be used for parameter estimation and for model evaluation (Wallach et al., 2006). Cross-validation is similar to the method of splitting a dataset into 2 parts and using one part for parameter estimation and one part for evaluation of the model. In cross-validation, an observation or group of observations is removed from the dataset and parameter estimation proceeds. Since the observations removed were not used for parameter estimation, the model can be safely evaluated for its ability to simulate the removed observations. Next, the observation or group of observations is replaced, and the next observation or group of observations is removed and the model calibrated again. This continues until all data have been removed and replaced. In the Wargal area, groups of 10 observations from the record of 50 were removed, meaning 5-fold cross-validation was used. The result is 5 different estimates of the parameter vector which are each used separately to predict the reservoir volume to evaluate the model. One of the advantages of cross-validation is that all the data are used in the same way for both model calibration and evaluation (Wallach et al., 2006).

Deciding which parameters to vary (and by how much) is an important part of model calibration. The literature on calibration of SWAT was used to assist with choices of parameters for calibration (Bosch et al., 2004; Van Liew et al., 2005 and 2007). A departure from typical practice was that saturated hydraulic conductivity (K_s) for soils was varied separately for rice croplands and other areas due to the uniquely low K_s of puddled rice soils. Puddling describes the tillage of rice fields when they are flooded; the resulting particle settling in order of particle size (largest to smallest) results in a soil of very low hydraulic conductivity (Kukal and Aggarwal, 2002; Marechal et al., 2006). More than 15 GLUE calibration/sensitivity runs (each of N=5000 or N=2500) were completed using anywhere from 5 to 14 parameters for calibration; these preliminary calibration efforts were used to decide on the final 13 parameters to calibrate and how much they should vary. Parameter ranges were carefully selected (based on observations in Wargal and literature values) to ensure values did not depart from realistic ranges for the soils and land use of Wargal.

Parameter sensitivity and uncertainty analysis

A complete, global sensitivity analysis of SWAT is not an objective of this work; this has been done well by others (van Greinsven et al., 2006), but it is important to have a meaningful ranking of parameters by order of importance. A sensitivity analysis was completed through SWAT-CUP3 to determine parameter sensitivities using the multiple regression system: $g = \alpha + \sum_{i=1}^{m} \beta_i b_i$ (Muleta and Nicklow, 2006; Abbaspour et al., 2007). This system regresses the Monte Carlo sampled parameters from GLUE against the predicted reservoir volumes, g. A t-test and accompanying p-value are used to compare the relative sensitivities of each parameter b_i; p-value is the probability that the absolute value of the regression coefficient β_i would be as large or larger if there was no relationship between that parameter b_i and the output, g (Helton and Davis, 2000). A low p-value corresponds to an important parameter (low probability of the parameter not making significant changes to predicted reservoir volume). The sensitivities calculated are based on linear approximations of the sensitivity of the model output to changes in a parameter while all other parameters are changing; therefore, it is a type of global sensitivity (Muleta and Nicklow, 2006); this method requires a large number of simulations and is dependent on choice of parameter ranges (Abbasour et al., 2007).

SWAT-CUP3 (Abbaspour, 2008) uses a flexible format to assist with generation of parameter sets for calibration and model sensitivity analysis. The following system defines the range of a parameter: x__<parname>.<ext>__<hydrogrp>__<soltext>__<landuse>__<subbsn>__<slope>. X is the type of change applied to the parameter (x = v, a, or r): v__ means the original parameter value is to be replaced by a value in the specified range, a__ means a value from the specified range is added to the original parameter value, and r__ means the original parameter value is multiplied by (1+ a value in the specified range). <parname> is the SWAT parameter name, <ext> is the SWAT file extension, <hydrogrp> is the soil hydrologic group (A, B, C, D; optional), <soltext> is the soil texture (optional), <landuse> is the landuse category (in this study it is just crop type, optional), <subbasin> is the number of the subbasin in the watershed (in this study it is 1 to 6, optional), and <slope> is the class of slope range (optional). The 13 parameters varied for sensitivity and uncertainty analyses were, in order of importance based on the step-wise regression-based global sensitivity analysis described earlier:

- SOL_AWC(layer#): available water holding capacity of the soil layer in mm water / mm soil. This was varied in soil layers 1 and 2 for Wargal.
- SOL_K(layer#): saturated hydraulic conductivity of the soil layer in mm/hr. This is actually 2 parameters as this was adjusted separately in layer 1 of rice croplands.
- RES_K: hydraulic conductivity (mm/hr) of a reservoir bottom.
- CN2: the initial SCS curve number for moisture condition II; it is a function of soil permeability, land use, operations, and soil moisture.
- EVRSV: reservoir evaporation coefficient (0-1) used to adjust for shading and vegetation cover.
- GWQMN: the threshold depth of water (mm) in the shallow aquifer required for baseflow to occur.
- EPCO: plant water uptake compensation factor; this is another calibration parameter similar to ESCO. EPCO ranges from 0.01 to 1, and the closer to 1 EPCO is the more plant water uptake is allowed to come from deeper soil layers.
- ESCO: soil evaporation compensation factor; this is a calibration parameter that adjusts the depth in the soil profile from which evaporation can occur. ESCO ranges from 0.01 to 1, and values closer to 1 increase the depth at which evaporation from soil can occur.
- ALPHA_BF: is an index of the groundwater flow response to recharge changes; it is close to 1 for land with fast baseflow response to recharge and it is around 0.1-0.3 for land with slow baseflow response to recharge.
- RCHRG_DP: the fraction of percolation from the root zone which reaches the deep aquifer.
- EVLAI: leaf area index at which no evaporation occurs from surface water beneath a canopy; this is used in wetlands and in this study is used for rice croplands.

- GW_DELAY: the number of days required for water that drains out of the root zone to reach the shallow aquifer where it is stored, becomes baseflow, or becomes recharge to deep aquifer.

It may be surprising to notice that CN2 is the fourth most important parameter even though Green-Ampt is used to predict runoff and infiltration in place of the SCS Curve Number method. This is because CN2 is used by SWAT in the equations to update the Green-Ampt effective hydraulic conductivity (K_{se}) each day based on soil moisture; CN2 is adjusted daily for soil moisture. The routine to calculate K_{se} was modified to remove CN2, but the subsequent calibration attempts showed that this code modification resulted in poor model performance; therefore, the original SWAT algorithm for K_{se}, which includes CN2, was retained.

An important objective of this research was to evaluate the inclusion of surface storage term in Green-Ampt infiltration to parameterize water harvesting tillage. The maximum surface storage term (MDS) was not included in the automated calibration and sensitivity analysis because the only areas under existing management with non-negligible MDS were rice croplands, and the depth of MDS (150 mm) in these areas is not really uncertain. The sensitivity of groundwater recharge and surface runoff to MDS in SWAT was evaluated after the overall sensitivity analysis by using the calibrated model with other parameters fixed while varying MDS depth in rainfed croplands in different seasons. This local sensitivity gives easily understandable information about the response of recharge and other water balance components at both basin and field scales to MDS changes.

Uncertainty analysis is a quantitative assessment of model prediction variability for the purpose of checking that model output behavior is acceptable for the given variability in model input variable and parameters. In this analysis, the variability in parameters was assumed to be the only source of input variability. The ranges of values for the 13 input parameters (same as those used for final model calibration) were developed based on measured data from the study area, on values from the literature, and on numerous GLUE parameter estimation runs. A graphical evaluation of uncertainty was used here by plotting the 95% prediction uncertainty range (95 PPU; Abbasour et al., 2007) together with the observed and simulated reservoir volumes. Given the ranges of parameters included in parameter estimation, simulated values can be expected to fall in the 95 PPU with probability 0.95. The 95 PPU was developed by calculating the 2.5th and 97.5th percentiles of the cumulative distribution for each simulated point (Abbaspour, 2008). Ideally, all the observations should fall in the 95 PPU and it should be as narrower as possible; though the narrowness depends on the variability assigned to each input parameter.

Reservoir volume

Before initiation of this project, the Wargal watershed was an ungauged basin, meaning that there were hydrologic observations of insufficient quantity or quality for many practical applications (Sivapalan et al., 2003). Some target for model calibration and evaluation is required; therefore, it was decided to use reservoir volume as an easily measurable runoff gauge. There are six small reservoirs in the 512 ha Wargal watershed. These were constructed several decades ago, according to farmers in the area, by excavating earthen dams (about 2-5 m high) at locations of seasonal surface flow for the purpose of storing rainfall runoff to increase groundwater recharge. The maximum storage volumes and surface areas of these reservoirs are listed in Table 4-2.

Reservoir characteristics were determined from a combination of topographic surveying and GPS tracking. The largest reservoir, called Kothakunta and found in subbasin one, is at the outlet of the watershed and this is the reservoir that was monitored. Detailed surveying in the reservoir was used to make geometric simplifications to develop an area-volume relationship. The equation relating reservoir area to volume that was used here is of the form $C = a * A^b$, (Sawunyama et al., 2006) where “C” is volume and “A” is area and “a” and “b” are fitted constants based on observations. This general form has been shown to perform very well in predicting reservoir volumes based on measured areas in west and southern African (Sawunyama et al., 2006; Liebe et al., 2009).

From measurements of reservoir geometry for reservoir number one in Wargal (this is at the outlet of the watershed), the area-volume relationship developed was $V = 0.00857 * A^{1.428}$, where volume is in m^3 and area is in m^2. This is very similar to that developed by Liebe et al. (2005). Reservoir depth and area were monitored weekly or sub-weekly. Depth was measured by reading the water level on a graduated staff that was installed in the reservoir. Area was measured by traversing the reservoir at the waterline with a handheld differential GPS unit and recording waypoints every few meters. The waypoint data were processed in a GIS to construct polygons of reservoir water surface area from which area could be calculated. Area and depth data on concurrent days were used to develop gauge depth to area relationships of $A = 9874.6 * D^{1.6005}$ for $A <= 105{,}000\ m^2$ and $A = 7564.9 * D^{2.0064}$ for $A > 105{,}000\ m^2$. Two methods were used for reservoir monitoring because of delays in installation of the level gauge; during this time, the GPS method was effective but more time consuming. The resulting time series of reservoir volumes (Figure 4-1) was used, in conjunction with recharge observations, for calibration and evaluation of SWAT.

Groundwater recharge

Reliable groundwater recharge predictions are probably the most important outcome of hydrologic modeling in the Wargal study area. Irrigation withdrawals are generally well-known, based on flowmeter data in Wargal and confirmed in the literature for a nearby watershed (Marechal et al., 2006). Groundwater recharge, however, is very difficult to measure; it is highly spatially variable due to the variety of land management in Wargal. Flooded rice croplands, water harvesting reservoirs, rainfed croplands, and unmanaged rangelands all have very different contributions to groundwater recharge. While being only a surface water model and not capable of simulating groundwater flow, SWAT is able to estimate recharge from all these different areas. Knowing recharge and irrigation withdrawals gives an evaluation of the simplified groundwater balance (see Chapter 1): groundwater recharge minus irrigation withdrawals.

It was decided that the best way to evaluate SWAT's ability to predict groundwater recharge was to use annual observations of recharge based on changes in groundwater levels during wet and dry periods. A method for quantifying recharge from water table changes, called the double water table fluctuation method (DWTF), allows both specific yield (Sy) and recharge to be estimated (Marechal et al., 2006). The DWTF method is useful only in areas where there are very clear wet and dry parts of the year, with negligible natural recharge occurring during dry parts of the year. The water table fluctuation method (WTF), discussed in Chapter 1 as the leading physical recharge measurement method, connects changes in groundwater table elevations to aquifer storage changes; it is only applicable in unconfined aquifers. These quantities are related by the aquifer characteristic, specific yield, Sy, sometimes called drainable or effective porosity. Sy is the volume of water drained from an aquifer divided by the total bulk aquifer volume: Sy = Vwd / Vt. The main weakness of the WTF method is that specific yield is generally not known or it is not known at the required scale; for a large aquifer, there can be significant spatial variability in Sy. The groundwater balance equation from Chapter 1 can be written as (Marechal et al., 2006):

$$R + RF + Qon = ET + IP + Qoff + \Delta S \tag{4-2}$$

where R is natural recharge, RF is return flow recharge, Qon and Qoff are subsurface flows in and out of the system, ET is evapotranspiration from groundwater, IP is irrigation pumping, and ΔS is change in groundwater storage. As discussed in Chapter 1, it is proposed that Qon = Qoff because of the similarity of the surrounding landscape and farming system management and ET from groundwater is negligible because of the large depth of groundwater (15 m). ΔS can be written in terms of specific yield and change in groundwater level: ΔS = Sy * Δh. The groundwater balance can then be written as:

$$R + RF = IP + Sy * \Delta h \tag{4-3}$$

This equation can then be used separately for wet and dry periods; for dry periods, R is zero and Δh is negative. The dry period can be used to calculate Sy; irrigation pumping (IP) is known from a sample of flowmeters on borewells and return flow recharge (RF) is known from upscaling plot scale water balances of irrigated rice and vegetables:

$$Sy = (RF_{dry} – IP_{dry}) / \Delta h_{dry} \tag{4-4}$$

The wet period is then used to calculate natural recharge:

$$R = IP_{wet} + Sy * \Delta h_{wet} – RF_{wet} \tag{4-5}$$

Results: SWAT Calibration, Evaluation, and Parameter Sensitivity

SWAT performance in predicting outlet reservoir volumes was very good for the calibration period (NSE = 0.954) and was satisfactory for the cross-validation period (NSE = 0.729). Graphical comparisons (Figures 4-1 and 4-2) of simulated and observed reservoir volumes also show acceptable simulation performance. Good agreement was found between annual groundwater recharge simulated by SWAT and recharge observed from DWTF method (Table 4-3). Due to the fewer data available for parameter estimation for cross-validation, model performance suffers as shown by the higher PBIAS and RSR values (14.7 and 0.525, respectively; Table 4-4). Cross-validation model performance can still be called satisfactory based on the Moriasi et al. (2007) recommendations: NSE > 0.5, RSR < 0.70, and PBIAS < |25%|.

To increase confidence that SWAT was indeed routing runoff (about 40 mm for whole watershed for the monitoring period) from the watershed to the monitored reservoir at the outlet of Wargal, some simple water balance calculations were completed. Direct rainfall input to the reservoir, was about 116,000 m^3, based on the observed reservoir areas and daily rainfall values. Maximum observed reservoir volume exceeded 350,000 m^3; therefore, considering evaporation and percolation of stored reservoir volume, it can be concluded that the majority of flow to the reservoir is from surface runoff from the watershed.

The regression-based sensitivity analysis from the GLUE generated parameter sets found that soil available water content (AWC) and saturated hydraulic conductivity in rice croplands were the most sensitive parameters. Having p-values less than 0.1, the 6 most important parameters of the 13 included in parameter estimation and sensitivity analysis were, in order of importance (Table 4-5): soil available water content in soil layers 1 and 2 (r__SOL_AWC(1,2).sol), saturated hydraulic conductivity of soil in layer 1 of rice croplands (v__SOL_K(1).sol______RICE), seepage rate of reservoirs (v__RES_K.res), SCS Curve Number for moisture condition 2 (r__CN2.mgt), reservoir evaporation coefficient (v__EVRSV.res), and saturated hydraulic conductivity of soil in layer 1 of all non-rice areas (r__SOL_K(1).sol). The best estimates of all parameters are given in Table 4-5 also.

Uncertainty of Model Predictions

Uncertainty of model predictions is represented by the 95% prediction uncertainty (95 PPU), the range of predicted reservoirs between the 2.5 and 97.5 percentiles of all predicted values as the 13 calibration parameters vary across their ranges. This is presented graphically in Figure 4-1: 64% of observations are contained by the 95 PPU. Typically, around 80% of observations can be expected to be contained in the 95 PPU (Abbaspour et al., 2007), the lower value obtained here (64%) can still be considered as an acceptable amount of uncertainty given the other measures of model evaluation that were quite good. The prediction difficulty increases as observation time step decreases (Moriasi et al., 2007), and it can be expected to be more difficult to be predict a cumulative output (reservoir volume) than a rate [L^3/t]. Therefore, the 64% of observations captured by the 95 PPU can be considered adequate.

