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Impact of water management interventions on hydrology and ecosystem services in Garhkundar-Dabar watershed of Bundelkhand region, Central India

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SUMMARY

Bundelkhand region of Central India is a hot spot of water scarcity, land degradation, poverty and poor socio-economic status. Impacts of integrated watershed development (IWD) interventions on water balance and different ecosystem services are analyzed in one of the selected watershed of 850 ha in Bundelkhand region. Improved soil, water and crop management interventions in Garhkundar-Dabar (GKD) watershed of Bundelkhand region in India enhanced ET to 64% as compared to 58% in untreated (control) watershed receiving 815 mm annual average rainfall. Reduced storm flow (21% vs. 34%) along with increased base flow (4.5% vs. 1.2%) and groundwater recharge (11% vs. 7%) of total rainfall received were recorded in treated watershed as compared to untreated control watershed. Economic Water productivity and total income increased from 2.5 to 5.0 INR m^{-3} and 11,500 to 27,500 INR ha^{-1} yr^{-1} after implementing integrated watershed development interventions in GKD watershed, respectively. Moreover IWD interventions helped in reducing soil loss more than 50% compared to control watershed. The results demonstrated that integrated watershed management practices addressed issues of poverty in GKD watershed. Benefit to cost ratio of project interventions was found three and pay back period within four years suggest economic feasibility to scale-up IWD interventions in Bundelkhend region. Scaling-up of integrated watershed management in drought prone rainfed areas with enabling policy and institutional support is expected to promote equity and livelihood along with strengthening various ecosystem services, however, region-specific analysis is needed to assess trade-offs for downstream areas along with onsite impact.

1. Introduction

Fresh water availability for producing a balanced diet for an increasing human population is an important concern. India's agricultural land is 142 million ha with 135% cropping intensity (NAAS, 2009) and 60% is rainfed which is characterized by water scarcity, land degradation, low inputs use and low productivity. Agricultural productivity of these areas oscillates between 0.5 and 2.0 ton ha^{-1} with average of one ton per ha (Rockstrom et al., 2010; Wani et al., 2011a, 2011b). Irrigated land which covers 40% of total agricultural area significantly contributes in satisfying 55% of total food requirement of the country (GOI, 2012) but on the other hand it consumes almost 70% of fresh water resources and has left limited scope for expanding irrigated area further (CWC, 2005). Thus achieving food security of the country in future is largely dependent on rainfed agriculture (Wani et al., 2009, 2012). It is realized that despite several constraints and limitations of rainfed areas, huge untapped potential exists for enhancing crop yield through improved land, water, nutrient and other natural resource management (Wani et al., 2012; Rockström et al., 2007).

Long-term (36 years) data collected at International Crops Research Institute for the Semi Arid Tropics (ICRISAT) heritage watershed and other studies from Asia and Africa demonstrated five folds higher crop yields by integrating land, crop and nutrient management interventions compared to traditionally managed farmers' practices under the rainfed conditions (Wani et al., 2003, 2012). Rockström et al., 2007 described that if all the green water captured in root zone is utilized fully by crop, yield of 3 ton ha^{-1} could be achieved in rainfed agriculture with appropriate management practices. If water which sinks as deep percolation and surface runoff is also made available to crop then production level would reach 5.0 ton ha^{-1} and further to 7.5 ton ha^{-1}. In reality, a fraction of rainfall is only used by plant

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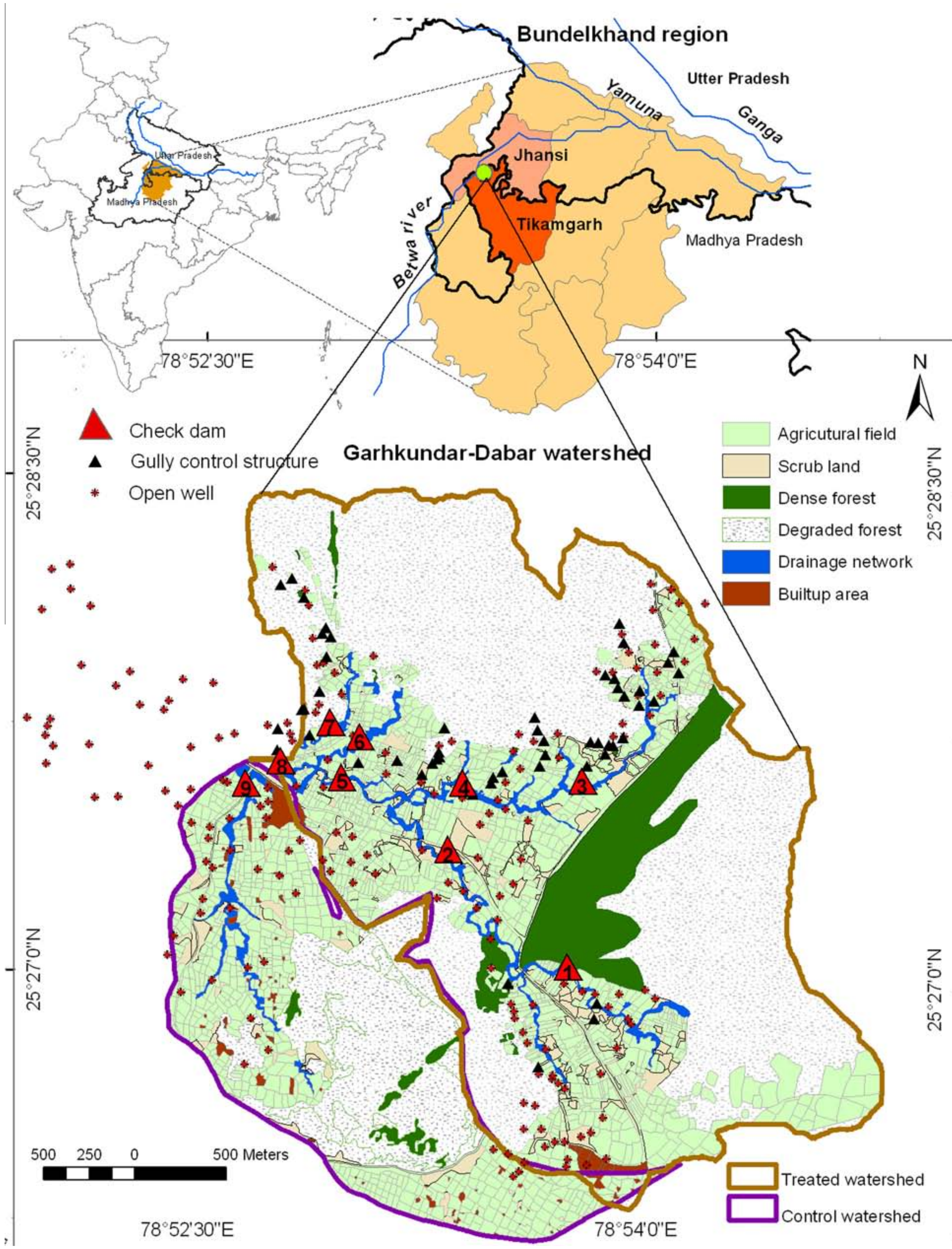

