groundwater

Opportunities to Build Groundwater Resilience in the Semi-Arid Tropics

by Kaushal K. Garg[1] and Suhas P. Wani[2]

Abstract

Agricultural water management (AWM) is the adaptation strategy for increasing agricultural production through enhancing water resources availability while maintaining ecosystem services. This study characterizes groundwater hydrology in the Kothapally agricultural watershed, in hard rock Deccan plateau area in India and assesses the impact of AWM interventions on groundwater recharge using a calibrated and validated hydrological model, SWAT, in combination with observed water table data in 62 geo-referenced open wells. Kothapally receives, on average, 750 mm rainfall (nearly 90% of annual rainfall) during the monsoon season (June to October). Water balance showed that 72% of total rainfall was converted as evapotranspiration (ET), 16% was stored in aquifer, and 8% exported as runoff from the watershed boundary with AWM interventions. Nearly 60% of the runoff harvested by AWM interventions recharged shallow aquifers and rest of the 40% increased ET. Water harvesting structures (WHS) contributed 2.5 m additional head in open wells, whereas hydraulic head under natural condition was 3.5 m, resulting in total 6 m rise in water table during the monsoon. At the field scale, WHSs recharged open wells at a 200 to 400 m spatial scale.

Introduction

Fresh water availability for producing a balanced food diet for an increasing population with changing food choices and increasing income is an important concern. Total cultivable land in India is 142 million ha with a cropping intensity [number of crops grown per unit (ha) of land in a year multiplied by hundred] of 135%. Groundwater and surface water sources irrigate about 27 and 21 million ha of agricultural lands, respectively (nearly 40% of total cultivable land) and rest of the cultivable area is rainfed. The Green Revolution during the 1970s along with advanced technology of water pumping made a significant impact on groundwater use: the number of bore-wells increased from less than one million during 1960s to 20 million by 2009 in India (Dewandel et al. 2010). As a result, groundwater withdrawals escalated from less than 25 km^3 in the 1960s to 250 to 300 km^3 in 2008 (Shah 2009), which is several times higher than withdrawals of any other developed and developing country in the world (Shah 2009). During this development process, groundwater use enhanced food production in the country but in many of the Indian states/regions there was a decline in groundwater sustainability. Reliable source of water availability for the end users, minimizing risk of crop failure, crop intensification, and better economic returns were the main drivers motivating the farmers to over-extract large-scale groundwater resources.

Degradation of agroecosystems and declining groundwater sustainability are major concerns for agricultural development in many poor regions of India where rural livelihoods depend directly on management of land and water resources (Rockström et al. 2004; Reddy et al. 2007; Wani et al. 2011a, 2011b). The volcanic hard rock

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aquifer in peninsular India is characterized by low-storage capacity and poor specific yield (0.01 to 0.03), and is subjected to poor groundwater recharge due to low rainfall and high evapotranspiration (ET) demands (Maréchal et al. 2006; Rao et al. 2006; Shah 2009). Development of various agricultural water management (AWM) interventions plays a significant role in building resilience in rural areas of the semi-arid tropics of India (Wani et al. 2012). There is increasing evidence that integrated watershed management programs have strengthened the social capital and significantly impacted groundwater recharge and other ecosystem services for human well-being (Kerr et al. 2002; Joshi et al. 2005; Barron 2009; Garg et al. 2011a, 2011b; Wani et al. 2011b). With this realization, the Indian collaborative (Government of India, National Institutes, Extension services, NGOs, and farming community) initiative of watershed management program has evolved since the 1970s (Wani et al. 2008).

Several previous studies have characterized hard rock aquifers, analyzed water balance at watershed and basin scale, and estimated groundwater recharge in peninsular India (e.g., Murthy et al. 2001; Maréchal et al. 2006; Saha and Agarwal 2006; Subrahmanyam and Khan 2007; Dewandel et al. 2010). However, few attempted to quantify the impact of AWM interventions on groundwater recharge and ecosystem trade-offs (Glendenning et al. 2012). Glendenning et al. (2012) described that some field studies described positive impact of AWM interventions at field and village scale (e.g., Rockström 2000; Barron 2009; Vohland and Barry 2009; Rockström et al. 2010; Wani et al. 2011a), while other studies indicated negative impacts at the watershed scale (e.g., Sharma and Thakur 2007; Bouma et al. 2011). They concluded that watershed scale analysis is under represented in field studies and is mainly approached through modeling. Most of these modeling studies examining AWM impact either have limited focus or had insufficient data (Glendenning et al. 2012). Thus, there is an urgent need to develop new modeling tools in combination with increased field data collection (Glendenning et al. 2012). Further, the impact of positioning of water harvesting structures (WHS) on well recharge is not well understood and this affected the impacts of watershed management programs in the country.

Long-term experiments (1975 to 2012) of ICRISAT showed that implementation of soil and water conservation practices and integrated nutrient management produced average crop yield 5.1 tons/ha/year (sorghum/pigeonpea intercropping) compared to 1.1 tons/ha/year (sole sorghum) with farmer's practices (Wani et al. 2003, 2011b). For scaling-out same technology in farmers' field, ICRISAT consortium with national partners, local NGOs, and farmers started watershed development program in Kothapally village of Musi sub-basin in 1999 (Figure 1). The Kothapally watershed was facing severe water scarcity; crop yields were low and 80% area was under single cropping till 1998 (Wani and Shiferaw 2005). Groundwater table was poor and several wells were drying-up soon after the monsoon period. A range of AWM initiatives have been adopted at community and individual farm levels. These include, check dams and low-cost gully control structures built on the primary drains, secondary drains, and river stream, open well recharging by diverting silt-free runoff water (ex situ interventions), and in situ interventions, such as contour and field bunds (soil mounds) in farmers' fields.

Here, we present the results from a study of the Kothapally watershed, which represents a typical semi-arid micro-watershed developed by adopting a science-led farmer-participatory consortium approach (Wani et al. 2002, 2003). The specific objectives of this study are: (1) to describe groundwater hydrology in hard rock agricultural watershed; (2) to partition total groundwater recharge into natural recharge and WHS stimulated recharge; and (3) to analyze positioning of WHS and its impact on groundwater recharge in open/dug wells.