Groundwater Balance

An important criterion used to compare results of different agricultural management was the groundwater balance: simplified in this case to mean groundwater recharge minus irrigation withdrawals (subsurface flows into and from the aquifer system were assumed equal). Recharge observations based on the DWTF are presented in Table 4-3; these matched well with recharge predictions from SWAT. The distinct wet and dry periods and the large changes in groundwater level observations are shown by Figure 4-3. Based on the DWTF method described above, specific yield (Sy) of the aquifer in Wargal was found to be 0.013 based on 2009 and 2010 groundwater levels (Table 4-3). This Sy value is typical of hard-rock aquifers and is consistent with that found by Marechal et al. (2006), Sy = 0.014, using the DWTF method in Maheshwaram watershed, very near to the Wargal watershed.

A small Sy means that even very small changes in the groundwater balance (ΔS) result in very large changes in the depth to the water table ($\Delta h = \Delta S$ / Sy); for example, under existing management and using generated weather data for 2000-2009, the average annual groundwater balance was -10.9 mm. This would result in water table decline of -835 mm for an aquifer having Sy of 0.013. Using measured weather data the groundwater balances were simulated to be -44.1 mm and 155.4 mm for 2009 and 2010, respectively, under existing management.

The groundwater balance defined as recharge minus irrigation pumping is a useful quantity for evaluating agricultural management impacts on groundwater supply, as it considers the subsurface water balance components that are managed more directly. However, it is a simplification of the actual subsurface water balance in which horizontal flows would be indirectly managed. For example, in Table 4-6, the management scenarios with large positive groundwater balances would not really be expected to realize the large increases in water table height (GW Δh) shown in the table. These values would be realistic only if the same management changes were made in the areas surrounding the watershed. So if the management changes that increased the groundwater balance were made only in the Wargal watershed, the resulting rise in water table height would be lower than that shown by Table 4-6 due to increased subsurface flows out of the Wargal groundwater system.

Results: Evaluation of Management Alternatives for Sustainable Groundwater

Detailed results of the effects of tillage and rice cropland management on the groundwater balance are given in the next 3 sections; the remainder of this paragraph is a brief summary of these results. SWAT simulations have predicted an average annual groundwater balance (recharge – irrigation = 535.1 mm – 546.0 mm) of -10.9 mm for the period from 2000-2009 using generated weather data. For years 2009 and 2010, SWAT predicted a groundwater balance of -44.1 mm and 155.4 mm, respectively, using observed weather data. The 6 water harvesting structures have a significant groundwater recharge impact; the predicted contribution to groundwater recharge was about 12% of the annual total (2009-2010 annual average: 75 mm recharge from tanks, 602 mm total groundwater recharge). Changing tillage in rainfed areas in kharif (June – September) season from conventional to tied-ridge (MDS = 15, 32.5, or 50 mm) resulted in an estimated 2-3.5% increase in basin-scale groundwater recharge. Tied-ridge tillage in rabi (October – February) season rainfed areas resulted in negligible basin-scale recharge increase due to the small amount of rainfall (around 20% of the annual rainfall total) and the reduce extent of rainfed croplands in the rabi season. As expected, changing the extent and irrigation management of rice croplands resulted in significant changes in the groundwater balance. The predicted changes in groundwater balances for alternative management are expectedly small (relative to total recharge and irrigation depths). Ideally, additional observations to evaluate the uncertainty of SWAT would be used to improve confidence in the water balance predictions. Without more observational evidence, the options are (1) to trust the quality of input data, process descriptions of SWAT, and the SWAT evaluations from observed reservoir volumes (NSE = 0.954) and groundwater recharge or (2) reject the quality of the predictions based on insufficient observations for evaluation. This is of course the typical quandary in hydrologic modeling (Kirchner, 2006): the challenge of knowing if a model user is getting the right answers for the right reasons. Given the long history of successful application of SWAT in a variety of systems (Gassman et al., 2007) and the good performance (based on guidelines of Moriasi et al., 2007) of SWAT demonstrated in Wargal, it is recommended that option (1) is chosen here.

Significance of Tillage and MDS

Changing tillage in rainfed areas from conventional to tied-ridge tillage (or another water-harvesting tillage) through the introduction of a non-negligible surface storage term (MDS, maximum depression storage), does make significant impacts on the groundwater balance of the watershed. Here, existing tillage (mouldboard or chisel plow) is assumed to have negligible MDS (Chapter 3). The rainfed crops in kharif season are largely corn and cotton: areas of 105.7 and 104.4 ha, respectively, or 20.6% and 20.4% of the watershed area. The rainfed crops in rabi season are largely potato and sunflower: areas of 65.6 and 37.4 ha, respectively, or 12.8% and 7.3% of the watershed area.

Basin-scale sensitivity of groundwater recharge to MDS depth (Figure 4-4) is not striking based on percent changes in recharge from existing management; groundwater recharge increased 1.8 to 3.5% compared to recharge under existing management. However, that amounted to a recharge increase of 9.5 to 18.4 mm/year, and adding a 32.5 mm MDS in rainfed crops in only in kharif season was enough to change the groundwater balance from negative to positive: -10.9 mm/year to 2.4 mm/year (Table 4-

6). For simulations using measured data (2009), adding a 32.5 mm MDS in rainfed crops only in kharif (rainy) season changed the groundwater balance from -44.1 mm/year to -34.2 mm/year (Table 4-7). Runoff depths at the basin scale are much smaller (around 30 to 60 mm/year, depending on management scenario) than recharge depths; therefore, the percent change in basin-scale runoff in response to tillage change is much greater (Figure 4-4). Compared to existing tillage, runoff is reduced by 48% for MDS depth of 50 mm in kharif corn and cotton, and runoff is reduced by 31% for MDS depth of 15 mm in kharif corn and cotton.

The extent of rainfed croplands (around 41% in kharif season and 20% in rabi season) suggests that in watersheds having a higher proportion of rainfed areas, tillage or water harvesting would have an even greater impact on the groundwater balance of a basin. Comparing runoff and groundwater recharge only from rainfed croplands where MDS changes were simulated gives a more direct assessment of MDS effects on water balance components. Figures 4-5 and 4-6 show the sensitivities of groundwater recharge and runoff to MDS depth in rainfed croplands for kharif season only (Figure 4-5) and for MDS in both kharif and rabi seasons (Figure 4-6). Compared to annual recharge from corn and cotton areas under existing tillage, groundwater recharge from these areas increased 14.2, 19.9, and 24.3% for MDS depths of 15, 32.5, and 50 mm, respectively, in kharif corn and cotton. For MDS depths of 15, 32.5, and 50 mm in both kharif and rabi rainfed areas, groundwater recharge from these areas increased by 6.7, 9.4, 12.3%, respectively. The increased groundwater recharge in response to changes in MDS provides evidence that there is greater average soil moisture (deep percolation and recharge are predicted in SWAT in response to soil water content that exceeds field capacity) resulting from tillage-induced MDS. Changes in ET in response to tillage were small but noticeable at the basin scale, and ET changes from tied-ridge tilled areas of kharif crops increased by as much as 5% compared to conventionally tilled rainfed kharif crops.

Sensitivities of recharge and runoff to MDS have been presented in the form of percent change in water balance component for different MDS. It was decided to add an additional local measure of sensitivity: a very basic measure, the simple derivative, δY / δX, where δY represents a change in some output variable Y and δX represents a change in some input factor X. Tables 4-8 and 4-9 give sensitivity of annual surface runoff and groundwater recharge to MDS (δRO / δMDS and δRCHG / δMDS, respectively) at the basin and field scales in mm change in depth (from existing tillage, MDS = 0) of recharge or runoff per mm depth of MDS. For MDS from 15 to 50 mm in kharif rainfed areas, the values of δRCHG / δMDS ranged from 1 to 1.9 in kharif rainfed croplands and from 0.3 to 0.6 at the whole basin scale. This suggests that in rainfed croplands having MDS > 15 mm, there is an increase in annual recharge of greater than 1 mm for each mm of MDS. Values for δRO / δMDS ranged from 0.6 to 3.3 for MDS from 15 to 50 mm in kharif rainfed areas. In summary, results showing sensitivity of simulated recharge and runoff to tillage management (varying MDS) can be found in Tables 4-6, 4-7, 4-8, and 4-9, Figures 4-4, 4-5, 4-6, and 4-7.

Changing Extent and Irrigation Management of Rice Croplands

The basin-scale groundwater balance under existing management was simulated to be -10.9 mm/year (546.0 mm irrigation, 535.1 mm recharge). Using the observed weather data for 2009 and 2010, the basin-scale groundwater balance under existing management was simulated to be -44.1 mm/year for 2009 (546.0 mm irrigation, 501.9

mm recharge) and 155.4 mm/year for 2010 (546.0 mm irrigation, 701.4 mm recharge). Comparing the water balance components (irrigation, recharge, ET, and groundwater balance) in Figures 4-7 and 4-8 (and Table 4-6) shows a much greater difference in water balance components in response to changes in rice cropland extent and irrigation management (Figure 4-8) than to changes in MDS from tillage (Figure 4-7). While the reduction of rice cropland areas by 50 and 75% in kharif and rabi seasons may be unrealistic, these scenarios do demonstrate the obviously substantial influence that the extent and management of rice croplands have on the groundwater balance of this watershed. However, even modest changes in irrigation or extent of rice croplands resulted in significant changes in the water balance. Decreasing daily irrigation depths by 25% in kharif season only resulted in a change in the basin-scale groundwater balance from -10.9 mm to 18 mm (472.9 mm irrigation, 492.9 mm recharge). Decreasing the extent of rice croplands in both kharif and rabi seasons by 25% (replacing with corn and cotton in kharif and potato and sunflower in rabi) resulted in the groundwater balance increasing to 34.3 mm (Table 4-6 and Figure 4-8): 418.3 mm irrigation, 452.6 mm recharge.

Alternatives to Rice: Irrigated and Rainfed Crops

The yield variability of rainfed crops is one of numerous objections by farmers in the area to replacing parts of rice croplands with alternative crops (Chapter 5). One of the ways to weaken this objection is by replacing rice croplands with other irrigated crops. In some of the alternative management scenarios simulated here, rice croplands in rabi season were replaced by irrigated corn. Irrigation depths for corn would be lower (4 mm/day compared to 8 mm/day for rice) and the absence of ponded irrigation water means ET depths would be lower. Replacing rice with irrigated corn would not necessarily be acceptable for farmers in Wargal, but it is expected that this replacement would have less yield variability than a rainfed rice replacement crop. Therefore, irrigated crops replacing rice might be preferred over rainfed crops replacing rice areas. A 25% reduction in kharif and rabi rice areas, with replacement crops of rainfed corn in kharif and irrigated corn in rabi (scenario code: red_rice_k-corn,r-irr-corn,25; Table 4-1 and 4-6), seemed a good compromise between the risk of increased yield variability and the need to address declining groundwater quantity. This scenario produced a groundwater balance of 18.5 mm (446.4 mm irrigation, 465.0 mm recharge; Table 4-6). The addition of water harvesting tillage in the rainfed kharif areas (red_rice_k-corn,r-irr-corn,25: mds33_kharif) improves the groundwater balance of this scenarios to 36.1 mm (446.4 mm irrigation, 482.5 mm recharge; Table 4-6).

Conclusions on Agricultural Management and Groundwater Supply in India

The objective to improve the widely used distributed hydrologic model, SWAT, was achieved. The process modifications to SWAT to include the complete representation of Green-Ampt infiltration by modeling a variable ponding depth, has been shown to be effective in parameterizing tillage for water harvesting. The changes are supported by the theoretical basis of Green-Ampt (Chapter 3), and they have resulted in the new ability of SWAT to use Green-Ampt methods to predict changes in runoff and infiltration in response to tillage management with varying MDS. This process modification allows rice croplands to be modeled as typical cropland hydrologic response units (HRUs) in SWAT; previously rice croplands had to be modeled at potholes, an HRU in which there was rarely surface runoff and the majority of outflow was by ET and deep percolation. Rice areas were a special HRU that was parameterized with a maximum conical storage volume, and this volume parameter meant that dynamically updating rice cropland areas (to model crop rotations) during the year using the lup.dat routine in SWAT was not possible. With the changes to SWAT, rice area MDS is easily adjustable, and rice croplands can be correctly and easily included in dynamic landuse updates. These improvements in SWAT are significant and can be expected to reduce prediction uncertainty as MDS estimates will likely be more certain than other important parameters like soil AWC or K_s.

Choosing the best management practices for sustainable groundwater in Wargal, or a similar watershed, is of course a complicated decision with some required subjectivity. Understanding the behavior of stakeholders is critical for management alternatives to be effective. The choice in this study is based on the predicted groundwater balances and on estimates of the agronomic and economic impacts of the management scenarios being compared. The results presented here give quantitative predictions of the groundwater balance (and other water balance components) for a multitude of management scenarios. The following 7 alternatives were chosen as the best management options for increasing groundwater supply based on (1) participation of growers in the area (constraints on labor, preferences for rice cultivation, little interest in alternative rainfed crops (Chapter 5), (2) the groundwater balance results (Chapter 4), and (3) consideration of yield variability and risk.

- red_rice_irr,k,r,25 (GW balance 38.2 mm/year): Irrigation depths for rice in both kharif and rabi seasons are reduced by 25% (from 8 to 6 mm/day). While there would not likely be any water stress for rice with these reduced irrigation depths, there may be small declines in yield and increases in labor requirements due to the intermittent absence of flooded conditions and the non-aquatic weeds that might result.
- red_rice_k-corn,r-irr-corn,25: mds33_kharif (GW balance 36.1 mm/year): The extent of rice croplands is reduced by 25%, being replaced with corn in kharif season and irrigated corn (4 mm/day) in rabi season. Water harvesting tillage

(MDS = 32.5 mm) is simulated for kharif rainfed crops. Moderate increases in yield variability can be expected due to the replacement of some areas of irrigated rice with rainfed corn. Yield and returns from irrigated corn in rabi would be comparable to those of rice. Small improvements in kharif rainfed crop yield may result from the water harvesting tillage.

- red_rice_k,r,25 (GW balance 36.1 mm/year 34.3 mm/year): The extent of rice croplands is reduced by 25%, being replaced with corn and cotton in kharif season and potato and sunflower in rabi season. Moderate increases in yield variability can be expected due to the replacement of some areas of irrigated rice with rainfed crops.

- red_rice_irr,k,25: mds33_kharif (GW balance 31.3 mm/year): Irrigation depths for rice in kharif season only are reduced by 25% (from 8 to 6 mm/day). Water harvesting tillage (MDS = 32.5 mm) is simulated for kharif rainfed crops. Small to negligible declines in yield may result from the irrigation reductions. Small improvements in kharif rainfed crop yield may result from the water harvesting tillage.

- red_rice_k-corn,r-irr-corn,25 (GW balance 18.5 mm/year): The extent of rice croplands is reduced by 25%, being replaced with corn in kharif season and irrigated corn (4 mm/day) in rabi season. Moderate increases in yield variability can be expected due to the replacement of some areas of irrigated rice with rainfed corn. Yield and returns from irrigated corn in rabi would be comparable to those of rice.

- red_rice_irr,k,25 (GW balance 18.0 mm/year): Irrigation depths for rice in kharif season only are reduced by 25% (from 8 to 6 mm/day). Small to negligible declines in yield may result from the irrigation reductions.

- mds50_kharif (GW balance 6.0 mm/year): Water harvesting tillage (MDS = 50.0 mm) is simulated for kharif rainfed crops. Small improvements in kharif rainfed crop yield may result from the water harvesting tillage.