Fig. 1. Location of the Bundelkhand region in northern India and important rivers; zoomed map shows stream network, major land use, Wells location, check dams and gully control structures in Garhkundar-Dabar watershed and control watershed.

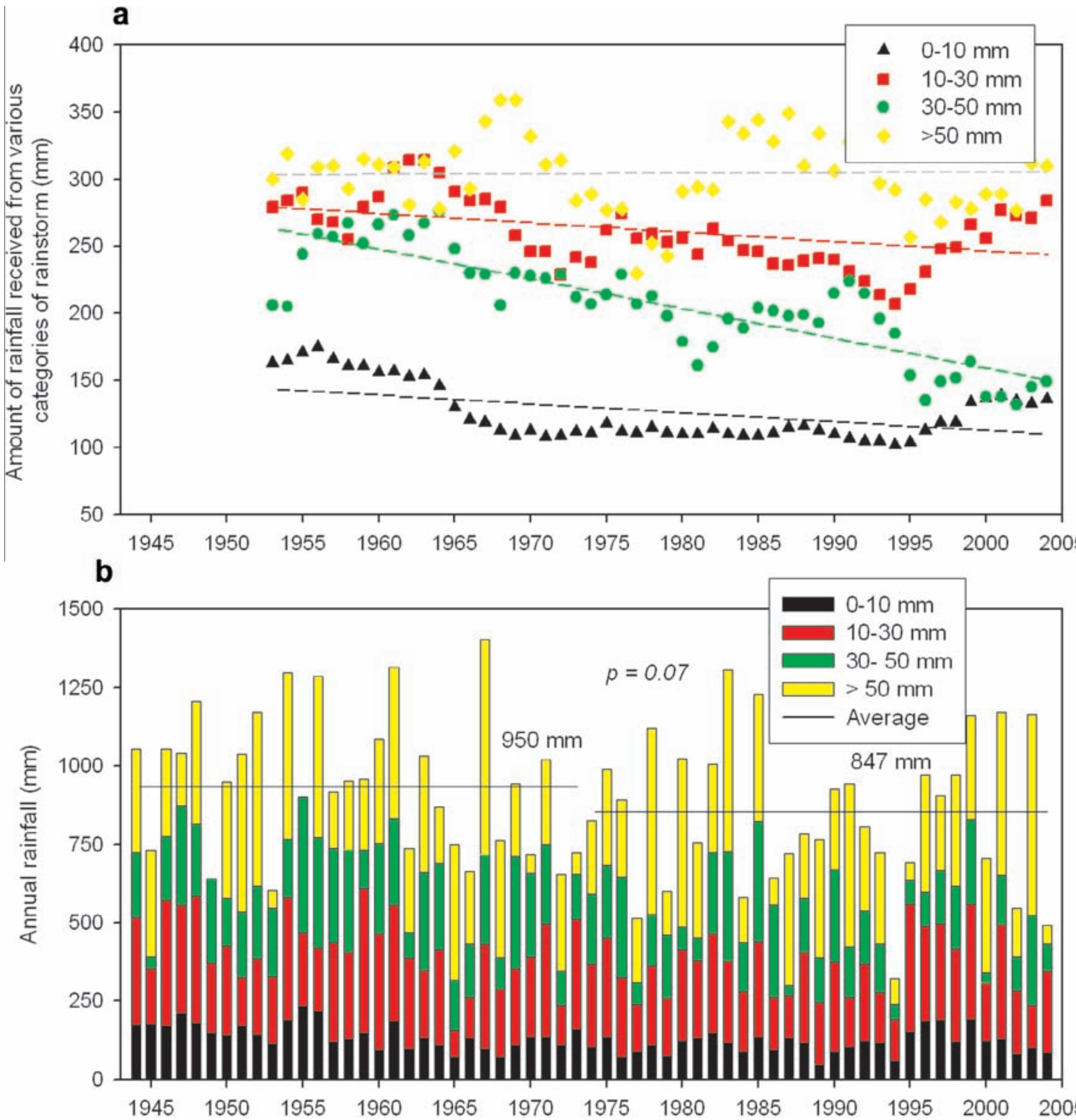

Fig. 2. (a): Moving average (10 years) of rainfall received from various categories of rain events between 1945 and 2004; (b) Comparing annual rainfall between 1945–1974 and 1975–2004.

(through transpiration) and rest gets channeled through non-productive use and lost from crop production system or partially joins into groundwater reserves and surface runoff to systems downstream. Water stress situation especially during critical growth stages decreases crop yield and more seriously damages the entire crop. Number of fields and modeling studies from Africa and Asia demonstrated large yield gaps between current farmers' yields and achievable potential yields in rainfed areas (Wani et al., 2003, 2009, 2011a; Rockström et al., 2007; Rockstrom et al., 2010; Barron and Keys, 2011).

With recognizing the importance of agricultural water management interventions, watershed development program in India was initiated in 1970s at national scale. The program is implemented by government of India, state government departments with involvements of consortium partners including non-government organizations in different phases. This program was initially designed mainly on engineering aspects such as constructing masonry check dams and measures for protecting soil erosion but village community was not directly involved in planning and implementation process. Therefore the program initially did not

Table 1
Soil characterization and current land use in treated and untreated (control) watersheds.