Study Area

The Kothapally watershed is located at 17°22′N latitude and 78°07′E longitude, and about 550 m above mean sea level in Ranga Reddy district of Andhra Pradesh, India. This watershed is part of the Musi sub-basin of the Krishna River basin, and is situated approximately 25 km upstream of the Osman Sagar reservoir (Figure 1). The geographical land area of the Kothapally village (administrative boundary) is 465 ha. The hydrological delineated micro-watershed of Kothapally used for this study encompasses 293 ha. The climate of the catchment is tropical monsoonal preceded by hot summers (minimum air temperature between 16 °C and 29 °C; maximum air temperature between 30 °C and 43 °C in May) and followed by cool winters (minimum air temperature between 6 °C and 20 °C; maximum air temperature between 23 °C and 32 °C in December), and an average annual rainfall of 800 mm (standard deviation, $\sigma = 225$ mm). About 80% to 85% of the rainfall is received during June to October. However, rainfall is highly erratic, both in terms of total amount and distribution over time.

About 90% of the area in Kothapally watershed is under cultivation during monsoon, of which 30% to 40% are under full or supplemental irrigation during some part of the year using available groundwater. Average land-holding per household is about 1.4 ha. There is no further potential for agricultural expansion, but only for intensification on existing land. Cotton is the dominating crop grown during June to December (included monsoon period) and is followed by sorghum, chickpea, or vegetables. Farmers with irrigation facilities provide life saving irrigation to cotton crop usually after end of the monsoon period (between November and December). The amount of irrigation and frequency are decided based on farmers' access to groundwater.

Soils in the Kothapally watershed are Vertisols reaching soil depth of 50 to 900 mm. The water holding capacity is medium to low (150 to 200 mm), and the soil organic carbon content is between 0.44% and 2.27% (Table 1). The geology of the study area (Upper Musi catchment) is dominated by hard rocks of Archaen granite

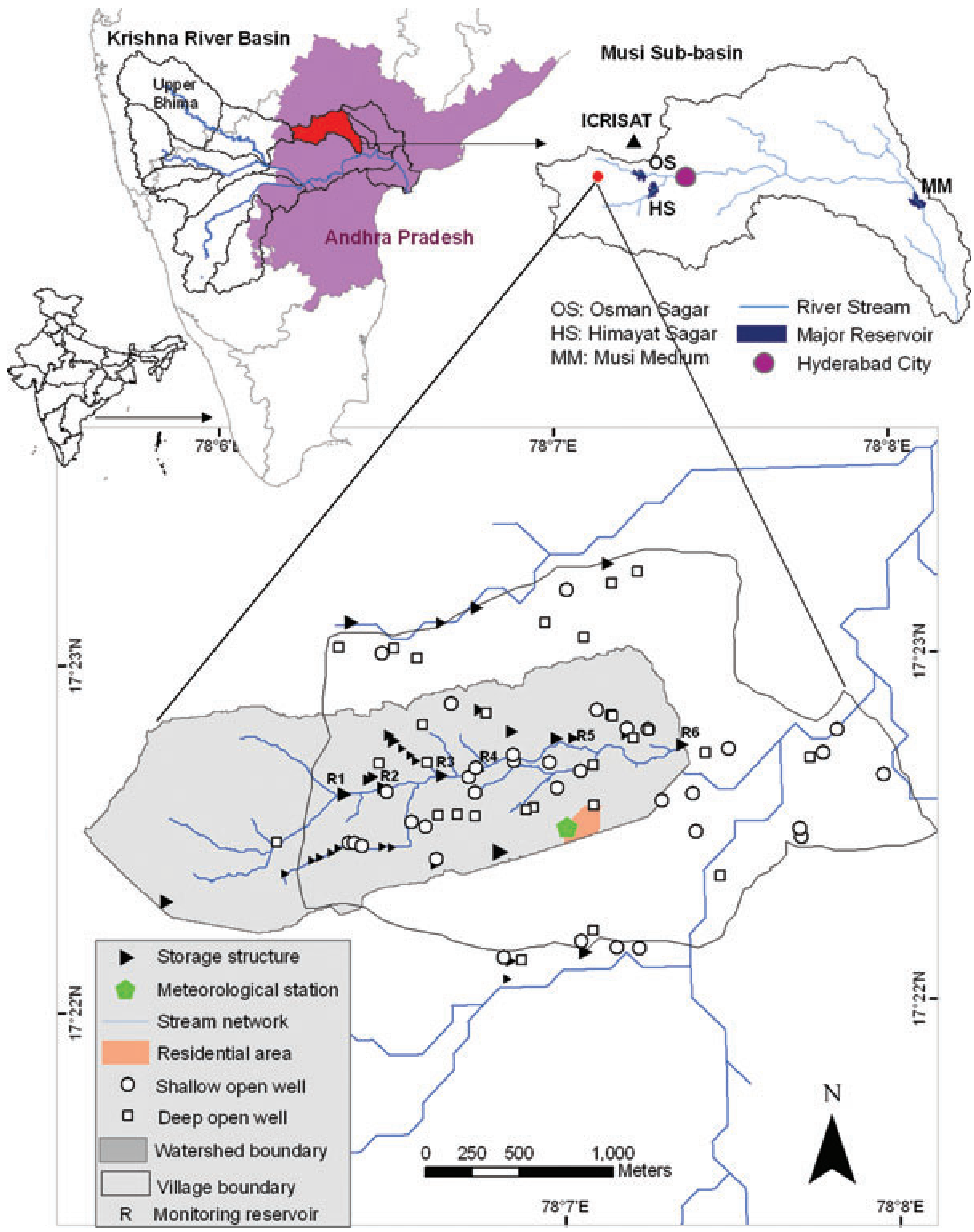

Figure 1. Location of Kothapally watershed in Musi sub-basin of Krishna river basin, including main reservoirs, ICRISAT, and Hyderabad City; and zoomed-in inset map shows stream network, location of storage structures, shallow and deep open wells, meteorological station, residential area, hydrological boundary, and village boundary of Kothapally watershed.

and gneiss (Biggs et al. 2008), and aquifers are either unconfined or perched, having poor storage capacity (specific yield ~2% to 3%; EPTRI and NGRI 2005; Massuel et al. 2007; Garg et al. 2011b). These aquifers were derived primarily from deep weathering and form a multilayered system (Massuel et al. 2007). Characteristics of weathered layers in this regions, from top to bottom, were explained by Maréchal et al. (2004, 2006):

- Unconsolidated weathered mantle, Saprolite (a clay-rich material) derived through prolonged weathering of bedrocks in top 8 to 10 m has high porosity and low permeability.
- An intermediate fractured layer (~10 to 30 m), generally characterized by dense horizontal fissuring with fracture density decreasing with increasing aquifer depth. This layer characterized the transmissive function of the aquifer and is tapped by most of the wells drilled in the region.
- Relatively impermeable basement at 25 and 30 m depth, locally permeable if fractures are present.