The first hypothesis given at the beginning of Chapter 4, that current rice cropland extent and management practices are depleting groundwater supplies, can be considered to have sufficient evidence to be supported based on observed field-scale water balances of rice croplands (Reddy, 2009), the water balance simulations (Chapter 4, Figure 4-8) of rice croplands and the whole watershed, and the regional data in Chapter 1. The second hypothesis, that tillage for water harvesting can significantly increase groundwater recharge in rainfed croplands, is also accepted based on the results of this chapter. A 2-3.5% increase is groundwater recharge at the basin scale and a 14-24% increase in recharge at the field scale gives sufficient evidence that tillage for water harvesting can be in important part of agricultural management strategies for improving groundwater supply. The third hypothesis, that there are combinations of tillage, crop selection, and irrigation that can improve groundwater recharge and reduce groundwater withdrawals, is also supported by the evidence from the water balance simulations. The third hypothesis was likely the easiest to test and is probably the most obvious result. It hardly requires water balance estimates from a distributed hydrologic model to know that there are combinations of tillage, crop selection, and irrigation that can improve the groundwater balance of the watershed, but the evidence from the simulation experiments does give reliable estimates on the extent of management changes required (i.e. how much rice cropland area reduction is needed to change the groundwater balance from negative to positive) and their quantitative impact on various water balance components.

As discussed in Chapter 1, it is essentially irrigation and recharge that are the directly manageable quantities in the groundwater balance. Simulations showed that irrigation changes (from reduced areas of irrigated crops and/or reduced depths of irrigation of irrigated crops) in rice cropland areas greatly influenced the groundwater balance of the Wargal area. Reduced irrigation and extent of rice croplands decreased groundwater recharge (less return-flow recharge from flooded croplands), but the reduction in irrigation at the basin scale was always greater than the reduction in recharge, resulting in consistent groundwater balance improvements. This is because of the lower evapotranspiration that resulted from the irrigation reductions.

The other major influence on groundwater recharge explored here was water harvesting tillage in rainfed croplands. Recharge from rainfed areas was significantly increased when water harvesting tillage (MDS of 15-50 mm) replaced conventional tillage. With growing evidence for rainfall patterns to be more commonly characterized by greater storms of high intensity (and fewer low/moderate intensity storms; Chapter 2), it is strongly recommended that tillage for increasing surface storage of excess rainfall be considered as an important management option for managing droughts and dry spells. The increased recharge associated with water harvesting tillage can result in more reliable groundwater resources for supplemental irrigation during droughts and dry spells; the increased infiltration associated with water harvesting tillage can result in soil moisture increases having direct agronomic benefits during droughts and dry spells.

Table 4-1. Descriptions of 25 alternative management scenarios with abbreviations used

Management scenario: abbreviation	Description
existing	current agricultural management in Wargal watershed
mds50_kharif	tillage change: MDS of 50 mm in kharif season corn and cotton
mds33_kharif	tillage change: MDS of 32.5 mm in kharif season corn and cotton
mds15_kharif	tillage change: MDS of 15 mm in kharif season corn and cotton
mds50_rabi	tillage change: MDS of 50 mm in rabi season potato and sunflower
mds33_rabi	tillage change: MDS of 32.5 mm in rabi season potato and sunflower
mds15_rabi	tillage change: MDS of 15 mm in rabi season potato and sunflower
mds50_k,r	tillage change: MDS of 50 mm in kharif and rabi
mds33_k,r	tillage change: MDS of 32.5 mm in kharif and rabi
mds15_k,r	tillage change: MDS of 15 mm in kharif and rabi
red_rice_k,r,25	reduce rice croplands in kharif and rabi by 25%; replace with equal parts corn and cotton in kharif, potato and sunflower in rabi
red_rice_k,r,50	reduce rice croplands in kharif and rabi by 50%; replace with equal parts corn and cotton in kharif, potato and sunflower in rabi
red_rice_k,r,75	reduce rice croplands in kharif and rabi by 75%; replace with equal parts corn and cotton in kharif, potato and sunflower in rabi
red_rice_k-corn,r-irr-corn,25	reduce rice croplands in kharif and rabi by 25%; replace with rainfed corn in kharif, irrigated corn in rabi
red_rice_k-corn,r-irr-corn,50	reduce rice croplands in kharif and rabi by 50%; replace with rainfed corn in kharif, irrigated corn in rabi

Table 4-1. Continued

Management scenario: abbreviation	Description
red_rice_k-irr-corn,r-irr-corn,25	reduce rice croplands in kharif and rabi by 25%; replace with irrigated corn in kharif, irrigated corn in rabi
red_rice_k-irr-corn,r-irr-corn,50	reduce rice croplands in kharif and rabi by 50%; replace with irrigated corn in kharif, irrigated corn in rabi
red_rice_irr,k,25	reduce rice daily irrigation depths by 25% in kharif to 6 mm/day
red_rice_irr,k,50	reduce rice daily irrigation depths by 50% in kharif to 4 mm/day
red_rice_irr,k,r,25	reduce rice daily irrigation depths by 25% in kharif and rabi to 6 mm/day
red_rice_irr,k,r,50	reduce rice daily irrigation depths by 50% in kharif and rabi to 4 mm/day
red_rice_r-irr-corn,25	reduce rice croplands in rabi season only by 25%; replace with irrigated corn in rabi
red_rice_r-irr-corn,50	reduce rice croplands in rabi season only by 50%; replace with irrigated corn in rabi
red_rice_k-corn,r-irr-corn,25: mds33_kharif	reduce rice croplands in kharif and rabi by 25%; replace with rainfed corn in kharif, irrigated corn in rabi; MDS of 32.5 mm in kharif corn and cotton
red_rice_k-irr-corn,r-irr-corn,25: mds33_kharif	reduce rice croplands in kharif and rabi by 25%; replace with irrigated corn in kharif, irrigated corn in rabi; MDS of 32.5 mm in kharif corn and cotton
red_rice_irr,k,25: mds33_kharif	reduce rice daily irrigation depths by 25% in kharif to 6 mm/day; MDS of 32.5 mm in kharif corn and cotton

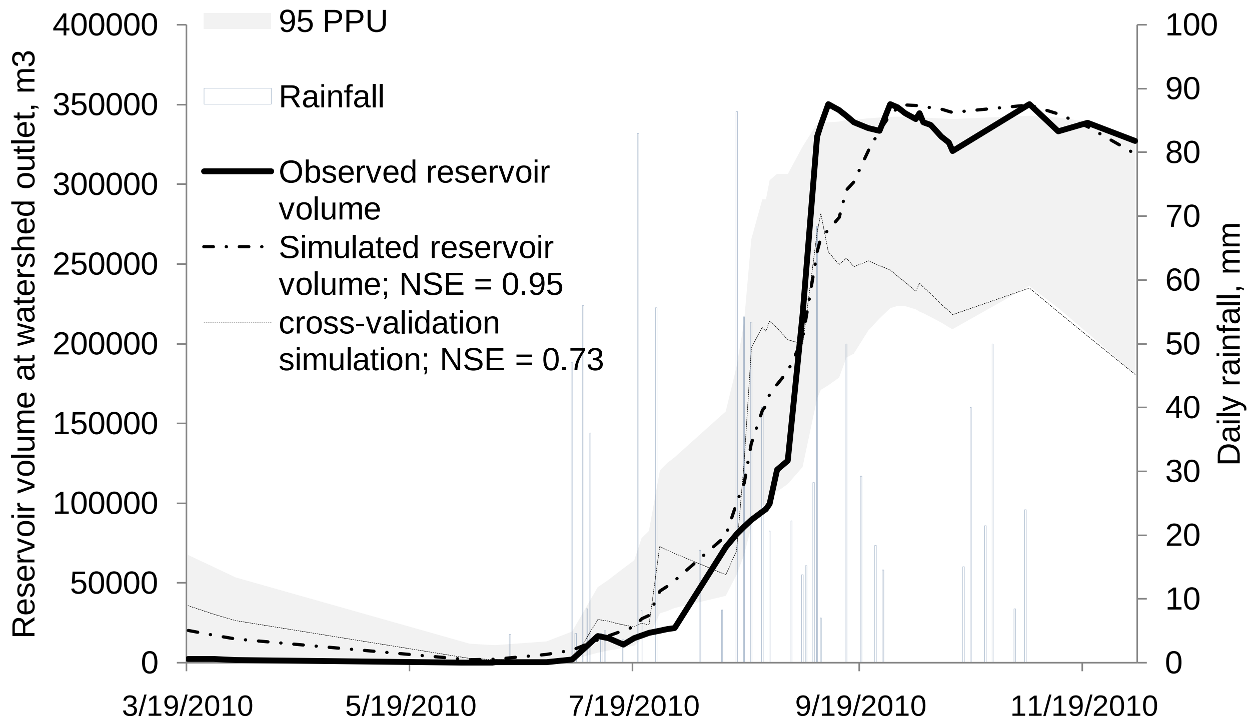

Figure 4-1. Observed and simulated (for calibration and validation) watershed outlet reservoir volume and rainfall in Wargal watershed; 3/19/2010 to 12/3/2010

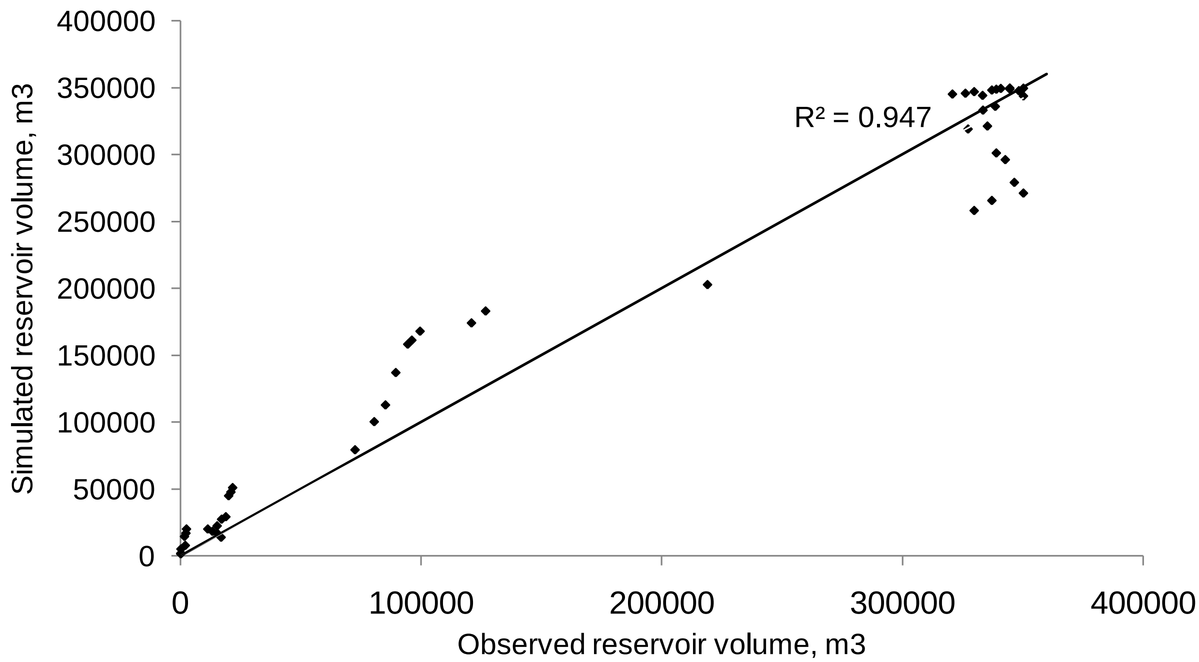

Figure 4-2. Simulated and observed reservoir volumes: 3/19/2010 to 12/3/2010

Table 4-2. Maximum surface area and volume of the six reservoirs (tanks) in Wargal watershed

Tank subbasin	Area, ha	Volume, 10^4 m^3
1	21.40	35.03
2	0.96	0.42
3	0.59	0.21
4	0.77	0.30
5	0.32	0.09
6	0.75	0.29

Table 4-3. Specific yield, natural recharge, and total recharge from DWTF method and total recharge from SWAT simulations in 2009 and 2010

	2009		2010	
	DWTF	SWAT	DWTF	SWAT
Sy	0.0139		0.0123	
R, mm	264.2		419.9	
R + RF, mm	496.1	501.9	674.7	701.4
Rainfall, mm	667.0	667.0	1022.0	1022.0

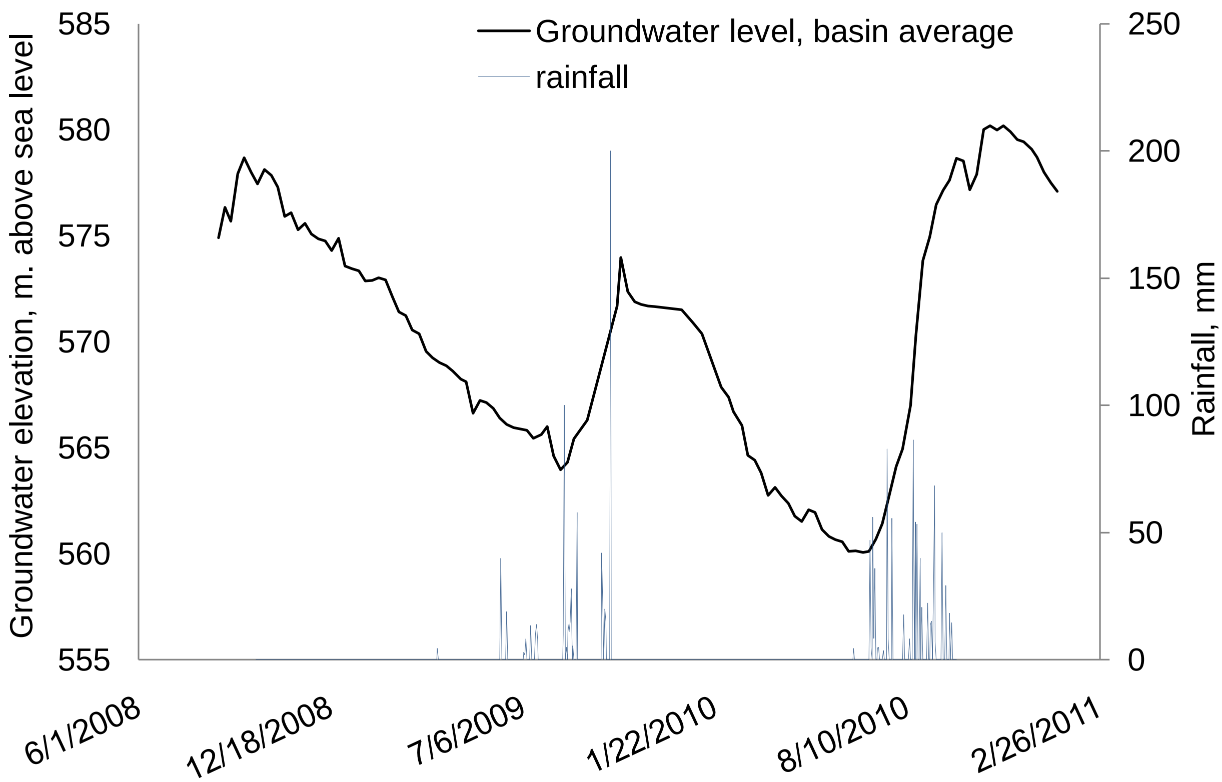

Figure 4-3. Observed groundwater level change and rainfall during wet and dry periods

Table 4-4. Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR). Calibration describes the parameter estimation using all observations, and evaluation describes the 5-fold cross-validation.

	NSE	PBIAS	RSR
Calibration	0.954	-3.185	0.215
Evaluation	0.729	14.657	0.520

Table 4-5. Parameter name, t-statistic, p-value, and range of the 13 parameters estimated during SWAT calibration. r__ indicates that the initial parameter is multiplied by (1+[value in range]); v__ indicates that the initial parameter is replaced by the value in the range.