Parameters	Treated watershed	Control watershed
Soil physical properties		
Sand (%)	71 (57–85)	69 (55–87)
Silt (%)	16 (8–25)	14 (5–23)
Clay (%)	13 (6–24)	17 (16–28)
Organic carbon (%)	0.44 (0.09–1.1)	0.41 (0.15–0.81)
Field capacity (gm/gm)	0.17 (0.07–0.34)	0.15 (0.05–0.30)
Permanent wilting point (gm/gm)	0.09 (0.04–0.17)	0.08 (0.06–0.17)
Number of samples analyzed	50	30
Current land use		
Total geographical area (ha)	850	298
Agricultural land (ha)	260 (31%)	136 (45%)
Waste (scrub) land (ha)	40 (4.5%)	15.8 (5.3%)
Dense forest (ha)	63 (7.3%)	6.3 (2.1%)
Degraded forest (ha)	443 (52%)	119 (41%)
Others (ha)	44 (5.3%)	20 (6.6%)

benefit to the farming community as it was expected (GoI, 1994). The main aim of recently revised integrated watershed management program (IWMP) is to enhance rural livelihoods and wellbeing, building ecosystem services, recognizing the value of well-managed water and land resources (GoI, 2008, 2012). This concept ties together the biophysical notion of a watershed as a hydrological unit with the social aspects of community and its institutions for building resilience in agriculture through sustainable management of land, water, and other resources (Wani et al., 2003; Reddy et al., 2007; GoI, 2008; Garg et al., 2012a).

Resilience is the capacity of the system to absorb disturbance and still retain its basic function and structure and the capacity to adapt to stress and change (Walker and Salt, 2006). Agricultural systems especially rainfed agriculture in semi-arid tropics are highly vulnerable to various types of climatic shocks and socio-economic pressures. Upcoming challenges such as climate change which is characterized with high frequency of occurrence of extreme events such as heavy downpour, longer duration dry spells, shifting length of growing period and temperature stress, are being recognized in many parts of India (Aggarwal, 2008; Boomiraj et al., 2010). In such conditions, integrated watershed development (IWD) interventions leverage and strengthen desirable development by improving capacity to cope with inherent dryspells and reducing their negative impacts on crop yields and subsequently livelihoods of people (Joshi et al., 2008; Barron et al., 2009; Garg et al., 2012a).

Watershed program in India has a long history of development however, few studies only have attempted to quantify the impact of IWD interventions on hydrology, soil loss and quantifying ecosystem services (Joshi et al., 2008; Glendenning et al., 2012). The impact of IWD interventions on ecosystem services is not well understood and this has under estimated the impact of watershed management programs in the country. There is also increasing concern about downstream water availability due to watershed interventions in upstream areas especially in dry lands regions (Bouma et al., 2011; Glendenning et al., 2012). Several studies showed positive impacts of IWD interventions at field and village scale (e.g., Barron et al., 2009; Vohland and Barry, 2009; Rockstrom et al., 2010; Glendenning and Vervoort, 2011; Wani et al., 2003, 2011a; Garg et al., 2012a, 2012b; Garg and Wani, 2012) and also for downstream areas (Sreedevi et al., 2006), while few studies indicated negative impacts at the watershed and catchment scale (e.g., Batchelor et al., 2003; Sharma and Thakur, 2007; Bouma et al., 2011; Clemens and Demombynes, 2011; Bump et al., 2012). Glendenning et al. (2012) concluded that watershed scale analysis is under represented in field studies and is mainly approached through modeling. Most of these modeling studies examining IWD impact either have limited focus or had insufficient data (Glendenning et al., 2012). Thus, there is an urgent need to intensify data monitoring at field and watershed scale to clearly understand the impact of IWD interventions in different rainfall and ecological zones (Glendenning et al., 2012).

Here, we present results from a study of the GKD watershed of Yamuna basin situated in Bundelkhand region of Central India. This represents a typical semi-arid sub-tropical watershed and recently developed by implementing IWD interventions. The impacts of various soil, crop and water management interventions carried out in watershed are compared to the near-by no-intervention control watershed by adopting random control treatment approach. The aim is to analyze the impact of IWD interventions on: (1) surface and groundwater hydrology; (2) crop yields, income from crops and water productivity; and (3) soil loss and sediment transport. This paper focuses on water balance components and quantifies several ecosystem services generated or maintained in watershed in different dry, normal and wet years.

2. Materials and methods

2.1. Study area: Garhkundar-Dabar watershed

The Garhkundar-Dabar watershed (GKD) is located at 25°27′N Latitude, 78°53′E longitude, and about 230–280 m above mean sea level in the Tikamgarh District of Madhya Pradesh, India. This watershed is part of the Betwa river catchment of Yamuna sub-basin (Fig. 1). The Yamuna is one of the tributaries of the river Ganga in northern India and large portion of the sub-basin lies in Bundelkhand region (Tyagi, 1997). Location of Bundelkhand is such that it acted as a gateway between the North and the South India and had acted as political hub previously (Tyagi, 1997). Large numbers

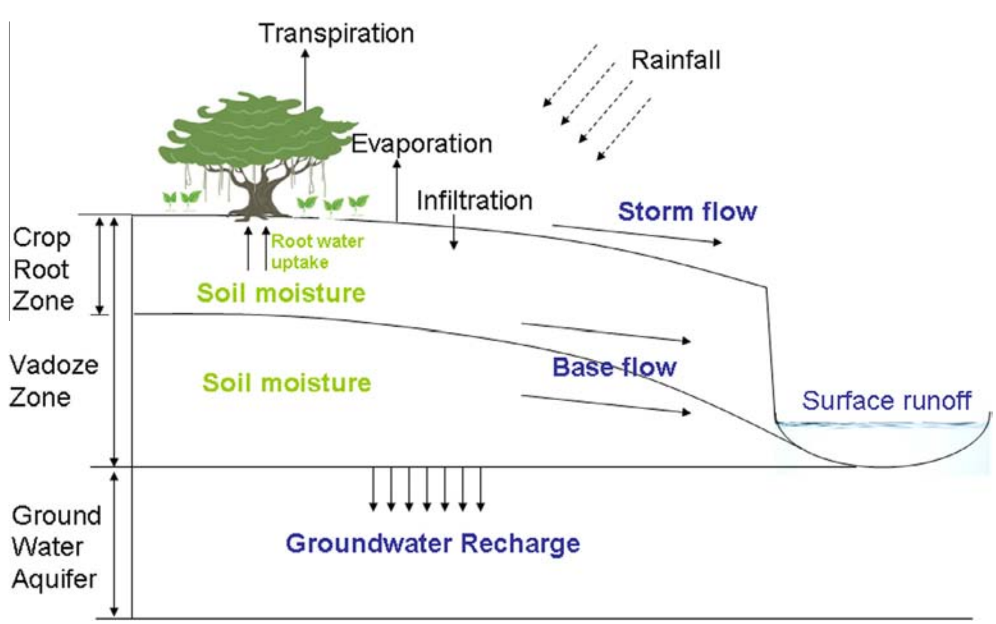

Fig. 3. Conceptual representation of principle hydrological processes and various hydrological processes at watershed scale.