Kothapally watershed is located at an upstream part of Musi sub-basin and no bigger river stream is intersecting or crossing near the village. Thus, probability of groundwater recharge, especially in shallow fractured zone from outside the watershed boundary is minimal. High level of groundwater pumping in this region is leading to sharp decline in water table (EPTRI and NGRI 2005). The average rate of groundwater depletion in

Table 1
Soil Physical Properties of Kothapally Watershed

Parameters[1]	Average Value (Range)[2]
Sand content (%)	47 (18–79)
Silt content (%)	22 (11–30)
Clay content (%)	31 (5–61)
Gravel fraction (%)	20 (5–48)
Bulk density (g/cm^3)	1.3 (1.1–1.6)
Available water content (mm H_2O/mm soil)	0.26 (0.17–0.33)
Organic carbon (%)	1.04 (0.44–2.27)
Soil depth (mm)	420 (50–900)
Hydraulic conductivity of the reservoir (WHS, mm/h)	4.0–20.0

[1]Data are based on 43 soil samples collected across the watershed.
[2]Values in the parenthesis indicate maximum to minimum range.

Musi river basin is estimated at 18 cm/year indicating overexploitation of groundwater resources (Massuel et al. 2007).

Methodology

Data Monitoring and Analysis

Kothapally watershed has been monitored heavily in terms of hydrology (surface runoff and groundwater table data), weather (daily rainfall, maximum and minimum temperatures, solar radiation, wind speed, and relative humidity), crop yields, and its inhabitants' since beginning of the watershed interventions from 1999 onwards. More specifically about groundwater data, the water table in 62 geo-referenced open wells is monitored at monthly intervals (Figure 1). Depth of monitored wells ranged between 8 and 20 m with an average depth of 11 m. Diameter or width of the majority of dug wells is 4 to 6 m, but may be as high as 15 to 20 m. Water in these wells is being used for agriculture and domestic purpose.

Water table fluctuation (WTF) method is a well accepted suitable technique for estimating groundwater recharge in hard-rock regions (Sharda et al. 2006; Dewandel et al. 2010; Glendenning and Vervoort 2010). Groundwater recharge in Kothapally watershed is estimated between 2000 and 2010. Water balance captured by WTF method is defined by mass balance equation such as:

$$\begin{aligned}\text{Net groundwater recharge} = {} & (\text{change inhydraulic}\\ & \text{head before and after monsoon}) \times \text{specific yield}\\ & + \text{water withdrawal during monsoon period}\\ & + \text{underlying deep drainage}\\ & + \text{evaporation losses from water table} \qquad (1)\end{aligned}$$

Model Set Up and Calibration

Long-term hydrological and climatic data are used to parameterize watershed hydrology using a semi-process-based model, Soil and Water Assessment Tool (SWAT). SWAT is a well recognized model for predicting water flows, sediment loss, and nutrient balances in complex watershed with varying soils, land use, and management conditions (Arnold et al. 1998; Srinivasan et al. 1998; Arnold and Fohrer 2005; Gassman et al. 2007). SWAT requires three basic layer files for delineating the watershed into subwatersheds: a digital elevation model (DEM), a soil map, and a land use/land cover (LULC) map. A detailed DEM of 10 × 10 m^2 resolution was developed from a topographic survey using a Nikon total station (DTM-851, Nikon Geotecs Co., Ltd., Tokyo, Japan) survey instrument, by taking 4252 survey observations (elevation shot) covering the entire watershed. The total watershed area has been divided into 110 subunits for study purpose. Soil samples on every 250 m grid were collected (total 43 samples) for analysis of soil physical properties and based on the results, the soil map was prepared. Locations of check dams and water storage structures (Figure 1) were identified using a Global Positioning System and their surface areas and storage volumes were measured. The year of construction and other salient features (i.e., surface area and total storage capacity) of WHS were provided as inputs into the model. The crop pattern in Kothapally is dominated by cotton (covering 80% to 90% agricultural land) which is planted in June and harvested in December; therefore, same crop is simulated into the model. Subwatersheds having open wells were considered for irrigation and aquifer is assigned as source of the water into the SWAT setup; the rest of the area was considered rainfed. A second crop, tomato, was grown only in irrigated fields. The model was calibrated for the Kothapally watershed based on discharge at the watershed outlet and water volume at six reservoir locations (Figure 1), and then validated using groundwater (water table) data. Discharge data were available for 53 runoff events monitored between 2002 and 2007 at the watershed outlet. The water level in reservoirs was monitored daily at six different locations between June and November 2009, and later converted into dam water volumes. Description of SWAT model setup, calibration, and validation process is detailed by Garg et al. (2011b).

Calibrated SWAT setup represented "AWM intervention stage" of the Kothapally watershed. The calibrated and validated SWAT was further used to develop "no intervention stage" (prewatershed development before 1999) scenario. A number of parameters related to surface runoff and water retention were modified (based on literature review and data collected from long-term strategic research at ICRISAT watersheds) in SWAT setup to represent "no intervention stage." For example, "curve number" values of subwatersheds were reduced by 5 to 6 units (Arabi et al. 2007, 2008; Ullrich and Volk 2009). Manning's roughness coefficient was changed from 0.14 to 0.05 as suggested by Neitsch et al. (2005) for unmanaged land. Similarly, all the check dams and reservoirs were excluded from the model setup to capture the watershed hydrology under "no intervention stage" and model was run for 11-year period between 2000 and 2010. Simulated results are analyzed to estimate groundwater recharge under "no intervention" (prewatershed development before 1999) and with AWM interventions (current status). This analysis provides water balance and groundwater recharge for the entire watershed. Still, recharge in specific wells induced through various WHS is not clear due to several model limitations. SWAT has limitation in simulating groundwater flow from one sub-basin to other sub-basin, because it is a semi-distributed model. Moreover, SWAT assumes unlimited water storages capacity of aquifer system which is less relevant especially of hard-rock aquifer which usually have poor specific yield and limited storage capacity.

Positioning and Capacity of WHS on Well Recharge

In order to capture the impact of positioning and capacity of WHS on groundwater recharge in open/dug wells, empirical relationship was developed considering topographical and physical parameters, such as storage capacity of structures, distance between storage structure and well location, and elevation difference between storage structure and well bottom (indicating hydraulic gradients) that control the recharge process. Locations of WHSs were identified and their storage capacity was measured during field surveys. In total, 35 WHSs containing 50 to 5000 m^3 of water storage were recorded in Kothapally, which created 45 m^3/ha of storage space in the watershed on average (Figure 1). Distance between different wells and WHSs was calculated using the "spatial analyst" tool in Arc-GIS. The DEM was used to calculate relative elevations of different WHSs and physical bottom of the open wells.