	Sensitivity		Range			
Parameter Name	t-Stat	P-Value	Min	Max	Best estimate	Units
r__SOL_AWC(1,2).sol	37.304	0.000	0.25	0.75	0.47	mm/mm
v__SOL_K(1).sol______RICE	-18.190	0.000	0.50	1.25	0.99	mm/hr
v__RES_K.res	-18.167	0.000	0.50	1.00	0.56	mm/hr
r__CN2.mgt	13.658	0.000	-0.10	-0.05	-0.09	none
v__EVRSV.res	-3.775	0.000	0.50	0.95	0.78	none
r__SOL_K(1).sol	3.136	0.002	0.25	0.75	0.26	mm/hr
r__GWQMN.gw	1.570	0.116	950.00	1100.00	1073.78	mm
v__EPCO.bsn	-0.932	0.352	0.50	0.95	0.78	none
v__ESCO.bsn	-0.900	0.368	0.50	0.95	0.80	none
r__ALPHA_BF.gw	-0.801	0.423	0.25	0.50	0.27	days
r__RCHRG_DP.gw	-0.548	0.584	0.70	0.80	0.76	none
v__EVLAI.bsn	-0.236	0.814	3.50	5.00	3.84	m^2/m^2
r__GW_DELAY.gw	0.213	0.832	30.00	50.00	30.70	days

Table 4-6. Summary of selected water balance components for existing and alternative agricultural management, sorted by groundwater balance (GW balance = recharge – irrigation). GW ∆h is predicted groundwater level change, mm, given specific yield of 0.013 from DWTF method. Simulations using generated weather 2000-2009, 792 mm rainfall.

	Average annual values, mm				
Management scenario	GW ∆h	GW balance	Irrigation	Recharge	ET
red_rice_k,r,75	10335.0	124.0	163.6	287.6	534.1
red_rice_k,r,50	6596.2	79.2	290.9	370.1	553.4
red_rice_irr,k,r,50	6477.1	77.7	290.4	368.1	585.4
red_rice_k-corn,r-irr-corn,50	3712.4	44.5	347.3	391.8	570.9
red_rice_irr,k,r,25	3183.8	38.2	418.0	456.2	591.8
red_rice_k-corn,r-irr-corn,25: mds33_kharif	3008.3	36.1	446.4	482.5	583.0
red_rice_k,r,25	2858.2	34.3	418.3	452.6	572.7
red_rice_irr,k,25: mds33_kharif	2610.4	31.3	474.9	506.3	593.9
red_rice_irr,k,50	2243.9	26.9	404.2	431.1	583.9
red_rice_k-corn,r-irr-corn,25	1543.2	18.5	446.4	465.0	583.0
red_rice_irr,k,25	1499.5	18.0	474.9	492.9	593.9
mds50_k,r	627.9	7.5	546.0	553.5	595.1
mds50_kharif	496.0	6.0	546.0	552.0	593.9
mds33_k,r	281.3	3.4	546.0	549.4	591.4
mds33_kharif	201.7	2.4	546.0	548.4	592.1
mds15_k,r	-60.7	-0.7	546.0	545.3	591.3
mds15_kharif	-117.5	-1.4	546.0	544.6	592.0
red_rice_r-irr-corn,50	-580.9	-7.0	488.7	481.8	587.1
red_rice_r-irr-corn,25	-603.9	-7.2	517.2	509.9	591.1
mds50_rabi	-778.0	-9.3	546.0	536.7	593.3
mds33_rabi	-829.6	-10.0	546.0	536.0	591.4
mds15_rabi	-852.4	-10.2	546.0	535.8	591.3
existing	-909.2	-10.9	546.0	535.1	592.1
red_rice_k-irr-corn,r-irr-corn,25: mds33_kharif	-1508.6	-18.1	548.5	530.4	595.8
red_rice_k-irr-corn,r-irr-corn,50	-2099.1	-25.2	475.9	450.7	587.2
red_rice_k-irr-corn,r-irr-corn,25	-3197.4	-38.4	548.5	510.1	595.9

Table 4-7. Summary of selected water balance components for existing and alternative agricultural management, sorted by groundwater balance (GW balance = recharge – irrigation). GW Δh is predicted groundwater level change, mm, given specific yield of 0.013 from DWTF method. Simulations using observed weather 2009, 667 mm rainfall.

	Average annual values, mm				
Management scenario	GW Δh	GW balance	Irrigation	Recharge	ET
red_rice_k,r,75	8967.2	107.6	163.6	271.2	493.0
red_rice_k,r,50	4813.1	57.8	290.9	348.7	531.7
red_rice_irr,k,r,50	3250.7	39.0	290.4	329.4	602.2
red_rice_k-corn,r-irr-corn,50	1288.3	15.5	347.3	362.7	558.3
red_rice_k,r,25	601.4	7.2	418.3	425.5	570.5
red_rice_k-corn,r-irr-corn,25: mds33_kharif	162.7	2.0	446.4	448.4	607.2
red_rice_irr,k,50	-210.9	-2.5	404.2	401.7	606.1
red_rice_irr,k,r,25	-331.0	-4.0	418.0	414.1	602.2
red_rice_irr,k,25: mds33_kharif	-1023.6	-12.3	474.9	462.7	582.0
red_rice_k-corn,r-irr-corn,25	-1100.4	-13.2	446.4	433.2	584.9
red_rice_irr,k,25	-1848.3	-22.2	474.9	452.8	606.8
mds33_k,r	-2843.4	-34.1	546.0	511.9	645.4
mds33_kharif	-2851.4	-34.2	546.0	511.8	636.9
mds15_kharif	-2854.1	-34.2	546.0	511.8	633.1
mds50_k,r	-2879.5	-34.6	546.0	511.4	632.5
mds50_kharif	-3052.1	-36.6	546.0	509.4	625.6
mds15_k,r	-3404.1	-40.8	546.0	505.2	669.2
red_rice_r-irr-corn,50	-3434.6	-41.2	488.7	447.5	600.3
red_rice_r-irr-corn,25	-3476.2	-41.7	517.2	475.5	605.9
mds50_rabi	-3499.9	-42.0	546.0	504.0	616.1
mds33_rabi	-3665.7	-44.0	546.0	502.0	617.7
existing	-3672.7	-44.1	546.0	501.9	609.3
mds15_rabi	-4225.6	-50.7	546.0	495.3	592.1
red_rice_k-irr-corn,r-irr-corn,25: mds33_kharif	-4405.2	-52.9	548.5	495.6	643.6
red_rice_k-irr-corn,r-irr-corn,50	-5806.7	-69.7	475.9	406.2	602.7
red_rice_k-irr-corn,r-irr-corn,25	-6874.0	-82.5	548.5	466.0	620.9

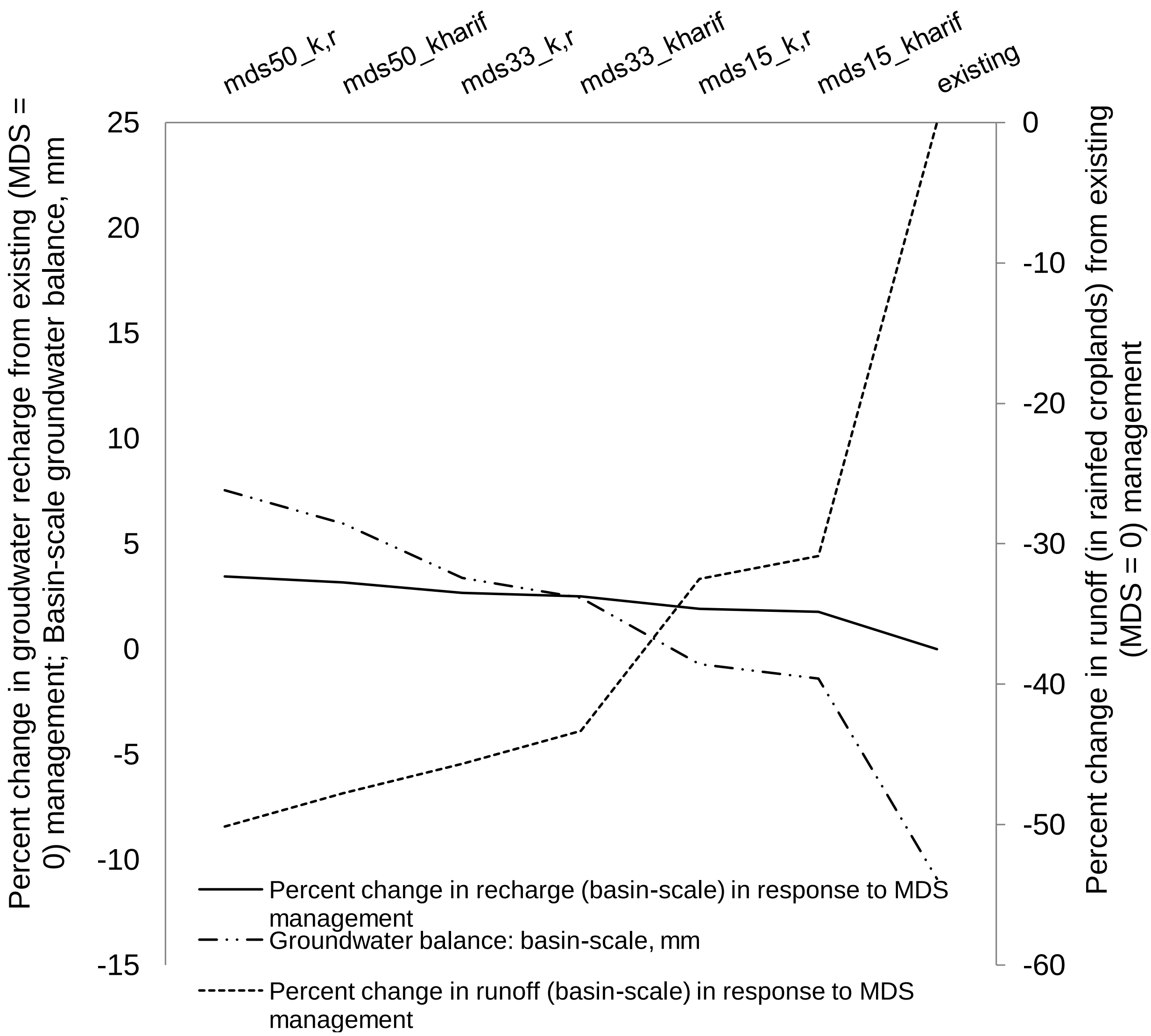

Figure 4-4. Basin-scale response of groundwater recharge, groundwater balance, and runoff to MDS changes in rainfed croplands in kharif season and in both kharif and rabi seasons. MDS of 15, 32.5 or 50 mm. 30 to 50% less runoff with tillage for 15 mm < MDS < 50 mm; groundwater balance from -11 mm for existing management to 7 mm for 50 mm MDS in rainfed areas in both seasons.

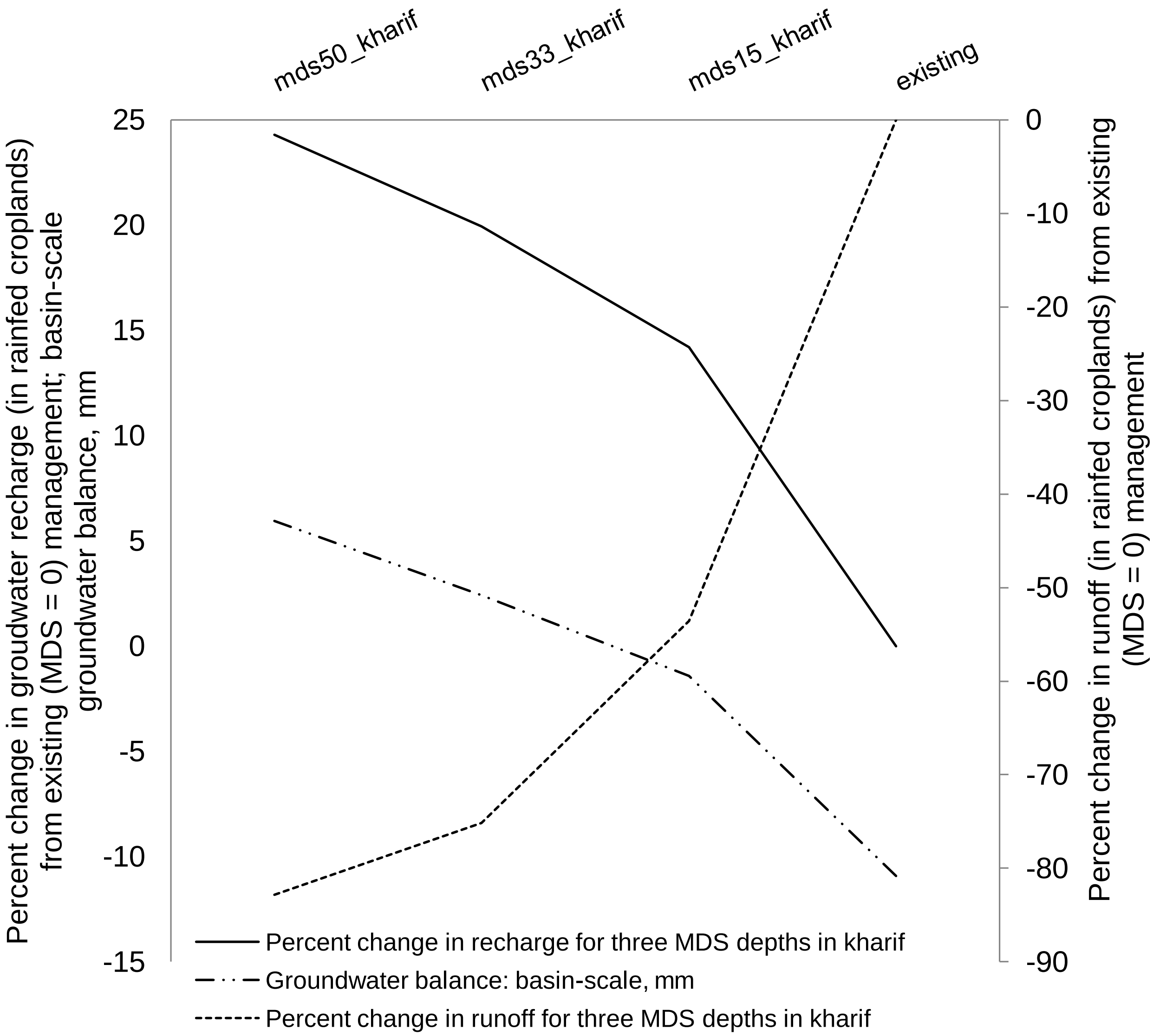

Figure 4-5. Field-scale response of groundwater recharge and runoff to tillage changes (MDS depth) in rainfed croplands in kharif season. MDS of 15, 32.5 or 50 mm. 54 to 83% less runoff from rainfed croplands with tillage for 15 mm < MDS < 50 mm; groundwater balance from -11 mm for existing management to 6 mm for 50 mm MDS in rainfed areas in both seasons.