of inhabitants in the Bundelkhand region are dependent mainly on livestock-based activities and approximately 33% of total geographical area is covered by degraded forest, grazing land and waste land (UPWSRP, 2001). Historically, Bundelkhand remained backward regions in the country because of outside invasions and repeated internal disturbances including wars and fighting (Tyagi, 1997). Due to undulated topography, poor groundwater potential, high temperature, poor and erratic rainfall, agricultural productivity in this region is very poor (0.5–1.5 t ha^{-1}). Most of the areas are single cropped and completely under rainfed conditions (Tyagi, 1997).

The geographical area of the GKD watershed is 850 ha. Rainfall is highly erratic, both in terms of total amount and its distribution over time. Long term weather data monitored at Jhansi station (nearby site) shows that annual average rainfall in study region is 877 mm (standard deviation, σ = 251 mm) with about 85% falling from June to September. The numbers of rainy days during the monsoon and non-monsoon period are 42 and 13, on average, respectively. Long-term data analysis showed that annual average rainfall has decreased from 950 mm between 1944 and 1973 as compared to an average of 847 mm between 1974 and 2004 (Fig. 2). This reduction was mainly due to decreased number of low (0–10 mm) and medium rainfall (30–50 mm) events (Fig. 2). Similarly, total number of rainy days in a year also decreased. Dry spells longer than 5–7 days are very common and occur several times (5–6 times) per season, whereas, 10–15 days or longer dry spell also may occur during the monsoon period. The climate of the region is tropical monsoonal preceded by hot summers (minimum air temperature between 17 and 29 °C and maximum air temperature between 31 and 47 °C in May) and is followed by cool winters (minimum air temperature ranges between 2 and 19 °C and maximum air temperature between 20 and 31 °C in January).

Soils in the watershed are shallow (10–50 cm), reddish to brownish red in color (Alfisols and Entisols) which is characterized by coarse gravelly and light textured with poor water holding capacity (Table 1). Large portion of the watershed is in degraded stage, poor in organic matter (Table 1) and nutrient status. The topography of watershed is surrounded by elevated hills and with agricultural areas in valley portion (Fig. 1). Nearly 30% watershed area is under agricultural use and rest is covered by degraded forest, wasteland and scrub land. Soils in upstream areas are excessively eroded and relatively shallow. The geology of the study area is dominated by hard rocks of Archaen granite and gneiss and largely composed of crystalline igneous and metamorphic rocks (Tyagi, 1997), and aquifers are either unconfined or perched, having poor storage capacity (porosity of 0.01–0.05%). These aquifers were derived primarily from weathering and developed into two layered system: (i) unconsolidated fractured layers derived through prolonged weathering of bedrocks within 10–15 m depending upon the topography, drainage and vegetation cover; ii) relatively impermeable basement starting from 15–20 m depth (CGWB, 2000). In such hard rock aquifers with poor transmissibility, shallow dug wells of 5–15 m depth are only primary source of water for domestic and agricultural use in this region.

National Research Centre for Agroforestry (NRCAF), Jhansi, Indian Council of Agricultural Research (ICAR) in partnership with farmers selected GKD watershed for implementing various agricultural water management interventions at field and watershed scale in 2005. The main purpose of developing GKD watershed was to establish a site for learning for farmers, rural community and also for researchers and other stakeholders (development agencies and policy makers) to understand the impact of integrated watershed management interventions in Bundelkhand region (NRCAF, 2009, 2012) which experience frequent drought.

2.2. Description of integrated watershed development interventions

Several *in situ* and *ex situ* interventions were implemented under the integrated watershed development program in GKD watershed. The most common *in situ* interventions were field bunding, contour bunding and cultivating crop across the slope, which harvest surface runoff, allow more water to percolate and dispose excess runoff safely from the fields. Field bunding was done in 40 ha land area (15% of agricultural land) and contour cultivation was promoted in rest of the agricultural land in GKD watershed. This practice created an opportunity to accumulate surface runoff along the contour line, and also protected soils from erosion. Building check dams and low-cost gully control structures on the stream network (*ex situ* practices) reduce peak discharge, reduce runoff velocity and harvest a substantial amount of runoff in watershed and increase groundwater recharge. At the same time, these structures trap sediment which protect the river ecosystem. Total nine check dams, including one in control watershed, having storage capacity between 1000 and 6500 m^3; 150 low-cost gully control structures (called gabions locally) of 30–100 m^3 capacity; and 15 drainage structures for safe disposal of excess water from agricultural fields were constructed (Fig. 1), all together developed 35,000 m^3 of water storage capacity (~40 m^3/ha) in watershed. The water in the check dams could be used directly for irrigation and also served as sites for artificial groundwater recharge. Other than soil and water conservation measures, focus on productivity enhance-

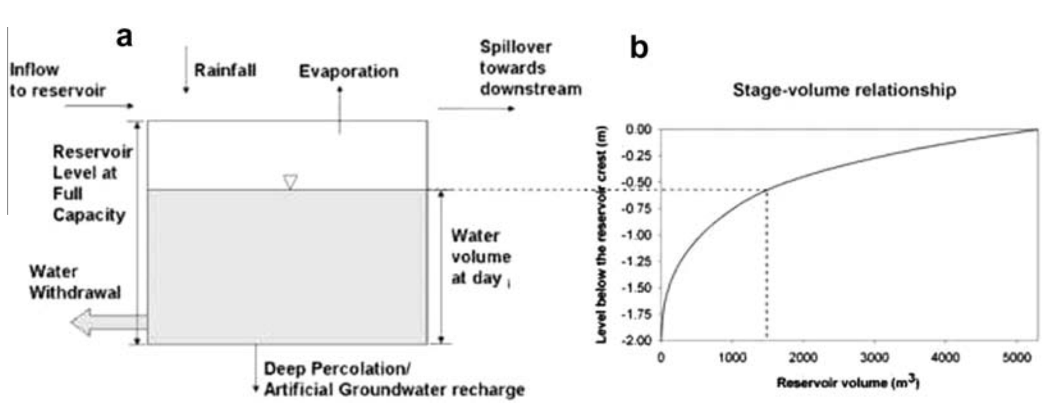

Fig. 4. Schematic diagram of reservoir hydrology for small and medium storages structures. Reservoir water balance is defined as: Water volume at day$_i$ = Water volume at day$_{i-1}$+Inflow received (runoff) + Rainfall over the water body – Evaporation from the water body – Spillover amount – Infiltration from reservoir bottom (Artificial groundwater recharge) – Water withdrawn or utilized.