Before developing an empirical relationship, change in hydraulic head from pre- to postmonsoon period in open wells is partitioned: recharge contributed through natural recharge and due to WHS. Results obtained from no intervention scenarios were used to estimate well recharge under the natural condition. Simulated groundwater recharge at different well locations was converted into pressure head (H_{NI}) by considering specific yield 2%. Pressure head which was estimated for no intervention condition (H_{NI}) was subtracted from the pressure head measured in current situation (represents AWM intervention; H_{AWM}) to calculate WHS induced groundwater recharge (O) as shown in Equation 2.

$$O = H_{\mathrm{AWM}} - H_{\mathrm{NI}} \tag{2}$$

A simple empirical model is developed to capture positing and capacity of WHS on well recharge such as:

$$\mathrm{RW}_i = P \sum_{j=1}^{j=n} \frac{a Z_{\mathrm{diff}}\, V^b}{D^c} \tag{3}$$

In Equation 3, RW is the hydraulic head in an open well due to WHS induced recharge (m); i is the well number; j is the structure number; P is the rainfall (m); Z_{diff} is the elevation difference of WHS and well bottom (m); V is the capacity of WHS (m^3); D is the horizontal distance between WHS and well location (m); and a, b, and c are the empirical constants. These constants were estimated through "solver" program, an excel-based optimization tool. Objective functions are defined as below:

$$\min f(Z_{\mathrm{diff},} V, D) = \sum_{i=1}^{i=p} (\mathrm{RW}_i - O_i)^2 \tag{4}$$

Results

Groundwater Recharge and Water Table Response

Data on hydraulic head in open wells recorded on monthly time scale between 2000 and 2011 covered wide range of weather generated variability. For example, the total amount of rainfall received during the monsoon period in the years 2000 to 2011 varied between 440 and 1100 mm with average value of 750 mm (σ = 225 mm). In addition, the maximum rainfall intensity varied from 40 to 300 mm/d, the latter figure representing an extreme event. Fluctuations of hydraulic head in open wells recorded at monthly intervals are depicted in Figure 2. On an average, 4.5 m difference in hydraulic head (difference in water table) is recorded in open wells before and after monsoon period.

In the present study, deep water movement from shallow to underlying layers (>20 to 25 m) was considered negligible as storage capacity and recharge rate significantly declined with increasing aquifer depth (Maréchal et al. 2006). Amount of groundwater extraction during monsoon period was minimal except during dry spells and critical crop growth stages. Based on ground survey, 30% of the farmers in Kothapally had provided on an average two irrigations each of 30 to 40 mm during the monsoon period. This irrigation is equivalent to 30 mm of groundwater extraction from the entire watershed area. Irrigation

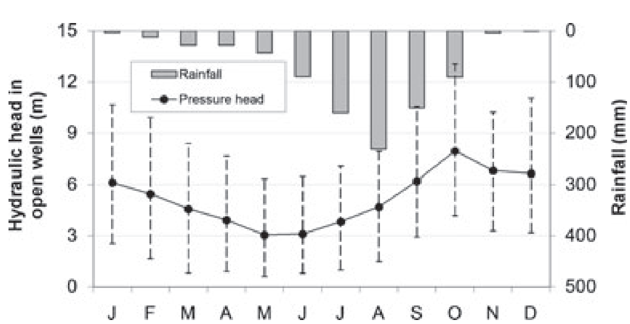

Figure 2. Fluctuation of hydraulic head in relation to rainfall received on a monthly time scale. Smooth line in figure represents average pressure head, whereas error bar indicates the variation (maximum to minimum range) within 62 open wells.

return flow is considered negligible. Evaporation from the groundwater table was calculated as 5 mm/year using Coudrain-Ribstein et al. (1998) depth−evaporation relationship. Thus average annual groundwater recharge for 2000 to 2011 was calculated as 125 mm/year or 16% of total rainfall (4.5 m × 0.02 + 30 mm + 5 mm).

Measured water table data in Kothapally show that groundwater availability (water levels in well) differed from year to year depending on variability in rainfall intensity and distribution. Water availability at the end of monsoon was dependent on two main components: (1) carry-over groundwater reserves from the pervious years and (2) groundwater recharge in current year. Table 2 shows groundwater balance for selected dry, normal, and wet years in Kothapally watershed. Groundwater balance in 2004 (normal year), 2005 (wet year), and 2006 (dry year), illustrated that groundwater recharge mainly took place during June to October and was negligible during rest of the year. Total groundwater recharge of 111 mm and extraction of 115 mm in 2004 was estimated. Thus, groundwater use for agriculture was found comparable to total recharge in a normal year. Groundwater recharge in a wet year was found significantly higher than the total extraction. About 58 mm of water was withdrawn for agriculture as against 136 mm of total recharge, which left over 78 mm surplus water in aquifers during 2005. Because of water stress condition, water requirements in 2006 increased which resulted in high water extraction from groundwater reserves. Groundwater recharge in 2006 was only 57 mm but groundwater withdrawal was calculated as 169 mm, which resulted in a declined water table.

Groundwater recharge in relation to cumulative rainfall presented for a selected normal year (2009) showed that over 300 to 400 mm of rainfall during the monsoon was required to cause a rise in water table of 1 m (Figure 3). Results from SWAT modeling showed that a large fraction of monsoonal rain was captured by soil layers initially and lost through evaporation and plant transpiration. After saturating the soil moisture profile, surplus water percolated down and recharged groundwater.

Water availability at the beginning of the monsoon, defined in terms of total number of wells that dried up was strongly correlated with total rainfall in previous year (Figure 4). For example, drying status of wells in May 2005 will be dependent on rainfall amount and variability between June and October 2004. The results showed that poor rainfall in any one or more preceding years limited refilling of the aquifer and affected groundwater availability in the following year resulting in drying-up of more shallow open wells. Similar results of more shallow open wells drying up after preceding low-rainfall years at larger river basin scale in Upper Bhima catchment of 46,000 km^2 of hard rock region have been reported earlier by Pavelic et al. (2012).

Within a given year, hydraulic head in open wells depended on well depth (Figure 5a). Figure 5b depicts location of shallow (well depth = 11 m, depicted with circle) and deep wells (well depth = >11 m, depicted with square symbol). Along the stream network well density was higher as compared to the watershed boundary or from elevated region (Figure 5b). Surface runoff which is generated from the watershed gets accumulated in the streams together and recharges shallow aquifers.

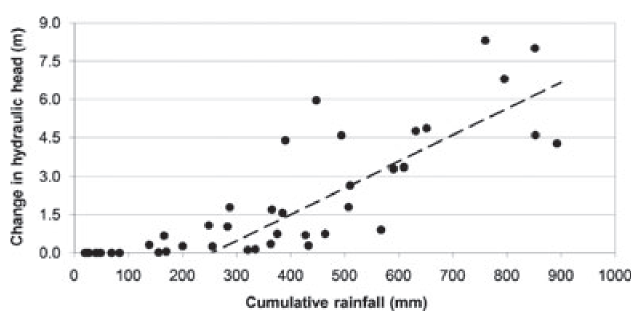

Figure 3. Groundwater recharge vs. cumulative rainfall in Kothapally watershed.