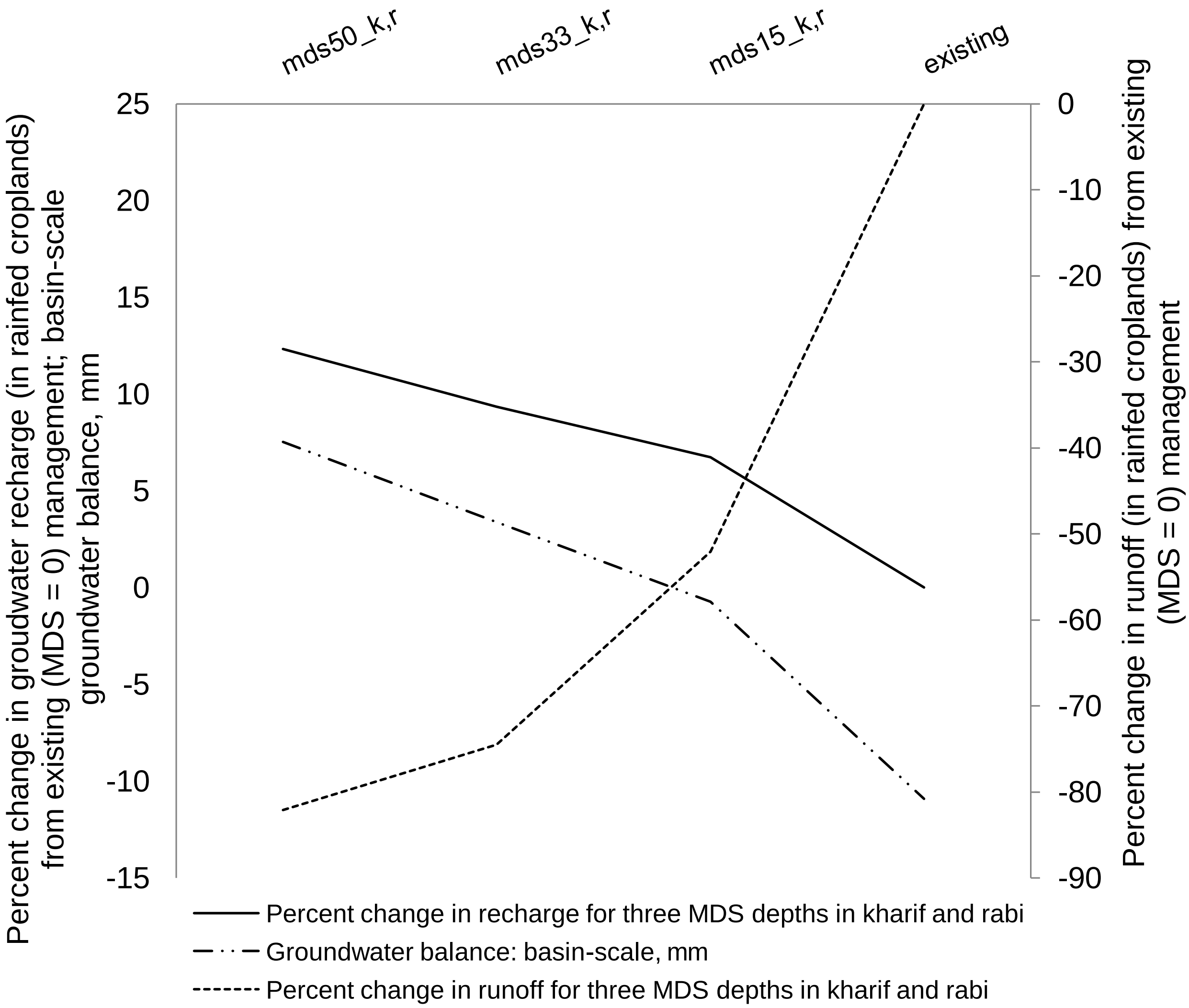

Figure 4-6. Field-scale response of groundwater recharge and runoff to tillage changes (MDS depth) in rainfed croplands in both kharif and rabi seasons

Table 4-8. Sensitivity of annual surface runoff and groundwater recharge to MDS at the basin scale: mm change in depth of recharge and runoff (from existing tillage, MDS = 0) per mm MDS

Management Scenario	MDS depth	Increase in recharge, mm	Increase in recharge per mm MDS	Decrease in runoff, mm	Decrease in runoff per mm MDS
mds50_kharif	50.0	49.9	1.0	76.1	1.5
mds33_kharif	32.5	40.9	1.3	69.0	2.1
mds15_kharif	15.0	29.1	1.9	49.2	3.3
existing	0	0	0	0	0

Table 4-9. Sensitivity of annual surface runoff and groundwater recharge in rainfed croplands (corn and cotton) in kharif season to MDS: mm change in depth of recharge and runoff (from existing tillage, MDS = 0) per mm MDS

Management Scenario	MDS depth	Increase in recharge, mm	Increase in recharge per mm MDS	Decrease in runoff, mm	Decrease in runoff per mm MDS
mds50_kharif	50.0	16.9	0.3	30.1	0.6
mds33_kharif	32.5	13.3	0.4	27.3	0.8
mds15_kharif	15.0	9.5	0.6	19.5	1.3
existing	0	0	0	0	0

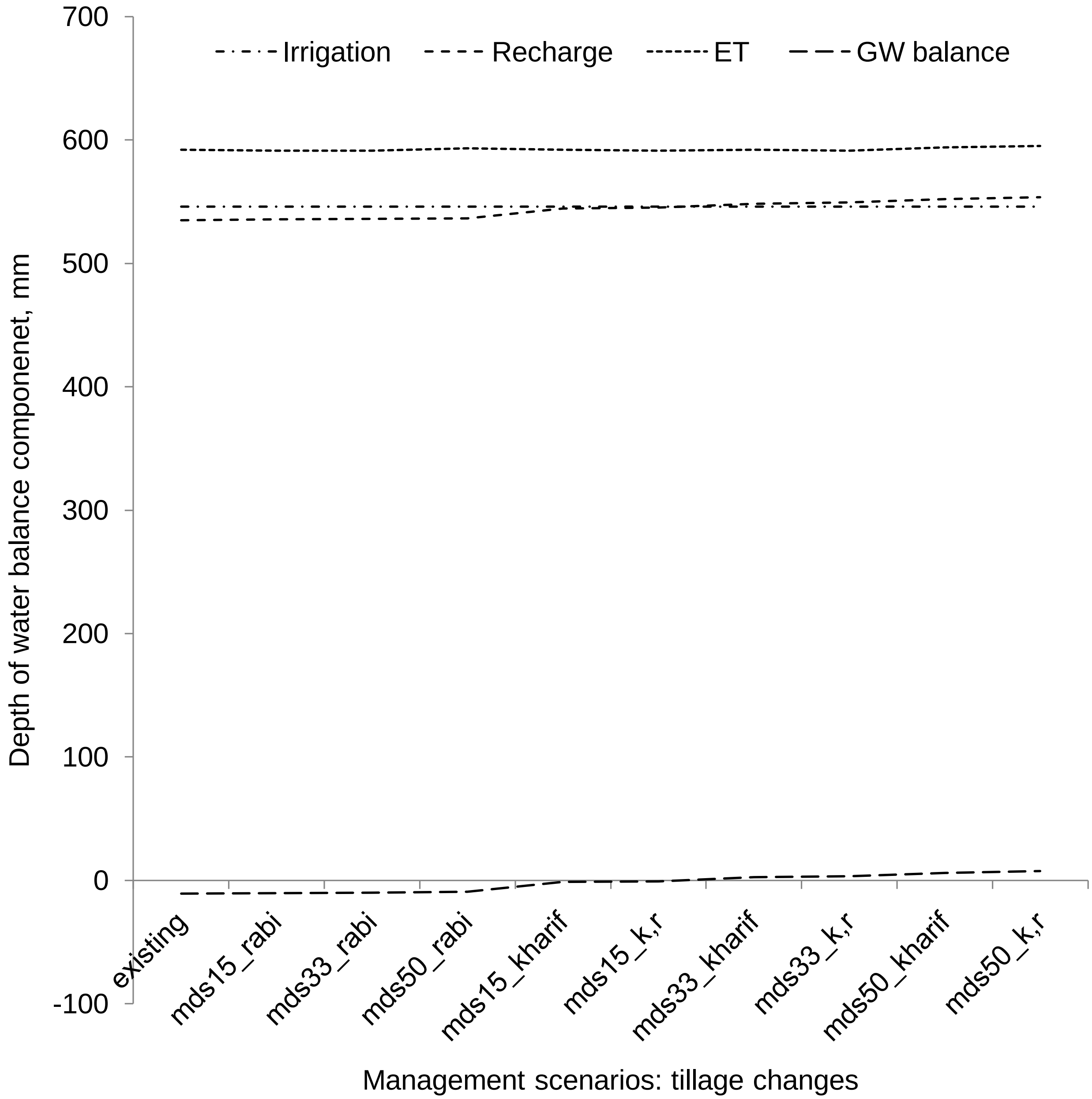

Figure 4-7. Irrigation, recharge, ET, and groundwater balance for tied-ridge tillage scenarios: 3 MDS depths in rainfed areas in kharif, rabi, and both seasons

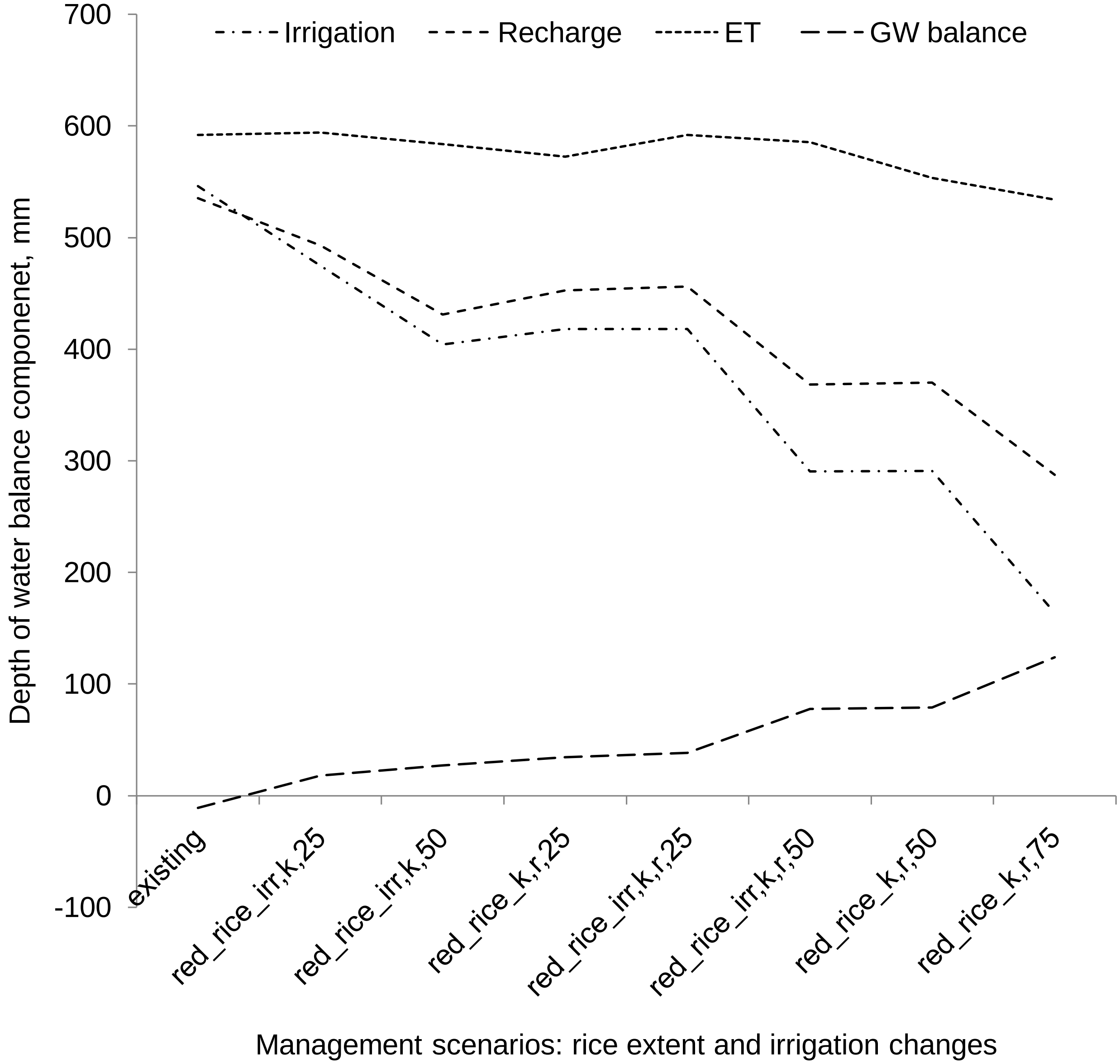

Figure 4-8. Irrigation, recharge, ET, and groundwater balance for selected changes in extent and irrigation management of rice croplands

CHAPTER 5
SOCIAL AND ECONOMIC ASSESSMENT OF GROUNDWATER MANAGEMENT

Groundwater and Indian Agricultural Economics

The groundwater irrigated areas of India nearly tripled in extent from 11.9 million hectares in 1971 to 33.1 million ha in 1999 (Mukherji and Shah, 2005), and it has been shown through analysis of over 240 districts across India that the productivity ($/ha) of groundwater irrigated areas are about 35% greater than those of surface water irrigated areas (Mukherji and Shah, 2005). Throughout Asia, and especially in India, irrigation from groundwater has become a major contributor to agricultural improvements in recent decades. However, as discussed in earlier chapters, there are mounting concerns about groundwater depletion in India (CGWB, 2007; Rodell et al., 2009), and there are also energy efficiency concerns associated with groundwater depletion that have resulted from increased groundwater irrigated areas. The decline of groundwater resources in some regions has decreased net energy ratios in agriculture (energy output / energy input) as a result of greater pumping and fertilizer inputs (Gurunathan and Palanisami, 2008). Groundwater scarcity in India is increasingly becoming a problem for livelihood security, and the research presented in this chapter focuses on (1) integrating gender, social, and economic analyses and to improve the relevance of science-based recommendations related to groundwater management regimes in rural India, (2) estimating the economic consequences of changing agricultural management, and (3) discussing application possibilities and policy options for alternative agricultural management.

Fieldwork on the Socioeconomics of Agricultural Management

In contribution to the analysis of social and economic effects of agricultural management changes, fieldwork was done to find the decision making processes involved in determining farm management practices in the Wargal watershed, including the nature of information used by stakeholders to decide about farm management. A thorough analysis required that the differences between decision making by men and women (involvement, power relations, access to and use of information) be understood. Fieldwork in the study area aimed to begin this process.

The related biophysical goal in Wargal was to find cropping system management options that can realize sustainable water resources and that are sufficiently productive. This was done through simulation experiments using a distributed water balance model. Watershed-scale analyses of groundwater responses to crop selection, tillage strategy, and irrigation management helped select the best management practices for improving groundwater supply for the people of the watershed (Chapter 4). Information from people of the study area has served three purposes for the biophysical experimentation aspect of this project:

- Validation of problem – confirms that the problem (groundwater depletion) is actually a concern to people in the watershed. Interactions with farmers in the area showed that groundwater depletion was observed by nearly everyone in the area, and this depletion was one of the major concerns of households in the area.
- Simulation of appropriate management options – participation from the community to recommend management options (alternative crops, tillage, and irrigation) that they would prefer, that they consider economically viable, and that they expect would reduce irrigation withdrawals. This information increases the relevance of hydrologic simulation experiments. Five weeks of preliminary fieldwork has provided some information on crop preferences, available tillage implements, and typical irrigation practices. This information is being used to choose implementable management scenarios for simulation experiments.

- Implementation and motivation to change – field trials and actual management changes by farmers in the area are expected to be easier to initiate as a result of the involvement of the community. An improved understanding of how certain farm management decisions are made (what information is used to make them) helps expose possible motivations for changes in decisions about resource management. From interactions with farmers in the area, it was learned that water availability was the most dominant information used in decisions about crop selection.

The interaction of research-generated management recommendations and the implementation of actual, local management changes is nuanced and requires significant understanding of local information systems (Roncoli et al., 2002; Shah et al., 2003). As stated in their study about local rainfall forecasting in rural Africa (Roncoli et al., 2002), “Evidence shows that local knowledge can and must be integrated with research-generated information and technology in efforts to improve rural livelihoods.” For research models generated in the highly developed parts of the world to have practical transferability to help improve rural livelihoods, their management recommendations must be able to fit into local knowledge systems.

Sustainability: Definitions

Broadly, this project focuses on sustainable water resource management in India; in the Wargal watershed, the specific concern is groundwater sustainability. The definition of sustainability (or security) of a biophysical quantity is generally straightforward. It is the maintenance of a state or process at a desired level or rate into the future. The subject of interest in this project is groundwater quantity; so sustainability can be more narrowly defined as some amount of groundwater (distance below ground level or aquifer storage volume) to be maintained. This chosen storage amount is informed by past and current groundwater levels and expert judgment. The groundwater balance has an obvious dependence on decisions by people, which is why it was decided that an improved understanding of how the people of Wargal make decisions would contribute to the overall goal of finding ways to sustainably manage water resources in the area.