ment through crop diversification and intensification, introduction of agroforestry system, introduction of improved seed variety, agronomic practices and balanced use of chemical fertilizers were initiated.

2.3. Data monitoring in Garhkundar-Dabar and control watershed

Since inception of the project, attention was given on data monitoring at GKD watershed and also in nearby randomly selected control watershed of 298 ha area. Topographic, soils, climate condition and socio-economic status of control watershed are almost identical to GKD watershed (Table 1). Agricultural land in GKD and control watersheds is 31% and 45% of total geographical area, respectively (Table 1). There are total 191 and 76 landholdings with average size of 1.55 ha and 1.78 ha in GKD and control watersheds, respectively. Farmers in control watershed follow traditional farming practices and no IWD interventions were implemented. Data on surface and groundwater hydrology, agricultural water use, crop yields, sediment losses and change in land use pattern were monitored in treated (GKD) and control watersheds.

2.3.1. Monitoring runoff, reservoir inflow and sediment transport

Surface runoff generated from different landuse is monitored at five different locations by using automatic runoff recorder in GKD watershed and at outlet of the control watershed, since 2007 onwards. Gauging station is set to record flow data at 15 min interval. Along with runoff measurements, soil loss is monitored at outlets of both the watersheds. Automatic sediment collection unit developed at ICRISAT (Pathak and Sudi, 2004; Pathak et al., 2013) is coupled with runoff recorder which was programmed to collect water sample for suspended sediment determination at every 60 min interval. This unit has capacity to collect 50 samples at user defined time interval without manual interference. Sediment samples from all runoff events (all together 35 events in treated watershed and 45 in control watershed) were collected between 2007 and 2011 at watershed outlets. Samples were analyzed in laboratory for estimating sediment concentration assuming the event-mean concentration was well represented by the grab samples and used for estimating total soil loss by multiplying it with the measured runoff-volume.

Moreover, water levels in check dams were monitored on daily time interval for estimating percolation rate and analyzing reservoir hydrology. Storage capacity of check dams and stage-volume relationship are estimated by conducting topographic survey at every one meter grid interval along and across the stream channel. Live storage capacities of different check dams were estimated and amount of silt deposition evaluated in year 2007, 2009 and 2011. Amount of water diverted (capacity of pump, pumping hours and date) in agricultural fields from each of these check dams are also recorded.

2.3.2. Monitoring groundwater table and irrigation water use

Groundwater table levels of all the open wells located at GKD watershed (116 wells) and control watershed (42 wells) are monitored at 15 days interval since August 2006. Moreover, water table in 26 open wells is also monitored at downstream location (Fig. 1). Average depth of wells (depth to the bottom of the excavation) in treated, control and downstream locations are 8.7 (standard deviation, $\sigma = 2.4$), 8.7 ($\sigma = 2.2$) and 8.8 ($\sigma = 2.6$) m, respectively. Water in these wells is being used for agricultural and domestic use. Amount of irrigation application (pumping hours and date of irrigation) are recorded for each well in GKD and control watershed. Groundnut, green gram, black gram, and sesame (oil seed crop) are main crops grown during monsoon (June to September); and wheat, mustard, chickpea, peas, and non-edible seed crops, are grown in winter season (November to February) with supplemental irrigation or fully irrigated conditions depending on water availability.

2.3.3. Monitoring crop yield and income

Data on cropping intensity, crops grown and crop yields in different farmers' fields are recorded since inception of the project start. Cost of cultivation and market price of different crops are recorded in selected fields (20 farmers in each watershed) for estimating net income generated in GKD and control watersheds.

2.4. Analyzing water balance

Fig. 3 shows a conceptual representation of the hydrological cycle at watershed scale. Rainfall is partitioned into various hydrological components as defined by mass balance equation such as:

$$\begin{aligned}\text{Rainfall} = {} & \text{Runoff from the watershed boundary(storm flow} \\ & + \text{base flow)} + \text{Change in groundwater storage} \\ & + \text{Change in reservoir storages} \\ & + \text{Evapotranspiration(Evaporation} \\ & + \text{Transpiration)} \\ & + \text{Change in soil moisture storages}\end{aligned} \tag{1}$$

In above equation, a fraction of rainfall stored in terms of soil moisture is known as green water; and amount of water partitioned in terms of surface runoff (storm flow and base flow), groundwater recharge, water stored into water harvesting structures is known as blue water (Falkenmark, 1995). Different hydrological components both for GKD and control watershed are estimated in current study using mass balance approach.

2.4.1. Storm flow and base flow partitioning

Rainfall which runs-on soil surface during and after the rainfall events is called overland flow. This water accumulates and joins into stream network shortly after the rainfall events depending on rainfall intensity and shape, size and topography of the watershed. Amount of rainfall which infiltrates into soils, moves at shallow and deeper depths and subsequently reaches the stream network is referred as base flow. It is important to understand how integrated watershed development interventions partitioned water yield into storm flow and base flow in terms of total amount and retention period.

In the current analysis, flow received at watershed outlet within 12 h of the rainfall event was referred as storm flow and flow received after 12 h was considered as base flow. The time of concentration (tc) in GKD watershed at different check dam locations is estimated as 0.5–2.5 h. The time of concentration is the time required for a drop of water to travel from most remote point of the catchment to the watershed outlet. Longest path of the GKD watershed is 2.5 km and average velocity of runoff water 1.0 km h^{-1} as defined by Kirpich, 1940. Thus considering 12 h as 'base time' indeed is sufficient enough for partitioning water yield into storm flow and base flow at any location in the study area.