Table 2
Groundwater Balance in Kothapally Watershed in Selected Dry, Normal, and Wet Years

	Normal Year (2004)			Wet Year (2005)			Dry Year (2006)			
Parameters[1]	**Jun–Oct**	**Nov–May**	**Total**	**Jun–Oct**	**Nov–May**	**Total**	**Jun–Oct**	**Nov–May**	**Total**	**Data Source**
Rainfall (mm)	649	60	709	872	214	1086	436	39	475	Measured
ΔWT (m)	3.4	−3.6	−0.2	4.3	−0.4	3.9	0.1	−5.7	−5.6	Measured
Q_{use} (mm)	43	76	119	30	28	58	55	114	169	Simulated
Groundwater (GW) recharge (mm)	111	4	115	116	20	136	57	0	57	Estimated using Equation 1
ΔS (mm)	68	−64	−4	86	−8	78	2	−114	−112	Estimated using Equation 1

[1]Groundwater balance equation is defined as: GWrecharge + $Q_{in} = Q_{out} + Q_{use} + \Delta S$; Q_{in} and Q_{out} are the groundwater flows across the watershed boundaries, considered negligible; ΔWT is the change in water table; ΔS is the change in groundwater storage; specific yield of aquifer is considered as 2%.

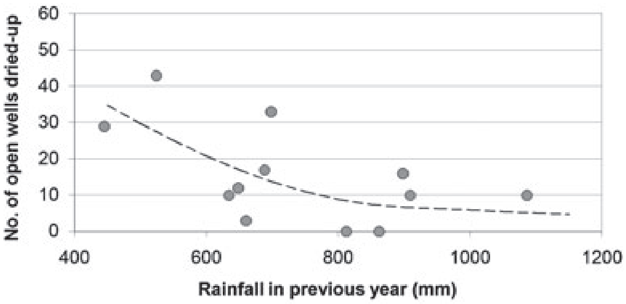

Figure 4. Number of open wells that dried at the beginning of monsoon period in relation to rainfall in previous year (data from 2000 to 2011).

The number of times shallow and deep wells dried-up during the 11-year study period is represented by color intensity in Figure 5b. Deeper wells dried-up less often compared to shallow ones. Water in deep wells was usually available throughout the year. Groundwater withdrawal and naturally generated base flow during non-monsoon period were the main causes for lowering water table and frequent drying up of shallow wells. Dewandel et al. (2010) described vertical distribution of storage capacity in one of the hard rock watersheds of southern India and found drastic reduction in fissures density after 17 to 20 m depth. This indicates that an impermeable layer starts roughly at 20 m depth. Recharge rates however, are low in hard rock areas but water moves slowly up to weathered zone through seepage and accumulates above the impermeable layer. Thus, shallow open wells are highly prone to drying up compared to deeper wells.

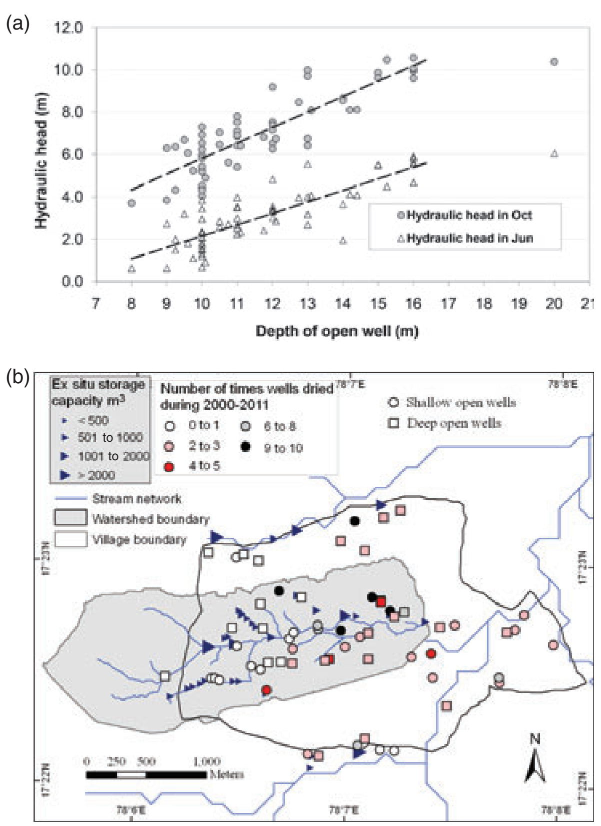

Figure 5. (a) Dug/open well depth vs. hydraulic head in June (before monsoon) and October (postmonsoon period) month. (b) Number of times wells (shallow and deep) dried up and their spatial distribution in Kothapally watershed.

SWAT Performance

Amount of discharge at watershed outlet is compared with simulated data on a daily time scale and shown by the scatter diagrams in Figure 6a. The performance of the model was assessed based on various statistical measures: coefficient of determination (R^2) and Nash–Suttcliffe efficiency (NSE) coefficient. The R^2 and NES coefficient for estimating flow was found to be 0.83 and 0.81, respectively. Similarly measured and simulated volume in reservoir at six selected locations was compared on a daily time scale (not shown). R^2 and root mean square error (RMSE) value at various locations were found to be in the range of 0.65 to 0.85 m^3 and 218 to 984 m^3, respectively. These RMSE values are equivalent to maximum at 20% storage capacity of reservoir volume (Garg et al. 2011b).