Methods for Learning about Wargal Agricultural Management

The plan for fieldwork in the Wargal watershed was focused on meeting the following objectives:

- Explore the perceptions of men and women concerning groundwater resources and changing climate
- Identify gender differences in constraints to changing farm management practices (tillage techniques, crop selection, irrigation management), and explore the local farm management decision-making processes

The intention was to meet with members of households having dependence on the study area for their livelihood sources. It was planned to meet with men and women both together and separately to discuss their decision-making processes, cropping system preferences and constraints, responsibility divisions, and perceptions of water resources and climate change. Meetings with community-level government were organized to understand the regulation of water and land use management. The local governing body, Panchayat, consisted of five men who are charged with tax collection, data acquisition (crop types, yield estimates, crop condition, rainfall, population), and settling local disputes.

Farmers who participated in interviews were selected partly by partners from ANGRAU (they knew some farmers who had agreed to metered borewells and other instrumentation in their fields) and partly by just approaching people who were working or resting in the fields. Most participants were selected by the latter method.

Translators from ICRISAT and ANGRAU (interviews were in Telugu) assisted with interviews.

The fieldwork tools consisted of informal interviews of open-ended questioning (Norman et al., 1995). Typically, interviews began with introductions and small talk and continued with informal discussions about main concerns in the community, changes in groundwater supply and climate, and how decisions were made and who was responsible for certain farm operations. Questions were grouped into these three themes during question preparation, but no mention of the themes was made during interviews. Questions were not read from a questionnaire; they were asked from memory in order for interviews to be more conversational. Note takers recorded all responses. Observations were regularly made of who was doing farm operations (tillage, weeding, planting, transplanting, controlling borewell pump).

Some respondents were direct owners of the farm we visited and these respondents were either alone or with family members (both men and women) who were working on the farm. Hired day laborers also participated in the discussions summarized here. For much of the results presented below, sample sizes of women are slightly larger than those of men (these numbers are totals, including responses in gender-separated and mixed groups). The larger numbers of women reflects the special efforts made to include women in discussions; also, due to the nature of many of the field operations for which they were responsible (for example, weeding by hand), women were more likely to be found working in groups. Interviews generally happened in groups, but responses were only recorded for people who gave answers. All members of a group were given the opportunity to respond to each question. Interviews lasted from 10 to 30 minutes. The informality of survey administration and method of participant selection resulted in some incomplete surveys; not all questions were answered by all participants. This is a common weakness of informal surveys, making them less suited to quantitative analysis (Norman et al., 1995).

Social and Biophysical Analysis Connections

During the design of simulation experiments, decisions have to be made by the user of the water balance model about the types of management practice scenarios to simulate. It was hypothesized that management scenarios developed from farmer-generated information would have higher productivity and greater chance of implementation. This hypothesis could not be tested by survey data collection, but would require farmers to implement management changes and to evaluate their effectiveness. Participation of farmers from the study area was expected to result in a more realistic range of management scenarios (Chapter 4).

Results of Household Survey Fieldwork

Wargal mandal is one of 45 mandals of Medak district, a Telugu language region. Medak district has a population of 2.8 million, 80% of which is rural. There are about 150 households working in agricultural systems in Wargal. There are about 190 active borewells; total land area is 512 ha. Cropping systems are dominated by irrigated rice, which represents 41% and 49% of cropland area in kharif and rabi seasons, respectively.

Questions are findings from interviews with community members were grouped into the following three themes: main concerns, changes in groundwater and climate, and management and decision making. Main concerns were responses about the most pressing issues in the community. Changes in both groundwater and climate captured responses about direction of changes observed, how they are measured, and what the causes of the changes are. Management and decision making explores the information used to make farm management decisions and who is responsible for selected management activities. These three themes were identified for organizational purposes during survey development.

Main concerns

One topic of interactions with farmers was their main concerns in the community. This was approached in a broad, open-ended manner to include information related to agriculture or other aspects of the livelihood system. Percentages of various responses are presented in Table 5-1. A few key themes stand out and warrant attention. The data suggest, based on numbers of responses for each concern mentioned by participants, that women are more concerned with social livelihood issues like education and adequate health care for their children, bus routes to town for easier access to markets, and sufficient, clean water for domestic use. Public transportation (bus route accessibility) was one of women's top concerns, suggesting they more regularly use public transportation. The most prevalent concerns of women tend to coalesce around their domestic roles of providing care and education for their children and their roles of going to market. As an example of the sometimes divergent responses of men and women, 59% of female participants mentioned access to higher education as a leading concern while 0% of male participants mentioned this. 41% of women and 3% of men mentioned access to healthcare services as a major concern. Some women did express concern about lack of groundwater and electricity for powering irrigation pumps. Men were mostly concerned with issues that directly impact their ability to be successful farmers and wage earners: such as affordable fertilizer, reliable and inexpensive seed, adequate electric power for running irrigation pumps, and availability of local non-farm employment. Participants of both genders expressed concern about there being less groundwater and an increasing rate of failing borewells, and both were concerned with power shortages that impact the functioning of irrigation pumps.

Generally, there is a discrepancy in the concerns between the men and women we interviewed. This is evidenced by noticing that four of the five top concerns for women are not mentioned as concerns by men except for one male respondent who did mention concern about quality of and access to water for domestic use. However, women seemed to share several of the most-mentioned concerns of the men. This is most likely because the overall economic prosperity of the family depends on agricultural quantities like seed, fertilizer, electricity, and water availability, and those are things men and women generally discuss together. Some women have also taken out loans through local women's self-help groups and this money is often used for farm inputs so that women have an added stakeholder concern in the success of their family farm.

It should be noted that these questions were left open; for example, "What are your main concerns for your life in Wargal?", so that although men did not respond that they are concerned with education and health care this does not mean that these issues are not actual concerns they also have. Rather, their more immediate concerns were farming related while women's immediate concerns were socially and family health related.

Changes in groundwater and climate

Water resource sustainability is an important objective of this work; therefore, it was decided that the perceptions of farmers about groundwater and climate changes should be explored. Farmers were asked if they had noticed any changes in groundwater levels in recent years; the question was always open, not assuming any direction of resource changes. The question was usually asked: “Have you noticed any changes in the amount of groundwater?” If groundwater depletion was observed, participants were asked to consider methods of noticing groundwater depletion, expected causes of groundwater depletion, and expected cause of reduced rainfall. Tables 5-2, 5-3, and 5-4 summarize their responses.

Table 5-2 summarizes the groundwater sensing or measurement options; without instrumentation changes in groundwater levels are still noticed by men and women in the research area. More women cited failed drilling attempts as a method of observing groundwater decline. This method likely has the most severe economic consequences for families in the research area. A failed borewell must still be paid for and this usually is done by taking out a loan but which requires a bountiful harvest so the loan may be paid back. Only a small percentage of responses indicated that groundwater decline was not observed; this gives more support (in addition to published groundwater decline data) to the effort to find farm management options for improving groundwater levels. Those that responded that they had noticed groundwater decline were asked what they thought was causing the decline. A few different responses were given and it sometimes took about one minute for participants to choose a cause. Table 5-3 summarizes the responses concerning cause of groundwater depletion.

A clear majority of research participants, whether female or male, have perceived a negative change in groundwater quantity. An equal number of both men and women claim to have noticed this change by visually noting the rate and strength of flow coming from borewell pumps. This shows that both men and women have an interest in observing flow rate. A clear majority of women have correlated changes in groundwater because of failed drilling attempts. Similarly, more women associate groundwater depletion with the proliferation of borewells over the last ten to fifteen years: of the 23 people who were asked about reasons for changes in groundwater, 15 associated this with more borewells being drilled and 12 of these were women. What is more relevant is that this recognition of correlation between borewell development and groundwater depletion shows that there is community knowledge about current farming systems and management decisions and how these may be contributing to groundwater depletion. This suggests that growers in the area would be somewhat receptive to farm management scenarios which show promise of improving groundwater levels.

Lastly, all research participants in the watershed, both men (N = 12) and women (N = 27), have noticed changes in rainfall. Data from India's Central Groundwater Board suggests noticeable rainfall declines in the Wargal study area. These data show a decline in rainfall from the long term mean (873 mm annually) of about 30% over the period from 2001- 2006 (CGWB, 2007). When discussing past rainfall and water levels in the area, a few farmers mentioned that they remember when there used to be puddles and little ponds all over the fields in the past but in recent years the fields dry up earlier because there is less rain. Participants who suggested reduced rainfall as a cause of groundwater decline were asked why rainfall amounts were less than average. Similar to the responses about cause of groundwater decline, there was little variability among responses. Shoulder shrugging was common and some suggested such a thing could not be known. As seen in Table 5-4, local knowledge, sometimes explains changes in rainfall as being associated with the work of the gods and the misdeeds of people.

Management and decision making

Management of farming systems in the study area is adaptive, considering diverse information from which decisions are made. Questions were asked of farmers about what information is used to make decisions about crop selection and irrigation management (Appendix B). Tables 5-5 and 5-6 present participant responses, and the associated percentages of total responses, to inquiries about how crop selection and irrigation management decisions are made.

Agreement in the responses of men and women is illustrated in Table 5-5. Responses for each question are ranked in the table from highest to lowest frequencies of occurrence. Both men and women reported that observations of water availability and conversations within the family and community are the most important sources of information for decisions about crop selection. One response about information for crop selection for which there was a noticeable difference between men's and women's responses was about expected produce price. In the sample interviewed (26 women, 20 men), a much higher proportion of men than women indicated that produce price would be considered for deciding on crop selection and extent. In discussions of timing and depth of irrigation, fewer women than men gave the response: electricity is on; therefore, irrigation happens (Table 5-6). That response was the most frequently occurring response by men. This supply-side management method may be partly the cause of the local groundwater depletion. Our initial fieldwork suggests that irrigation management is generally the responsibility of men, but for some growers, women did have some irrigation responsibility.

Considering the biophysical goal of improving groundwater levels in this watershed, the prevalence of water availability as an important influence on crop selection decisions suggests that people in the community would be responsive to management scenarios that are designed to do well under limited water availability. This suggests that water balance simulations be designed to find management options that broaden the range of crops under consideration when there is low water availability. Some tillage techniques which result in greater rainfall infiltration (and greater estimated yield) could achieve this. However, observations in the field and participation of community members have revealed that there is limited labor availability and very little mechanization available for field operations. Therefore, management scenarios for water balance simulations were designed with consideration of these constraints on labor and mechanization.

The sources of information used for decision making, based on conversations with growers (Tables 5-5 and 5-6), can be summarized into the following 6 categories – ranked in order of decreasing frequency of occurrence:

Decision support information

- Water availability
- Observation of plants and soil
- Family communication
- Discussion with neighbors
- Expected market price of produce
- Personal experience

This information is used to shape decisions about crop selection, irrigation, and fertility management. Decision-making information that could be categorized as water availability was reported by nearly all farmers involved, suggesting that groundwater decline and rainfall variability are significant concerns. Water availability is observed by impressions of rainfall of the previous year, water tank levels, soil moisture, plant appearance, and flow rate (intermittency) of borewells. Figure 5-3 displays a reservoir (one of six in the study area) after a recent rain. These reservoirs were excavated decades ago and are maintained to delay runoff of monsoon rains and increase groundwater recharge.

In areas where agriculture is the dominant livelihood activity, attention to water availability and other limiting factors is nearly universal among stakeholders (Roncoli et al., 2002). Tools used to predict risk of agricultural activities typically have some measure of water availability being the most sensitive input (Kazianga and Udry, 2006), so it is not surprising that growers indicated that water availability is the most important factor in decisions about crop selection. Table 5-7 illustrates the consistency between men and women in the most frequently observed responses concerning farm management. Table 5-7 lists the responses mentioned by the greatest number of male and female participants for four farm management questions: what is information used to decide about (1) crop selection and (2) irrigation management, (3) what is the preferred rice cropland replacement, and (4) who is responsible for borewell pump operation. Only in the replacement of rice crop did responses diverge; the men suggesting growing cotton and the women opting for a cover crop or fallow, which would require much less labor and management but would provide no direct cash income. In a report on the changing roles of men and women in response to desertification, Gurung et al. (2006) suggest that women are more responsible for food crop production and land conservation and men are typically more responsible for cash crop management. The limited data presented here is consistent with that finding: women responding to a question about crop selection if there was insufficient irrigation water for rice cultivation said that they would prefer a cover crop or fallow (which would likely improve productivity of future plantings of food crops) and men suggested cotton (which would increase short term household income).

Discussions with farmers provided information about who turns on and off the borewell pumps used for irrigation withdrawals and who goes to the market to buy seeds and fertilizer. Tables 5-8 and 5-9 summarize responses to these two questions. From both and women, only one response was given: “men; women only if man is unavailable”. This meant that it was the general understanding that men controlled borewell pumps and were responsible for seed and fertilizer acquisition, but women would occasionally do these jobs if needed. This arrangement seemed to work well and appeared satisfactory to all involved. However, some investigators have suggested that the dominance of men in water control marginalizes women’s water rights (Lambrou and Piana, 2006; Zwarteveen, 2008). Considering what a productive resource groundwater is, it may be that women’s limited management experience with it does afford them less power than men (Pangare, 1998). Women usually reported that they were afraid of the electrical box where the pump switch (or wire connectors) was located. Similarly, the purchasing and delivery of seed and fertilizer was typically the responsibility of the men (Table 5-9), possibly increasing their access to information about marketing and crop suggestions from vendors.

Valuing Groundwater

Much of consideration of agricultural management alternatives for Wargal is focused on groundwater sustainability, meaning the assurance of sufficient groundwater quantity indefinitely. For a more complete analysis of the possible management options, beyond hydrology (Chapter 4) and simple economic estimates (Chapter 5), the present and future values of groundwater resources should be estimated to assist in decision-making about groundwater management. While uncertainties in policy, climate change, and national and global economies make future value estimates highly uncertain, it is plausible that groundwater in the Wargal area will be much more valuable in the future. Groundwater valuation must always be based on the context (NRC, 1997), meaning that the value of the service provided by groundwater should be quantified for each situation. There are both in situ and extractive services provided by groundwater. In situ services are generally more difficult to quantify in terms of economic value; these services include subsidence avoidance, saltwater intrusion prevention, recreational flow maintenance, and provision of water supply buffer. Extractive services include municipal, industrial, and agricultural supply; these are usually easier to value. In contexts like that of Wargal, where groundwater services are almost entirely irrigation of agricultural areas, valuation is based largely on incomes from sale of irrigated crops. No quantitative estimate of present or future value of the groundwater resource was made here due to the large uncertainties in aquifer thickness and irrigated crop values. However, groundwater valuation in Wargal would be an important extension of the research presented here.

Economics of Alternative Agricultural Management

There are important economic impacts – at the household level and at the regional and national levels – of changing agricultural management. Household level impacts are estimated here based on predicted yield changes and expected prices for different management scenarios. While there are predicted improvements in the groundwater balance resulting from shifting some rice croplands to rainfed crops, there is likely much greater variability in yield (and income) from rainfed areas. This is a substantial obstacle for growers and water managers concerned with the future of groundwater resources in India. There are 3 policy options that could contribute to the implementation of management changes that show promise for improving the groundwater balance. One option would be to change the minimum support price (MSP) structure; lowering the MSP of rice and increasing the MSPs of popularly grown rainfed crops could lead to the required rice cropland reductions. MSP is an Indian national agricultural policy to set the lowest prices that producers receive for farm yields. The MSP system is administered by a variety of commodity-specific, public organizations. Similarly to the MSP adjustments, if rainfed or less-irrigated grains were offered as rations, through India's Public Distribution System, to low-income families instead of rice (or instead of a portion of the rice), this could increase the demand for rainfed or less-irrigated grains. A third option may be to subsidize equipment for TR tillage. Plows that are tractor or animal drawn can create the ridges and ties for water harvesting tillage in rainfed croplands.