2.4.2. Estimating groundwater recharge

Water table fluctuation (WTF) method is a well accepted and convenient technique for estimating groundwater recharge in hard-rock regions (Sharda et al., 2006; Dewandel et al., 2010; Glendenning and Vervoort, 2010; Garg and Wani, 2012). Water balance captured by WTF method is defined by mass balance equation such as:

$$\begin{aligned}\text{Net groundwater recharge during monsoon} \\ &= (\text{change in hydraulic head before and after monsoon}) \\ &\quad \times \text{specific yield} \\ &\quad + \text{water withdrawal during monsoon period} \\ &\quad + \text{underlying deep drainage} \\ &\quad + \text{evaporation losses from water table} \qquad (2)\end{aligned}$$

Hydraulic head in open wells at different time period was obtained from water table data. We conducted several pumping tests in study area and estimated specific yield in range between 0.5% and 1.5% with average value of 1.0%. Central Ground Water Board (CGWB, 2000) also reported specific yield of Bundelkhand hard rock region in the same range. Amount of water pumped and its utilization for agriculture is monitored for each well in GKD watershed. Underlying deep percolation is assumed negligible due to presence of impervious granite layers. Evaporation losses from the groundwater aquifer were calculated as 5–10 mm year^{-1} for the study area using Coudrain-Ribstein et al. (1998) depth–evaporation relationship. Using the Eq. (2), groundwater recharge during monsoon period (June–September) is estimated for GKD and control watershed for different years between 2007 and 2012.

2.4.3. Reservoir hydrology

Check dams and water harvesting storage structures play an important role in augmenting water resources at community or village scale. Reservoir hydrology of small or medium storage structures are shown by a schematic diagram in Fig. 4 and also described by the mass balance equation such as:

$$\begin{aligned}\text{Water volume at day}_i = \text{Water volume at day}_{i-1} \\ &+ \text{Inflow received} \\ &+ \text{Rainfall over the water body} \\ &- \text{Evaporation from the water body} \\ &- \text{Spillover amount} - \text{Percolation} \\ &- \text{Water withdrawn or utilized} \qquad (3)\end{aligned}$$

Reservoir data are analyzed to understand the impact of water harvesting structures on groundwater recharge, surface water availability and enhanced irrigation potential during dry, normal and wet years in GKD watershed. According to the Indian Meteorological Department, Pune, India, (http://www.imdpune.gov.in) rainfall that is 20% lower than the mean (rainfall < 680 mm) = dry or deficit year; rainfall between + 20% and −20% (680 < rainfall < 1020 mm) of the mean = normal year; rainfall greater than 20% (rainfall > 1020 mm) of the mean = wet or surplus year.

2.5. Estimation of crop water productivity

Crop Water Productivity (WP) is the amount of grain yield obtained per unit of water consumption (Tuong and Bouman, 2003; Garg et al., 2012c). Depending on the type of water sources considered, WP is expressed as grain yield per unit water evapotranspired (WP_{ET}) or grain yield per unit total water input (irrigation plus rainfall) (WP_{IP}). In this study, technical WP is calculated using consumptive water use (ET_a) and yield values of different crops (from $i = 1$ to $i = n$, number of crop fields) over the entire watershed area.

$$WP_{ET}\ (\text{kg m}^{-3}) = \frac{\sum_{i=1}^{i=n} \text{Grain yields (kg)}}{\text{Consumptive water use (ET in m}^3)} \qquad (4)$$

Due to different economic values and cost of production of various crops, economic water productivity, EWP (INR m^{-3}) is calculated in different years both for GKD and control watershed using the following equation:

$$EWP\ (\text{INR m}^{-3}) = \frac{\text{Gross income generated (INR)} - \text{Cost of cultivation (INR)}}{\text{Water consumption (ET in m}^3)} \qquad (5)$$

Crop yield was measured in selected 20 farmers' fields from each of the watersheds in different years. Consumptive water use (ET) was calculated from a one dimensional water balance model called as "Water Impact Calculator" (WIC) developed by ICRISAT (Garg et al., submitted for publication). WIC requires soil (water retention and soil depth), weather (ET_0 and rainfall), crop growth [biomass (k_c) and root growth function], topography (land slope, land form conditions), and crop management (date of crop sowing and harvesting, irrigation method) details as an input to the model.

In WIC, evaporation and transpiration values are estimated based on imposed surface boundary conditions and moisture accessibility between surface soil layer and root zone. Water available in top 10 cm layer is contributed in satisfying the evaporation

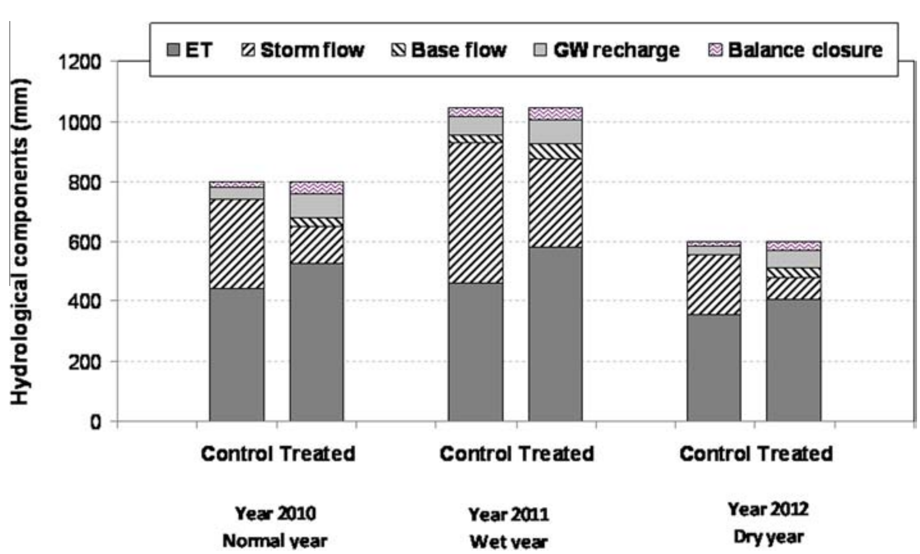

Fig. 5. Water balance components (monsoonal) of selected normal, wet and dry years.