Calibrated and validated SWAT results showed a comparison of simulated groundwater availability (stored volume in aquifer) with observed water table on monthly time scale (Figure 6b). Rising water table indicates groundwater recharge, while a falling water table indicates

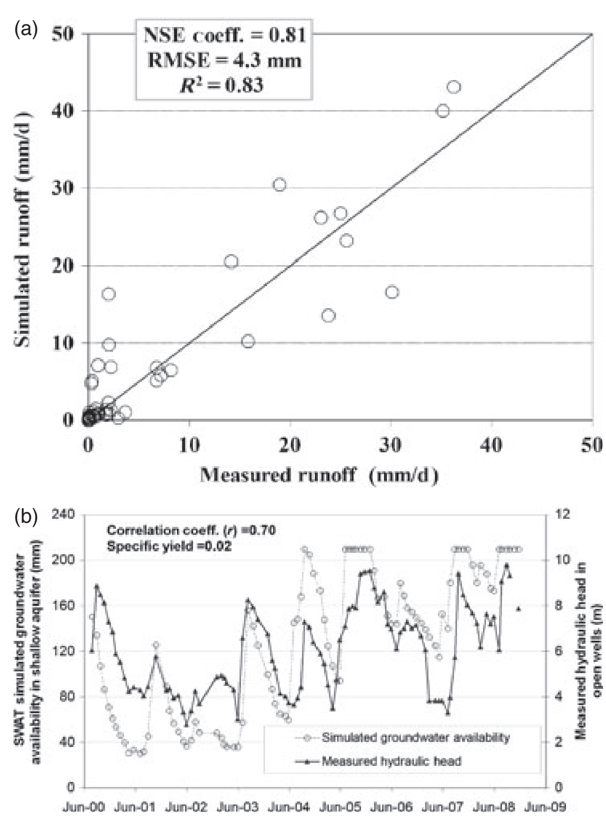

Figure 6. (a) Measured and simulated discharge at watershed outlet on a daily time-step for $n = 53$ events during 2002 and 2007. (b) A comparison of SWAT simulated groundwater availability with measured hydraulic head (average over 62 open wells) in Kothapally watershed in June during 2000 to 2009.

utilization during monsoon and postmonsoon periods. In general, simulated and observed data followed similar patterns (correlation coefficient, $r = 0.70$), suggesting that the model successfully captured both recharge and pumping (utilization) trends. In addition, it is found that simulated data in first few years are lower than observed values; however, after 2003 this trend found reversed (Figure 6b). SWAT considers a set of management practice and single LULC throughout the simulation period. In present modeling, we assumed that farmers those have wells are only cultivating postmonsoon crop, whereas in actual condition, with development of AWM interventions, farmers started water trading to neighboring farmers and irrigated area further expanded in subsequent years.

Impact of AWM Interventions on Watershed Hydrology and Groundwater Recharge

AWM interventions significantly changed the water balance components in the watershed (Table 3). Under the no intervention condition, approximately 68% (512 mm) of the rainfall was partitioned into ET, while approximately 9% (70 mm) recharged the aquifer and 19% (143 mm) was lost from the watershed boundary as runoff during the monsoon season. When the watershed development program was implemented (AWM Interventions)

Table 3
Monsoonal Water Balance of Kothapally Watershed Under Two Different Management Scenarios (Results from SWAT Simulations)

Hydrological Component	After AWM Interventions (Current Stage)	No Intervention (Before 1999)
Rainfall (mm)	750	750
Runoff (mm)	60 (8%)	143 (19%)
ET (mm)	540 (72%)	512 (68%)
Groundwater (GW) recharge (mm)	120 (16%)	70 (9%)
Balance closure (mm)	30 (4%)	25 (3%)

Water balance of a watershed is described as: Rainfall = Runoff + ET + GW recharge + Balance closure (other components such as change in soil moisture storages).

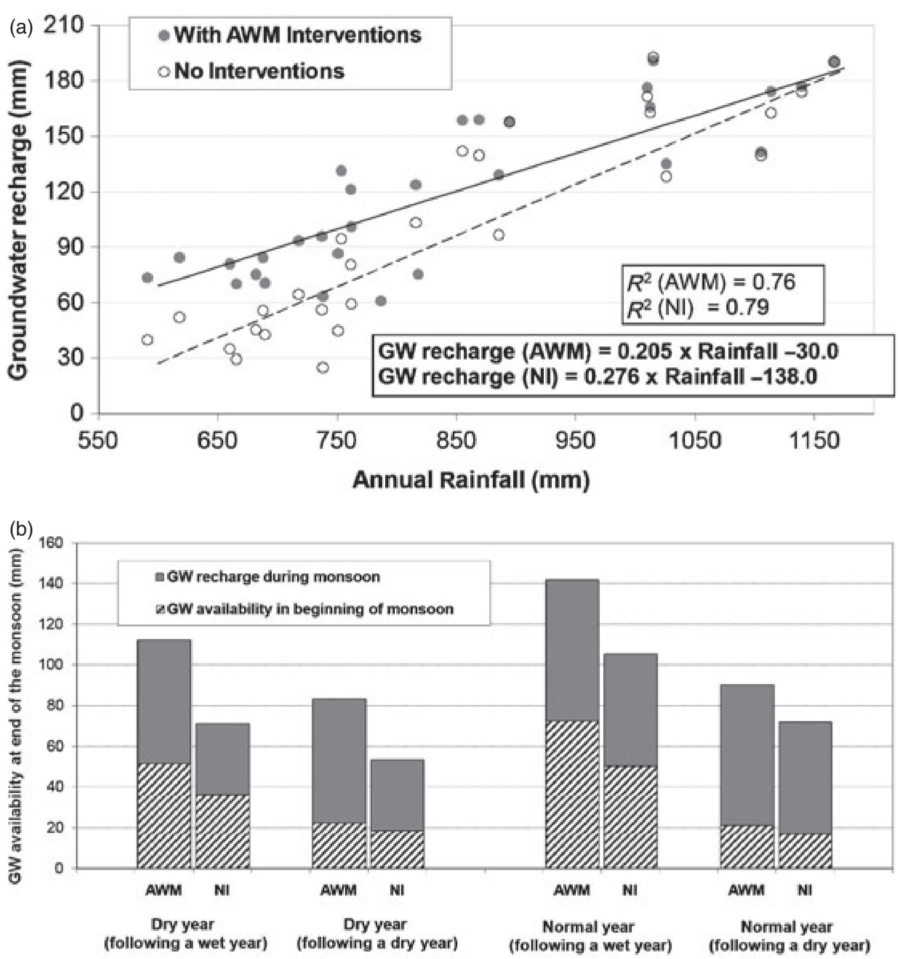

Figure 7. (a) Groundwater recharge in relation to monsoonal rainfall under no intervention (NI) and AWM intervention stage in Kothapally watershed. (The relationship is developed from SWAT generated results.) (b) Impact of AWM interventions on groundwater (GW) availability at the end of the monsoon period. AWM indicated GW availability with AWM practices, NI indicates GW availability with no interventions. (Result is developed from SWAT simulations.)