To evaluate the expected economic impacts of selected management alternatives, estimates of the total watershed-scale value of crop yields were made for existing management and for the leading 7 management scenarios using average observed yields, cropland areas, MSPs for 2009-2010 (Tables 5-10 and 5-11). As described in Chapter 4, the leading 7 management scenarios were selected from the 25 alternatives based on (1) participation of growers in the area (constraints on labor, preferences for rice cultivation, little interest in alternative rainfed crops (Chapter 5), (2) the groundwater balance results (Chapter 4), and (3) consideration of yield variability and risk. A literature review of yield response to tied-ridge (TR) tillage was completed (Table 5-10) to estimate the expected yield increase in rainfed areas where TR was simulated (MDS: 15-50 mm). Based on the review of 9 studies of yield response to TR, excluding yield increases greater than 100%, the average increase in yield was 27.4%. To be conservative in estimates of yield increase in Wargal, a 13% increase was used as the estimated change in yield for rainfed crops under TR. For simulated scenarios having 25% reduced rice irrigation depths in kharif and rabi seasons, rice yields were estimated to decrease by 25%. For simulated scenarios having 25% reduced rice irrigation depths only in rabi season, rice yields were estimated to decrease by 15%. For simulated scenarios having irrigated corn in rabi season, corn yields were estimated to increase by 25%. With these estimates of yield changes, the cropland areas from each management scenario, and the crop values from MSP data, the watershed-scale values of existing and leading 7 management scenarios were calculated (Table 5-12). Surprisingly, the mds50_kharif scenario, TR tillage of MDS=50 mm in kharif corn and cotton, was found to be the most valuable ($351,021), followed closely by existing management ($342,234). While there is an unknown amount of uncertainty in the estimates of yield changes, these estimates do seem reasonable and are consistent with the literature. Water harvesting tillage was shown to have positive impacts both on the groundwater balance and on the economic yields of the Wargal watershed.

Discussion and Summary of Fieldwork on the Socioeconomics of Agricultural Management

Some investigators have suggested that the groundwater socio-ecology in Asia, and particularly in India, is at a critical point. The progression of groundwater use in agriculture has been organized into four stages (Shah et al., 2003): expansion of borewell installations, groundwater-based agrarian boom, onset of groundwater depletion concerns, and collapse of groundwater-based systems. Observations (from groundwater level measurements and local household perceptions) in Wargal suggest that this area is in stage three of the progression: groundwater depletion is an observed and growing concern. The data from interviews with farmers of Wargal suggests that farm management decisions in Wargal do consider this, but farmers are understandably still trying to maximize their groundwater irrigated areas.

For Wargal residents to have sufficient groundwater resources for domestic and agricultural needs in the future, they will likely need to implement changes in the way farming systems are managed. The types and extent of changes can begin to be answered from the results of the water balance simulations experiments (Chapter 4). Considering this context, the main findings of this initial assessment of social and gender issues related to farm management decision-making in the area are summarized:

- Groundwater availability is a concern for many people in the study area; of all their concerns in the community it ranks in the middle (for both men of women) in terms of frequency of responses from participants. If the four stages of the progression of groundwater-based agrarian societies are correct, the stage that follows the current one (observation of depleted groundwater) is a rapid decline in productivity and livelihood security. It seems now may be an important time for finding the best ways to increase productivity, yet require the least groundwater-based irrigation.

- Households have observed groundwater depletion by noticing more failed drilling attempts and more intermittent, lower pressure flow from borewells. If substantial management changes are achieved which reduce groundwater withdrawals, these means of measurement will be important indicators to farmers of the increased availability of groundwater. Without any preemptive management changes, local methods of groundwater measurement will require management changes to reduce groundwater use, but there would likely be a period of high vulnerability as local people adjust to the very limited availability of groundwater. Data from farmer participation suggests more women than men attribute the cause of groundwater depletion to increased borewells, so it may be that women are more amenable than men to adopt management alternatives which reduce dependence on borewells.

- For both men and women, water availability was the information most commonly used to make decisions about crop selection. Concerning irrigation management: a common response was that irrigation timing and depth depended mostly on electricity supply (if power is on, irrigation happens); this supply-side management perspective may be part of the reason for groundwater depletion in the area. It was almost exclusively the responsibility of men to control borewell pumps, but participants indicated that both men and women were involved in deciding when to turn pumps on or off.

Efforts to find combinations of management options that are most promising for improving groundwater levels, while still maintaining economic viability of farms, have focused on the improvement and use of water balance simulation tools (Chapter 4). Water balance simulations have been used to estimate changes in the groundwater balance (recharge – estimated irrigation withdrawals) in response to changes in rice cropland extent, tillage, and irrigation management. It is hoped that field trials of the management options most likely to improve groundwater quantity (based on simulations) will be initiated. The participation of local farmers in development of management scenarios has resulted in more relevant and sustainable management scenarios being considered, and therefore, a greater chance for successful on-farm implementation of management recommendations.

Table 5-1. Concerns of community members ranked (for women) in order of decreasing frequency of reporting

Issues most concerning to participants	Women % of total responses	Men	Women rank of concern	Men
No local higher education	59	0	1	10
Bus routes are limited into Wargal	55	0	2	10
Limited power for irrigation	41	50	3	2
Water quality for drinking in homes	41	3	3	9
Limited service at healthcare clinic; no staffed doctor	41	3	3	10
Less groundwater, failed bores, water availability	31	28	4	5
Vulnerability due to irregular rains	28	9	4	7
Seed is expensive and not reliable	14	34	5	3
No available non-farm work	14	31	5	4
Lack of affordable fertilizer	10	59	6	1
Labor availability/rising cost of labor	10	22	6	6
Less land, more children	10	0	6	10
Total number of participants	29	32		

Table 5-2. Ways of observing groundwater depletion

Methods of observing groundwater decline	Women % of total responses	Men
Failed drilling attempts	71	20
Time of continuous flow, pressure of flow visually noted	57	80
Not observed	10	20
Total number of participants	21	15

Table 5-3. Perceived causes of local groundwater depletion

Suggested causes of groundwater decline	Women % of total responses	Men
Less rain	58	75
More borewells	83	50
Total number of participants	24	12

Table 5-4. Suggested reasons for recent reductions in local rainfall amounts

Reasons for observed changes in rainfall	Women % of total responses	Men
gods, more population, people doing bad things	86	63
Less greenery (forest plantations logged; trees around croplands cut)	3	26
Unknown	10	32
Total number of participants	29	12

Table 5-5. Information used to decide about crop selection: ranked (greatest to least – women's column) percentages of responses

Decision information: crop selection	Women % of total responses	Men
Observe water availability	81	80
Talk with family	65	50
Talk with neighbors	38	40
Market price information	8	30
Personal experience	0	45
Total number of participants	26	20

Table 5-6. Information used to decide about irrigation management: ranked (greatest to least – women's column) percentages of responses

Decision information: irrigation timing and depth	Women % of total responses	Men
Observing plants, soil	85	77
Irrigate when power is on; occasional shutoff if sufficient rain	40	62
Rainfall depth and timing	30	23
Keeping 3 inches of water in rice fields	0	15
Total number of participants	20	13

Figure 5-1. Some women take a break for lunch and to participate in discussions for this research

Figure 5-2. One of six water harvesting structures (tanks) in the Wargal watershed used for increasing groundwater recharge

Table 5-7. Decision category and associated most important responses

Decision type or responsibility	Dominant response Women	 Men
crop selection	observe water availability	observe water availability
irrigation management	observe plants, soil	observe plants, soil; irrigation if electricity is on
rice cropland extent	1/8 to 1/4 of cropland	1/8 to 1/4 of cropland
rice crop replacement if insufficient water	cover crop, fallow	cotton
pump responsibility	men	men

Table 5-8. Percentages of responses concerning who is responsible for irrigation pump control

Responsibility for borewell pump control	Women % of total responses	Men
Men; women only if man is unavailable	100	100
Women	0	0
Total number of participants	19	8

Table 5-9. Percentages of responses concerning who is responsible for purchase farm inputs (seed and fertilizer)

Responsibility for purchasing of farm inputs	Women % of total responses	Men
Men; women only if man is unavailable	100	100
Women	0	0
Total number of participants	10	6

Table 5-10. Literature review of yield increase for selected crops in response to tied-ridge tillage; methods are measured yield (obs) or simulated yield (sim)

Crop	Location	% yield increase	Methods	Reference
corn	Nebraska	12	obs	Duley, 1960
sorghum	Kansas	17	obs	Luebs, 1962
sorghum	Kansas	22	obs	Musick, 1981
cotton	Texas	32	obs	Gerard et al., 1983a
sorghum	Texas	33	obs	Gerard et al., 1984
cotton	Texas	36	obs	Clark, 1983
sorghum	Texas	40	sim	Krishna et al., 1987
sorghum	Texas	104	obs	Gerard et al., 1983b
sorghum	Texas	176	obs	Jones and Clark, 1987

Table 5-11. Yields of crops commonly grown in Wargal based on household surveys and state agency data. Sample size indicates number of households that responded to surveys about yield data. Value ($/kg) based on 2009-2010 government of India minimum support prices (MSP)

	Corn	Cotton	Rice	Potato	Sunflower	Green bean
yield: kg/ha	1936	398	2866	5389	917	2047
sample size	19	5	11	9	3	11
value: $/kg	0.188	0.617	0.213	0.186	0.497	0.448

Table 5-12. Groundwater balances (mm) and estimated values (USD) of the selected top seven management scenarios (Chapter 4)

	Annual values, watershed scale	
Management scenario	GW balance, mm	USD, $
red_rice_irr,k,r,25	38.2	304,770
red_rice_k-corn,r-irr-corn,25: mds33_kharif	36.1	339,998
red_rice_k,r,25	34.3	335,593
red_rice_irr,k,25: mds33_kharif	31.3	337,433
red_rice_k-corn,r-irr-corn,25	18.5	329,358
red_rice_irr,k,25	18.0	328,646
mds50_kharif	6.0	351,021
existing	-10.9	342,234

CHAPTER 6
LIMITATIONS, APPLICATIONS, AND CONCLUSIONS OF THE WARGAL STUDY OF GROUNDWATER DEPLETION AND AGRICULTURAL MANAGMENT

Limitations

The simplified groundwater balance is one weakness of this study; extending this research to more explicitly represent groundwater flow in three dimensions would certainly add valuable information. This would allow changes in water table elevation to be predicted with more certainty than the one dimensional estimates used here based on observed specific yield. Increased groundwater monitoring would be required to model flow across the watershed boundaries, and more certain information on the hydraulic properties of the aquifer system would need to be observed.

Increased field-scale water balance data would have improved confidence in SWAT's predictive abilities. There are a variety of challenges when working in a "new" watershed having no previous initiatives or instrumentation. It was a limitation of this research to have few hydrologic observations available to calibrate and evaluate SWAT. Observations of soil moisture, field-scale runoff, and reservoir areas/volumes of the other five reservoirs would have added to the quality of the water balance modeling.

The preliminary fieldwork to learn about decision-making and management of farmers in Wargal was not designed and completed in a way that allowed for any quantitative or any rigorous qualitative findings. While there was a lot of important information that was learned (this enriched the project and made the modeled scenarios more realistic), an improvement in the depth of the socio-economic analysis would add a lot to this work. A better understanding of: (1) agricultural policy and farmers' ideas about changes in policy, (2) the ability/willingness of farmers to change tillage strategy (detailed cost and labor information), and (3) the preferred alternatives to rice croplands.

Applications

This research should add to a growing body of evidence that extent of rice croplands in some parts of India is beyond what is sustainable for long term supply of groundwater resources. Agricultural policy changes to reduce support for rice cultivation or to favor rainfed crops may be required to manage groundwater depletion. It is not meant to suggest here that there is something inherently unsustainable about flooded rice cultivation, only that the extent should be carefully managed.

This research provides an improved method of describing tillage management using an expanded form of Green-Ampt infiltration that includes a time-varying surface storage depth. This change is supported by the theoretical foundations of Green-Ampt and by detailed sensitivity analyses (Chapter 3). SWAT was modified to include the modified infiltration description and was used to simulate management alternatives for the Wargal area, demonstrating the significance of tillage management in a way that was previously unavailable in SWAT (and other landscape hydrology models). SWAT is a very widely used water balance simulation tool, and the modified form developed and used here can be useful in numerous other applications.

Another application of this research is to increase the consideration of tillage management for increasing groundwater recharge. Water harvesting tillage is not effective in all systems, particularly in soils having very low hydraulic conductivity, but this research has demonstrated that water harvesting tillage can make moderate increases in groundwater recharge. Surface water storage through tillage may become a more important management factor, especially given evidence of increasing rainfall variability, in areas where groundwater depletion is a concern.

Conclusions

This research of the Wargal watershed in peninsular India is a case study of the causes and possible solutions to groundwater depletion in India. In Chapter 1, the national and state-level data on rice production in India and the field-scale water balances of rice croplands gave strong indications that the extent and management of rice croplands is likely a significant contributor to groundwater depletion. Chapter 1 also highlighted the importance of improving simulation tools for making predictions about the hydrologic impacts of management changes in ungauged basins.

In Chapter 2, the rainfall IDF analysis, together with the literature on changing rainfall character, showed that rainfall patterns are likely becoming more episodic in the Wargal region, leading to a lower proportion of rainfall contributing to infiltration and recharge. The application being that surface storage will become a more important management concern for agronomic and groundwater recharge improvements.

The sensitivity analyses of Chapter 3 compared the importance of the 5 parameters used for Green-Ampt infiltration predictions, finding that the parameter describing tillage-induced surface storage (MDS) was important (2^{nd} only to effective hydraulic conductivity) for infiltration predictions in areas under water harvesting tillage. MDS is usually neglected or only included in a surface water balance for Green-Ampt infiltration, and it was shown in Chapter 3 that MDS should be included both in the water balance and in the Green-Ampt equations to improve infiltration predictions for areas having water harvesting tillage.

In Chapter 4, the improved infiltration equations were implemented in SWAT to evaluate tillage for increasing groundwater recharge in Wargal. It was found that tillage was indeed effective at increasing recharge, changing the annual groundwater balance from -11 mm (existing management, 535 mm recharge) to 6 mm (MDS=50 mm in kharif rainfed crops, 552 mm recharge) with water harvesting tillage applied in the rainfed croplands during kharif/rainy season (41% of the watershed area). For watersheds with more extensive rainfed areas, this suggests that water harvesting tillage could have even more significant improvements to the groundwater balance. Also in Chapter 4, small reductions (25%) in rice cropland irrigation or areal extent shifted the groundwater balance from negative to positive, increasing the evidence that the extent and management of rice croplands is a probable contributor to groundwater depletion.

Chapter 5 recounted the participation of growers in Wargal, reporting on the information used in decision-making, preferred agricultural management, and major concerns in the community. Groundwater depletion was a common concern of participants. Estimates of watershed-scale economic yield were made to compare existing and the most promising alternative management scenarios. These estimates showed the possible economic gains associated with water-harvesting tillage and the probable losses associated with reduced rice cropland extent or irrigation.

The participation of farmers from the study area during the early stages of the design of this research has substantially improved this research. The problem of groundwater depletion was verified by farmers in Wargal. The management scenarios for water balance simulations were developed with consideration of farmers' constraints (labor, capital) and management preferences (rainfed and irrigated crops that work best for them). This combination of hydrologic and socio-economic sciences has the potential to improve the adoptability of management recommendations. The cooperation of farmers in learning about water resource availability and decision-making for farm management improves the relationship between scientists and stakeholders; this may mean that farmers would be more open to on-farm trials of alternative management.

It could be said that groundwater depletion in India is a self-regulating problem: declining water tables will naturally lead to less groundwater withdrawal as it becomes more expensive and less predictable to pump groundwater from greater depths. This is of course true, but without any early management changes there are serious costs associated with allowing the groundwater resource to reach the stage of self-regulation. Depleted hard rock aquifers can have serious fluoride and arsenic contamination, and the loss of a reliable water source for irrigation during droughts and dry spells can lead to much more vulnerable agricultural systems.