demand, whereas, moisture available within root zone is used to meet crop water demand. Crop water requirement (CWR) for a given crop is calculated such as:

$$\text{Crop water requirement}_{\text{day}=i} = [Kc]_{day=i} \times [ET_0]_{day=i} \quad (6)$$

$$\textit{if}: \sum_{j=1}^{rootzone} \text{Available water} > \text{Crop water requirements; ET}_{\text{day}=i} = \text{Crop water requirements} \quad (7)$$

$$\text{otherwise ET}_{day=i} = \sum_{j=1}^{rootzone} \text{Available water}$$

where i denotes days after sowing; j symbolize each cm increment in soil layer reaching up to root zone; and K_c is the crop coefficient. Root zone depth is dynamic variable and controlled by crop growth stage (days after sowing) as defined by Allen et al., 2005. It was assumed that evaporation from soil surface was inversely proportional to vegetative growth/stage. Thus, after achieving full vegetative crop growth ($K_c \geqslant 1.0$), evaporation from the soil surface was considered almost negligible. If moisture in root zone was not sufficient to meet crop water requirement then WIC counted crop under water stress situation. With given rainfall, irrigation and management, number of days crop experienced with water stress situation was estimated both for treated and control watershed in different years as shown in Eq. (8). Detailed description of WIC, model development, testing and validation procedure are shown by Garg et al. (submitted for publication).

$$\text{Crop water stress}(-) = 1 - \frac{\text{Actual ET}}{\text{ET under non limiting water condition}} \quad (8)$$

2.6. Cost-benefit analysis

Cost-benefit analysis is a systematic process for calculating benefit and cost of the development project and considered as an important indicator for assessing economic feasibility of targeted interventions. We considered direct benefits, in present case increased agricultural income, due to project interventions compared to control watershed. Gross income generated from the agricultural outputs (crop yield) was estimated from the market price. Subsequently, net economic returns were calculated by subtracting the cost of cultivation from the gross income. Capital spent for implementing *in situ* and *ex situ* interventions were considered as development cost. Moreover, institutional cost (staff involved, transport and data monitoring) were included to cover full project cost in current analysis. Net present value is estimated by considering 10% interest rate per annum on capital investment

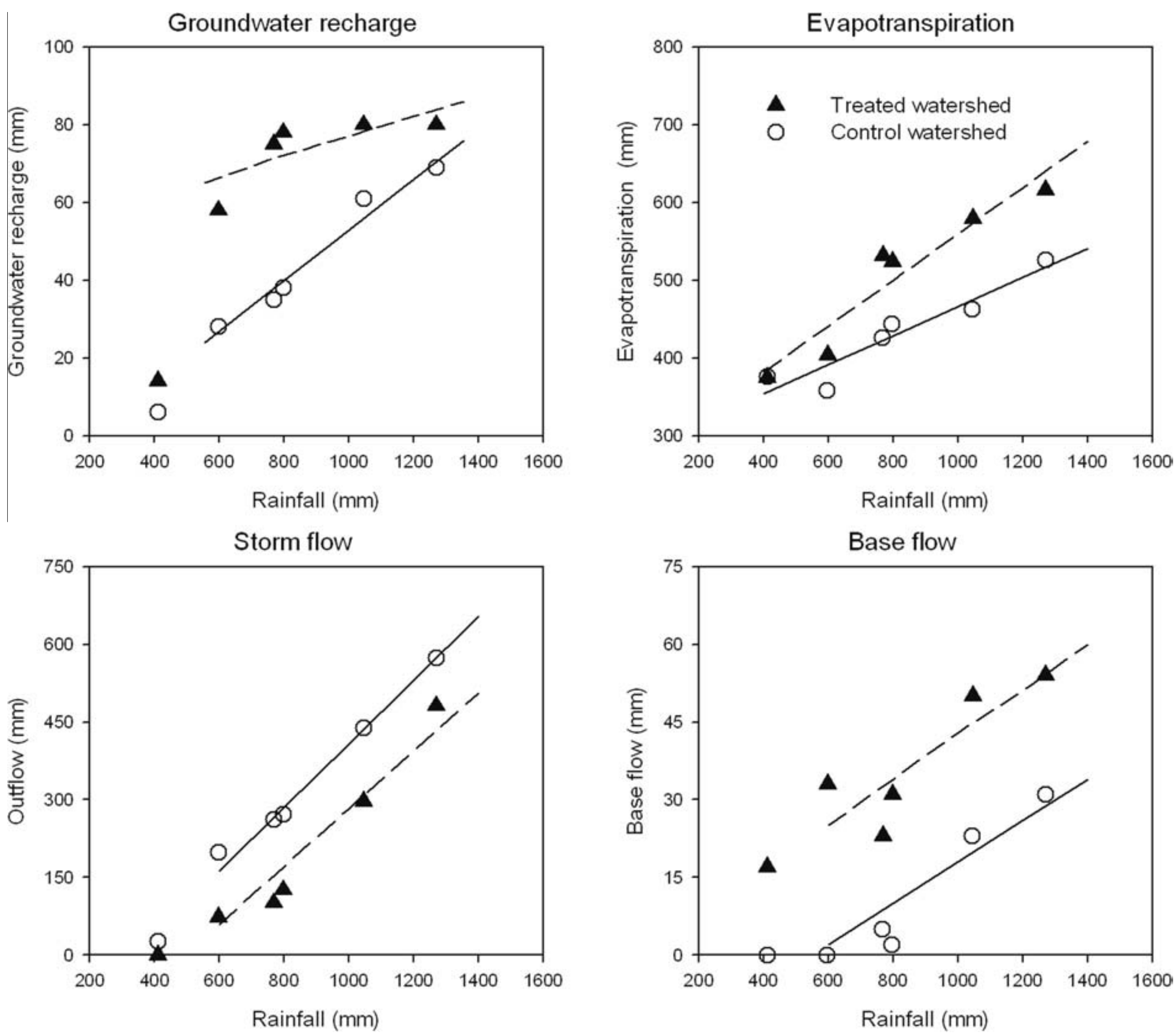

Fig. 6. Impact of IWD intervention on (i) groundwater recharge, (ii) ET, (iii) storm flow and (iv) base flow generation. Open circles and triangles in figure presents control watershed and treated watershed, respectively (data from 2007 to 2012).