Table 4
Groundwater Recharge (R, mm/year) Estimated for Kothapally Watershed Using Recharge Relationships Developed in Previous Studies for Hard Rock Deccan Plateau of Southern India

GW Recharge Relationship	Estimated Kothapally Recharge[1] (mm)	Methodology Used/Model Used	Relationship Developed from/Study Area	Reference/Source
$R = 0.172\ P - 44$	85	Direct recharge estimated using tritium injection method	Granite and gneiss (Andhra Pradesh Southern, Central, and Northern India)	Rangarajan and Athavale (2000), Sukhija et al. (1996)
$R = 0.2507\ P - 105$	83	Based on water balance and groundwater budgeting	Semi-arid, hard rock (granite, gneiss, schist) regions, Maheshwaram watershed, Andhra Pradesh, Southern India	Dewandel et al. (2010)
$R = 0.094\ P$	71	MODFLOW hydrological modeling	Musi sub-basin, Krishna basin, Southern India (direct recharge)	Massuel et al. (2007)
$R = 0.17\ P$	128	MODFLOW hydrological modeling	Musi basin, Krishna basin, Southern India (direct recharge + artificial recharge + irrigation return flow)	Massuel et al. (2007)
$R_{\mathrm{NI}} = 0.276\ P - 138$	70	Based on water balance and SWAT modeling	Kothapally watershed (no intervention; before 1999)	Current study
$R_{\mathrm{AWM}} = 0.205\ P - 30$	125	WTF method and validated by SWAT modeling	Kothapally watershed (with AWM interventions; in current stage)	Current study

[1]Average monsoonal rainfall = 750 mm recorded during 2000 and 2011 in Kothapally watershed, where R is the total groundwater (GW) recharge; P is the rainfall received in monsoon period; R_{NI} is the recharge estimated in no intervention stage; and R_{AWM} is the recharge estimated with AWM intervention stage in current study.

the amount of water partitioned as ET increased to around 540 mm, equivalent to 72% of average rainfall in monsoon. Higher ET under AWM interventions indicated that 28 mm of additional rainfall was converted into soil moisture due to various in situ practices and useful for the plant uptake. Groundwater recharge was also higher (125 mm or 16%), while runoff from the watershed was less than 8% of the total water balance, that is, 60 mm or less than half of what it was before the interventions. Constructing WHS increased groundwater recharge, while reducing runoff. Results indicated that implementing AWM interventions are suitable adaptation strategies for addressing declining groundwater status in the semi-arid tropics. Nearly 60% harvested water by AWM (in situ and WHS) interventions recharged the shallow aquifer and rest 40% enhanced soil moisture and ET.

Groundwater recharge varied between years and with water management interventions (Figure 7a). A direct linear relationship was found between rainfall and groundwater recharge both for no interventions and AWM interventions stages which is represented by simple empirical equations as shown in Figure 7a and Table 4. Both simulated and observed data indicated that nearly 300 to 400 mm is the minimum threshold needed to begin recharge process. Recharge was 3- to 4-folds higher during wet years compared with dry years. With AWM interventions higher recharge was found especially in dry years (nearly double), but this difference in wet year was less significant.

Figure 7b shows impact of AWM interventions on water availability in dry and normal years. Further grouping dry and normal years following a wet year and following a dry year demonstrated carry-over storage which was found significantly higher following a wet year and this amount was further increased with AWM interventions in the watershed. AWM interventions helped in enhancing groundwater availability by recharging more water.

Positioning of Water Harvesting Structures on Well Recharge

The optimized constants of empirical relationship (Equation 2) were found as: $a = 0.33$, $b = 0.1$, and $c = 0.692$. The performance of the empirical equation was assessed (Figure 8a) based on sum of square (SSQ = 0.79 m) and coefficient of determination ($R^2 = 0.69$). The optimized equation suggested that water levels in wells are directly proportional to storage volume of WHS and their respective locations, and inversely proportional to distance from the source.

The storage capacity of WHS influenced recharge zone and WHS induced artificial recharge benefited wells

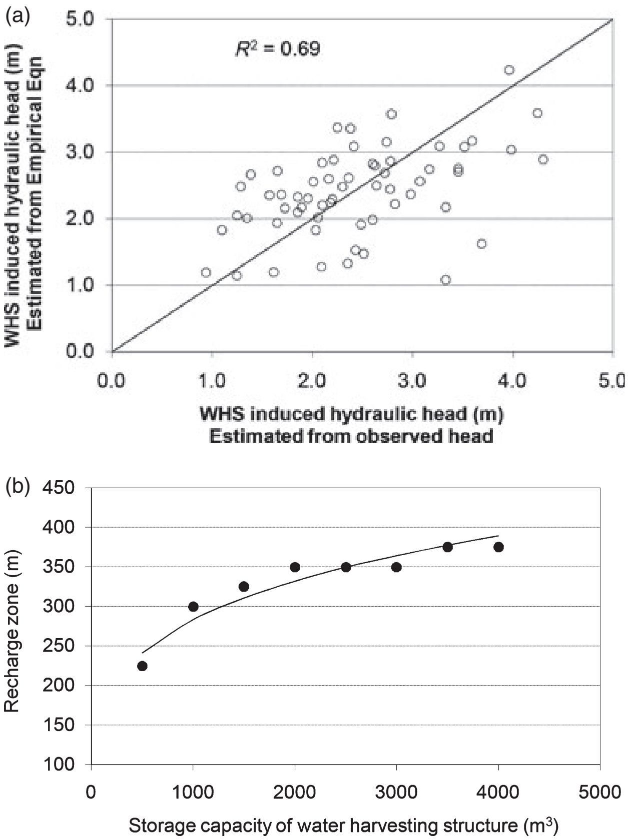

Figure 8. (a) Performance of empirical relationship. (b) Maximum distance benefiting dug/open wells by WHS in relation to their storage capacity.

located within 200 to 400 m radius (Figure 8b). Two or more WHS and their interaction further could expand the area of influence (not shown). Therefore, series of WHS constructed in Kothapally (shown in Figure 5b) resulted in 2.5 m rise in hydraulic head in wells in addition to the 3.5 m rise that is attributed to natural recharge. Moreover, wells located near the WHS benefited more in terms of rising water level compared to those located at further distance.

Discussion

Watershed interventions in agriculture in the forms of in situ and ex situ water harvesting systems are important for strengthening the groundwater resilience in the semi-arid tropics, which are the hot spots of poverty, water scarcity, and land degradation (Sophocleous 2000; Wani et al. 2002, 2003; Kendy and Bredehoeft 2006; Shiferaw and Rao 2006; Shiferaw et al. 2009; Garg et al. 2011b). Construction of WHS led to higher groundwater recharge, which enabled improved supplementary irrigation of the monsoon crop (in this case cotton). Higher groundwater levels expanded farmers' ability to grow fully irrigated second cash crop (normally vegetables) during the dry season, which made an important financial contribution to the household budget. Sreedevi et al. (2004) and Wani et al. (2002, 2003, 2006, 2011b) reported that water availability and crop yields were substantially improved after the watershed development program was implemented in Kothapally watershed. Since 1999, several shallow wells that were dry or had low-groundwater levels were reverted to active wells for irrigation (Figure 9). The cropping pattern has changed in recent years due to improved soil moisture availability and irrigation access. Farmers who cultivated traditional cotton varieties, sorghum, maize, and paddy before the onset of the watershed development program, have switched to cultivating higher yielding improved *Bacillus thuringiensis* cotton and high-value vegetable crops.