So what is the solution to groundwater depletion in agricultural areas of India? The silver bullet is an idiomatic expression describing something that is completely effective at resolving some kind of problem, and as is often the case in any type of search for the best management practices, there is no silver bullet agricultural management for groundwater depletion in Wargal. There is no technology or single management option that is clear leader in reducing or reversing groundwater depletion. It could be argued that groundwater depletion in Wargal (and in numerous regions like Wargal) has socio-economic roots; agricultural systems have become established that depend heavily on irrigation from groundwater sources. Groundwater has supported booms in the agricultural economies of Asia, and it will continue to be an important resource for irrigation. However, the risks associated with reduced irrigation from groundwater (more yield variability) should somehow be compared to the risks of a severely depleted groundwater system (water quality, possible complete loss of irrigation source).

While groundwater depletion has socio-economic causes and solutions, part of those solutions will be technological and managerial. It was shown in Chapter 4 that are several combinations of alternative management options that show promise for improving groundwater supply. Expanding the use of water harvesting tillage and reducing rice cropland extent or irrigation depths are two options that considerably improved the groundwater balance. The required extents of these changes, in order to make substantial groundwater balance improvements (Chapter 4), can be useful quantities for evaluating these management options in other regions where groundwater depletion is a problem.

APPENDIX A
SWAT CODE MODIFICATIONS

Changes to the following 22 subroutines of SWAT were required to correctly operationalize the modified GAML infiltration. Please contact the author for the source code or for details about the code changes. It is expected that the next official SWAT release will include these modified routines (Arnold, 2010):

- surq_greenampt.f
- etact.f
- irrsub.f
- newtillmix.f
- readtill.f
- surface.f
- volq.f
- simulate.f
- operaten.f
- readhru.f
- rchday.f
- rchmon.f
- readmgt.f
- subbasin.f
- resetlu.f
- readlup.f
- watbal.f
- zero0.f
- header.f
- allocate_parms.f
- modparm.f
- parm.mod

The complete, modified subroutine for SWAT GAML infiltration is included below. Other subroutines requiring major changes were those for evapotranspiration (etact.f), irrigation (irrsub.f), and tillage (newtillmix.f and readtill.f).

```
      subroutine surq_greenampt

!!    ~ ~ ~ PURPOSE ~ ~ ~
!!    Predicts daily runoff given breakpoint precipitation and snow melt
!!    using the Green & Ampt technique

!!    ~ ~ ~ INCOMING VARIABLES ~ ~ ~
!!    name        |units         |definition
!!    ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
!!    cnday(:)    |none          |curve number for current day, HRU and at
!!                               |current soil moisture
!!    idt         |minutes       |length of time step used to report
!!                               |precipitation data for sub-daily modeling
!!    ihru        |none          |HRU number
!!    iyr         |year          |year being simulated (eg 1980)
!!    mds(:)      |mm H2O        |maximum depression storage for HRU
!!    nstep       |none          |max number of time steps per day
!!    newrti(:)   |mm/hr         |infiltration rate for last time step from the
!!                               |previous day
!!    nstep       |none          |number of rainfall time steps for day
!!    precipdt(:) |mm H2O        |precipitation for the time step during day
!!    sol_k(1,:)  |mm/hr         |saturated hydraulic conductivity of 1st soil
!!                               |layer
!!    sol_por(:,:)|none          |total porosity of soil layer expressed as a
!!                               |fraction of the total volume
!!    sol_sumfc(:)|mm H2O        |amount of water held in the soil profile
!!                               |at field capacity
!!    sol_sw(:)   |mm H2O        |amount of water stored in soil profile on
!!                               |any given day
!!    swtrg(:)    |none          |rainfall event flag:
!!                               |  0: no rainfall event over midnight
!!                               |  1: rainfall event over midnight
!!    wfsh(:)     |mm            |average capillary suction at wetting front
!!    ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

!!    ~ ~ ~ OUTGOING VARIABLES ~ ~ ~
!!    name        |units         |definition
!!    ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
!!    h_depth(:,:)|mm H2O        |surface storage depth for time step
!!    h_day(:)    |mm H2O        |end of day or daily surface storage depth
!!                               |in HRU
!!    hhqday(:)   |mm H2O        |surface runoff generated each hour of day
!!                               |in HRU
!!    newrti(:)   |mm/hr         |infiltration rate for last time step from the
!!                               |previous day
!!    surfq(:)    |mm H2O        |surface runoff for the day in HRU
```

```
!!    swtrg(:)    |none          |rainfall event flag:
!!                              |  0: no rainfall event over midnight
!!                              |  1: rainfall event over midnight
!!    ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

!!    ~ ~ ~ LOCAL DEFINITIONS ~ ~ ~
!!    name        |units         |definition
!!    ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
!!    adj_hc      |mm/hr         |adjusted hydraulic conductivity
!!    cuminf(:)   |mm H2O        |cumulative infiltration for day
!!    cumr(:)     |mm H2O        |cumulative rainfall for day
!!    df(:)       |mm H2O        |incremental infiltration for time step
!!    dthet       |mm/mm         |initial moisture deficit
!!    excum(:)    |mm H2O        |cumulative runoff for day
!!    exinc(:)    |mm H2O        |runoff for time step
!!    incro(:)    |mm H2O        |incremental actual runoff for time step
!!                               |accounting for surface storage for time step
!!    f1          |mm H2O        |test value for cumulative infiltration
!!    j           |none          |HRU number
!!    k           |none          |counter
!!    kk          |hour          |hour of day in which runoff is generated
!!    psidt       |mm            |suction at wetting front*initial moisture
!!                               |deficit
!!    rateinf(:)  |mm/hr         |infiltration rate for time step
!!    rintns(:)   |mm/hr         |rainfall intensity
!!    soilw       |mm H2O        |amount of water in soil profile
!!    tst         |mm H2O        |test value for cumulative infiltration
!!    ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

!!    ~ ~ ~ SUBROUTINES/FUNCTIONS CALLED ~ ~ ~
!!    Intrinsic: Sum, Exp, Real, Mod

!!    ~ ~ ~ ~ ~ ~ END SPECIFICATIONS ~ ~ ~ ~ ~ ~


      use parm

      integer :: j, k, kk
      real :: adj_hc, dthet, soilw, psidt, tst, f1
      real, dimension (nstep+1) :: cumr, cuminf, excum, exinc, rateinf
      real, dimension (nstep+1) :: rintns, df, incro


        !! array location #1 is for last time step of prev day

      j = 0
```

```
    j = ihru


!! reset values for day
    cumr = 0.
    cuminf = 0.
    excum = 0.
    exinc = 0.
    rateinf = 0.
    rintns = 0.
    ro = 0.
    incro = 0.

      !! h_depth from last time step of previous day is
      !! is already defined as initial h for current day
      !! at the end of this routine

      if (h_day(j) >= 0.) then
    h_depth(j,1) = h_day(j)
  end if

      !! calculate effective hydraulic conductivity
      adj_hc = 0.
      !! calculate effective hydraulic conductivity as half of saturated
  !! conductivity to remove CN from calculations for sensitivity analysis
 adj_hc = (56.82 * sol_k(1,j) ** 0.286) /
  &                    (1. + 0.051 * Exp(0.062 * cnday(j))) - 2.
    if (adj_hc <= 0.) adj_hc = 0.001

  !! adj_hc = sol_k(1,j) * 0.5
      !! if (adj_hc <= 0.) adj_hc = 0.001


      dthet = 0.
      if (swtrg(j) == 1) then
        swtrg(j) = 0
        dthet = 0.001 * sol_por(1,j) * 0.95
        rateinf(1) = newrti(j)
        newrti(j) = 0.
      else
        soilw = 0.
        if (sol_sw(j) >= sol_sumfc(j)) then
          soilw = 0.999 * sol_sumfc(j)
        else
          soilw = sol_sw(j)
        end if
```

```
        dthet = (1. - soilw / sol_sumfc(j)) * sol_por(1,j) * 0.95
        rateinf(1) = 2000.
      end if

      psidt = 0.
      psidt = dthet * wfsh(j)

      k = 1
      rintns(1) = 60. * precipdt(2) / Real(idt)
!       if (j == 1) write(126,5002) k, precipdt(1), cumr(1), rintns(1), &
!     &            rateinf(1), cuminf(1), excum(1), exinc(1)
      do k = 2, nstep+1
        !! calculate total amount of rainfall during day for time step
        !! and rainfall intensity for time step
        cumr(k) = cumr(k-1) + precipdt(k)
        rintns(k) = 60. * precipdt(k+1) / Real(idt)

        !! if rainfall intensity is less than infiltration rate
        !! everything will infiltrate
        if (rateinf(k-1) >= rintns(k-1).and.h_depth(j, k-1)==0.)  then
          cuminf(k) = cuminf(k-1) + rintns(k-1) * Real(idt) / 60.
          if (excum(k-1) > 0.) then
            excum(k) = excum(k-1)
            exinc(k) = 0.
          else
            excum(k) = 0.
            exinc(k) = 0.
          end if
        else


           !! if rainfall intensity is greater than infiltration rate
    !! or if h_depth > 0
        !! find cumulative infiltration for time step by successive
        !! substitution
          tst = 0.
          tst = adj_hc * Real(idt) / 60.
          do
            f1 = 0.
                     f1 = cuminf(k-1) + adj_hc * Real(idt) / 60. +
           (psidt + dthet*h_depth(j, k-1)) *     Log((tst + psidt + dthet*h_depth(j, k-1)) /
           (cuminf(k-1) + psidt + dthet*h_depth(j, k-1)))


            if (Abs(f1 - tst) <= 0.001) then
              cuminf(k) = f1
```

```
      !! Calculate the actual surface storage, h_depth,
      !! according to a parameterized mds; limit h_depth to mds
      !! Calculate the actual runoff for the time step as
      !! incro = h_depth (before mds constraint) - mds
              df(k) = cuminf(k) - cuminf(k-1)
              h_depth(j, k) = h_depth(j, k-1) + precipdt(k) - df(k)
              if (h_depth(j, k) < 1.e-6) then
                h_depth(j, k) = 0.
              end if
                 ! if (h_depth(j, k) > mds(j)) then
    if (h_depth(j, k) > mds(j)) then
            ! incro(k) = h_depth(j, k) - mds(j)
     incro(k) = h_depth(j, k) - mds(j)
          h_depth(j, k) = mds(j)
        end if


      !! Calculate cumulative runoff, excum(k), for the day as the sum
      !! of previous step RO, excum(k-1), and RO for current time step, incro(k)
                excum(k) = excum(k-1) + incro(k)
        exinc(k) = excum(k) - excum(k-1)
        if (exinc(k) < 0.) exinc(k) = 0.
        kk = 0
        kk = (k - 1) * idt
        if (Mod(kk,60) == 0) then
          kk = kk / 60
        else
          kk = 1 + kk / 60
        end if
        hhqday(kk) = hhqday(kk) + exinc(k)
        surfq(j) = surfq(j) + exinc(k)
        exit
      else
        tst = 0.
        tst = f1
      end if

     end do
    end if

    !! calculate new rate of infiltration
          rateinf(k) = adj_hc * ((psidt + h_depth(j, k)*dthet) /
&        (cuminf(k) + 1.e-6) + 1)
      !         if (j == 1) write(126,5002) k, precipdt(k, cumr(k), rintns(k),&
```

```
        !    &            rateinf(k), cuminf(k), excum(k), exinc(k)
      end do

        !! define h_depth for first time step of following day and define daily
h_depth, h_day
        !! as the same as h for last time step of previous day
        h_depth(j, 1) = h_depth(j, nstep+1)
        h_day(j) = h_depth(j, nstep+1)

      if (Sum(precipdt) > 12.) then
        swtrg(j) = 1
        newrti(j) = rateinf(nstep)
      end if


     return


 5000 format(//,'Excess rainfall calculation for day ',i3,' of year ',  &
    &       i4,' for sub-basin',i4,'.',/)
 5001 format(t2,'Time',t9,'Incremental',t22,'Cumulative',t35,'Rainfall',&
    &      t45,'Infiltration',t59,'Cumulative',t71,'Cumulative',t82,  &
    &      'Incremental',/,t2,'Step',t10,'Rainfall',t23,'Rainfall',   &
    &      t35,'Intensity',t49,'Rate',t58,'Infiltration',t73,'Runoff',&
    &      t84,'Runoff',/,t12,'(mm)',t25,'(mm)',t36,'(mm/h)',t48,     &
    &      '(mm/h)',t62,'(mm)',t74,'(mm)',t85,'(mm)',/)
 5002 format(i5,t12,f5.2,t24,f6.2,t36,f6.2,t47,f7.2,t61,f6.2,t73,f6.2,  &
    &      t84,f6.2)
     end
```

APPENDIX B
INTERVIEW QUESTIONS FOR WARGAL FARMERS

The following questions were used as a general guide for interviews with farmers in Wargal. Questions were sometimes asked differently, as the interviews became better adapted to the phrasing of questions that would be most easily understood by participants. Grouping of questions into themes of main concerns, groundwater and rainfall changes, management and decision making, and general questions was done simply for organizational purposes. Questions were asked to individuals and to groups. In group settings, all participants were asked to respond separately. While responses in groups could be expected to differ from those of individuals, no distinction in responses (between individual alone or in a group) was made in the results shown (Chapter 5).

Main concerns

What problems are most concerning about life in Wargal? What things would you most like to see improved about your life?

Perceptions on groundwater and rainfall changes

Have groundwater levels been changing?

If yes, how is this observed? What is the cause of groundwater decline? Is anything done to increase groundwater supply?

Have you noticed changes in rainfall?

If yes, what kinds of changes? What do you think caused the changes in rainfall?

How is rainfall measured/observed?

Management and decision making

How do you decide what to grow on your farm? Who makes the decisions? What information helps with this decision?

How much of your cropland is in paddy each year? Why do you grow this?

What would you grow in place of paddy if there was not enough water for this crop?

Have you considered crops ICRISAT promotes? (millet, sorghum, pigeon pea)

How are fields tilled, planted, weeded, harvested? Who does these operations?

How do droughts and dry spells affect crop selection, tillage, irrigation?

Who makes decisions about drought mitigation strategies?

How do you decide when to irrigate and how much to irrigate?

Who irrigates or who turns pump on and off?

What changes in management would increase water availability?

Who buys farm inputs like seed and fertilizer?

General questions

How often does the government ag. Dept./extension come to talk to you?

Do you visit the local progressive farmer/s?

Are you on subsidized rations?

Are you a member of a SHG or is someone in your household a member?

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BIOGRAPHICAL SKETCH

Daniel Dourte was born in Harrisburg, Pennsylvania. Pursuing an undergraduate degree in mechanical engineering, he studied at Rochester Institute of Technology and Messiah College. He graduated 2004 with a B.S. in mechanical engineering from Messiah College. Working on assistive devices for persons with disabilities resulted in two trips to Burkina Faso in 2004 and 2005. Interactions with farmers there inspired an interest in agriculture and water management.

To test this interest and start the process of learning about farming systems, Daniel worked for vegetable farm in Hustontown, Pennsylvania as an irrigation and crop manager. In the spring of 2006, he started a Master of Engineering program in agricultural and biological engineering at the University of Florida. In this program he performed water balance experiments to measure crop water use of mature southern highbush blueberries. A planning trip to several areas in India in January 2008 began his work on groundwater depletion in India. The results of his work in India have provided an improved hydrology model (SWAT), a demonstration of the importance of surface storage for infiltration predictions, and an assessment of agricultural management alternatives for groundwater sustainability.

Daniel has been married to Natalie Dourte for 3 years, and they have a 1 year old daughter, Aubrey. Daniel volunteers as a vegetable garden instructor at Howard Bishop Middle School and is an active vegetable gardener at home. He rides his bike instead of driving as often as possible and enjoys all kinds of exercise. Daniel enjoys international travel and it is a goal of his to be involved in agricultural development and water management in the global South.