Rainfall-recharge relationship developed in earlier studies for hard rock Deccan plateau (Sukhija et al. 1996; Rangarajan and Athavale 2000; Massuel et al. 2007; Dewandel et al. 2010) were used for estimating groundwater recharge in Kothapally watershed and compared with current estimates (Table 4). Groundwater recharge estimated in current analysis for "no intervention" and AWM scenarios were similar to values reported by Massuel et al. (2007) and other researchers. Relationship developed by Massuel et al. (2007) estimated groundwater recharge (on an average basis) for Kothapally as 71 and 128 mm under "no intervention" and AWM scenarios compared to 70 and 125 mm in current analysis, respectively. Massuel et al. (2007) had developed groundwater recharge relationship using MODFLOW modeling in Musi sub-basin of Krishna river basin; and Kothapally is a part of this larger catchment located at most upstream position (Figure 1). In this comparison, the scales are different but hydrogeology is expected to be identical. Groundwater recharge in Kothapally calculated as described by some researchers (Sukhija et al. 1996; Rangarajan and Athavale 2000; Dewandel et al. 2010) was 80 to 85 mm, which probably represents an intermediate development stage of the landscape between "no intervention" and AWM interventions.

From a water management perspective, groundwater in hard rock aquifers has high-retention period and less evaporation losses than reservoirs or canals (Keller et al. 2000). Pavelic et al. (2012) explained average residence time between 1 and 4 years in the hard rock shallow aquifer (in Upper Bhima sub-basin of Krishna river basin; Figure 1). Evaporation losses from aquifer are estimated as 5 to 10 mm/year in semi-arid tropics (Coudrain-Ribstein et al. 1998; Dewandel et al. 2010). On the other hand, evaporation losses from surface reservoirs/dams are reported as 10% to 15% (e.g., Osman Sagar, Garg et al. 2012) and even higher up to 30% in Ujjani reservoir in Upper Bhima basin, Southern India (Garg et al. 2011a) of the inflow received.

With more erratic rainfall and weather generated uncertainty due to changing climatic situation, AWM interventions in India and elsewhere are essentially important for securing agricultural yields in upstream areas to achieve food security and improve livelihoods of small and marginal farmers. However, on the other hand, that may result in reduced water flows to downstream systems.

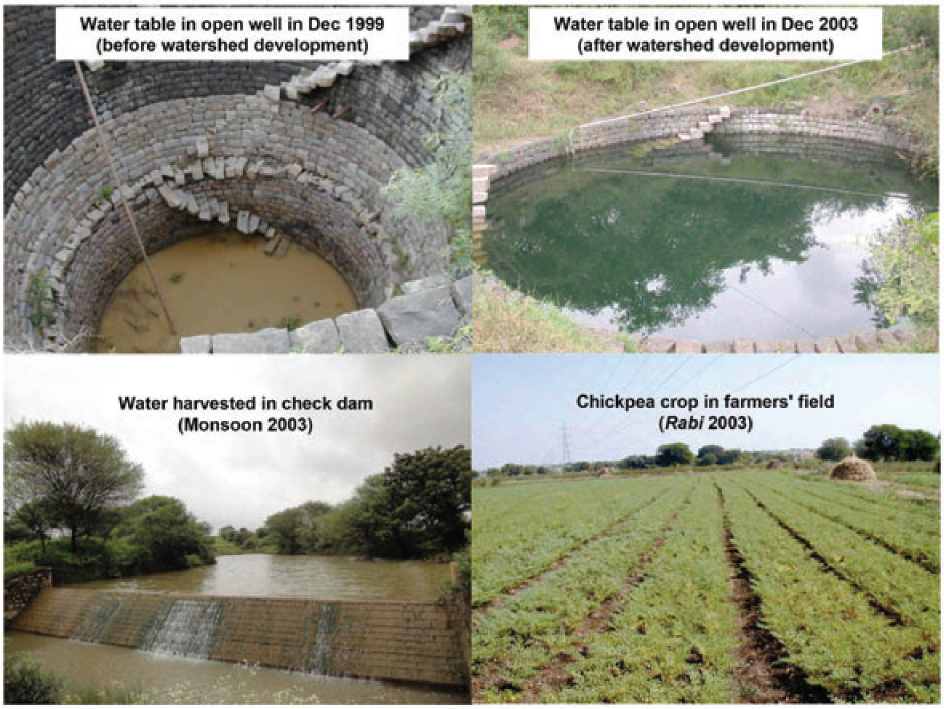

Figure 9. Impact of AWM interventions in Kothapally shown by groundwater table before and after interventions; selected well in picture is located near the check dam (nearly 50 m distance) which harvested runoff water during monsoon period; farmer is able to take chickpea as the second crop with supplemental irrigation.

High rainfall intensities may cause flooding and large sediment loads to downstream systems, which may partly be counteracted by better soil and water management practices carried out within the watershed development programs. It is important to clearly illustrate impacts and trade-offs in both upstream and downstream locations for different AWM interventions, accounting for changes in climate, water-related ecosystem services as well as the important goal of achieving food security and poverty alleviation in the developing tropical regions.

Conclusion

In this study, groundwater recharge in hard rock agriculture watershed was analyzed using field measurements in combination with hydrological modeling. The key findings of this study are:

1. Rainfall in the watershed ranged from 400 to 1100 mm, the majority of which occurred during June to October. AWM interventions changed the hydrological components as ET increased from 68% to 72%, runoff reduced from 19% to 8%, and groundwater recharge enhanced from 9% to 16% of rainfall received in monsoon as compared to no intervention stage. WHSs built in Kothapally resulted in 2.5 m additional recharge rise as that of under natural condition (only 3.5 m), thus resulting in total rise of 6 m in open wells.
2. Nearly 60% of harvested runoff by WHS recharged shallow aquifers and remaining 40% enhanced soil moisture and ET.
3. Groundwater availability in watersheds was highly dependent on carry-over storages from the previous years and recharge in the current year. Groundwater recharge was proportional to rainfall received during monsoon period. Moreover, 300 to 400 mm rainfall was the minimum threshold needed to begin recharge process effectively.
4. At the field scale, WHS influenced recharge zone benefited open/dug wells up to 200 and 400 m of spatial scale.
5. This study shows huge potential to build groundwater resilience by implementing AWM interventions in the semi-arid tropics.

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