Table 2
Impact of IWD interventions on hydrology and ecosystem services compare to non-intervention stage (Data from year 2007 to 2012).

Parameters	Treated watershed	Control watershed
Rainfall (mm)	815	815
Storm flow (mm)	164 (21%)	274 (34%)
Base flow (mm)	35 (4%)	10 (1%)
Groundwater recharge (mm)	96 (12%)	59 (7%)
ET (mm)	520 (64%)	472 (58%)
No of days base flow received (days)	110	35
Average annual soil loss(t ha^{-1})	1.5–6.5	3.0–11.5
Cropping intensity (%)	180%	110%

(development and institutional cost) and benefit-cost ratio is derived for 10 years period between 2006 and 2015.

3. Results

3.1. Impact of integrated watershed development interventions on water balance components

Integrated watershed development interventions significantly changed different hydrological components in GKD watershed. Fig. 5 describes water balance components of three consecutive years, 2010–2011, 2011–2012 and 2012–2013 those experienced with normal (798 mm), surplus (1046 mm) and deficit (598 mm) rainfall occurrence in GKD watershed, respectively. In control watershed, 35–45% of the rainfall was partitioned as surface runoff, 5–6% contributed in groundwater recharge and 45–60% was utilized as evapotranspiration. In treated watershed, surface runoff was reduced (20–35% of rainfall), and increased groundwater recharge (8–10% of rainfall) and ET (55–70% of rainfall).

Water partitioning differed from year to year depending on rainfall amount and its distribution. Fig. 6 shows impact of IWD interventions on selected hydrological components (groundwater recharge, ET, storm flow and base flow) in different rainfall years. Strong linear relationship was observed between hydrological components and total rainfall amount for control and treated watersheds. In general, groundwater recharge increased with increasing rainfall amount. Groundwater recharge increased linearly in control watershed; whereas groundwater recharge in treated watershed reached to its maximum capacity (75–80 mm) with 700–800 mm rainfall. Storage capacity of groundwater aquifer is limited therefore additional rainfall could not help in further groundwater recharge. Impact of IWD interventions on groundwater recharge was observed positive but highly significant in dry and normal years.

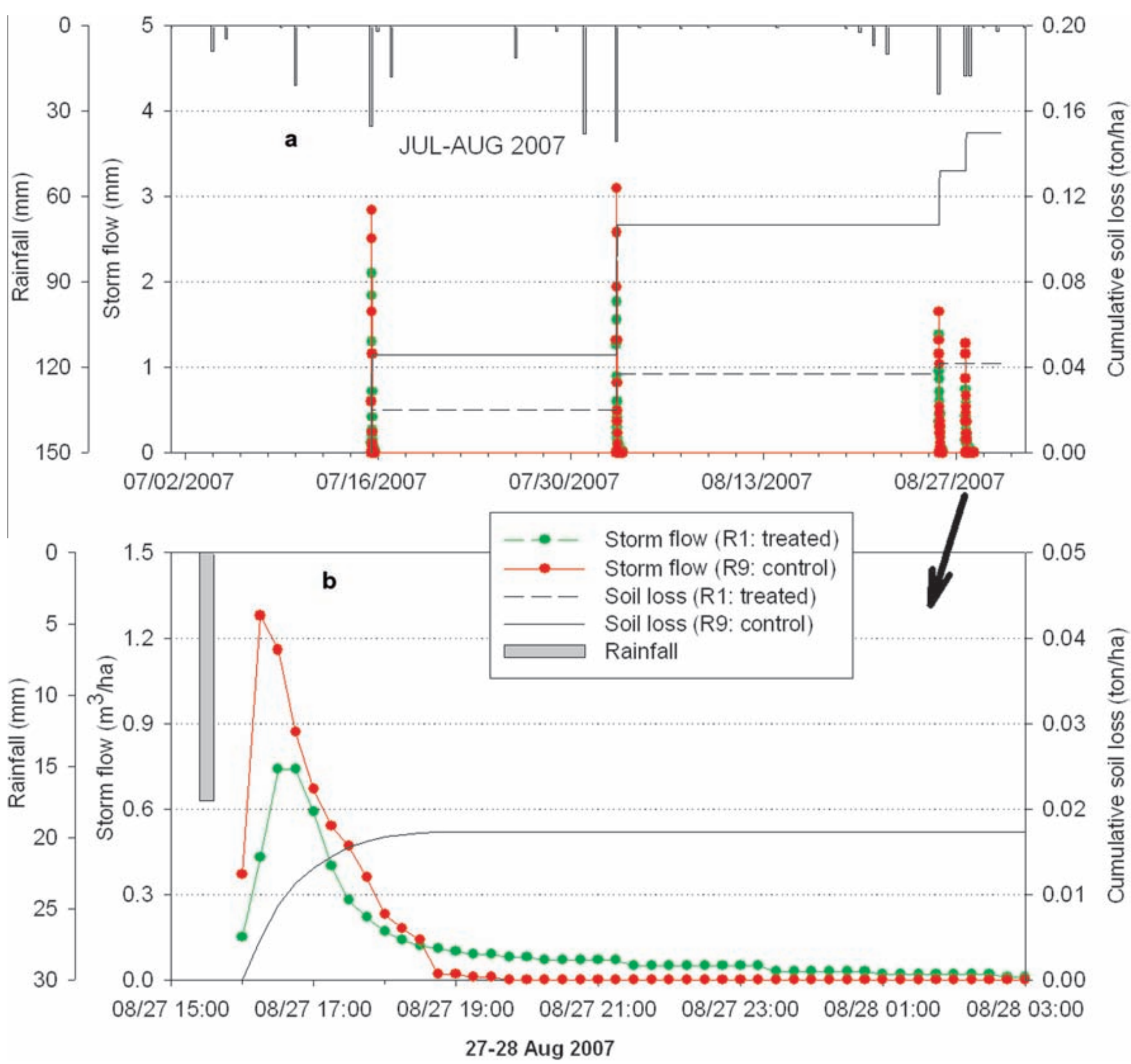

Fig. 7. (a) A comparison of storm flow and cumulative soil loss measured at reservoir-1 (R1) in treated watershed and R9 at control watershed in 2007; (b) zoomed-in figure shows hydrograph and soil loss of selected event on 27–28th August 2007 measured at R1 and R9.

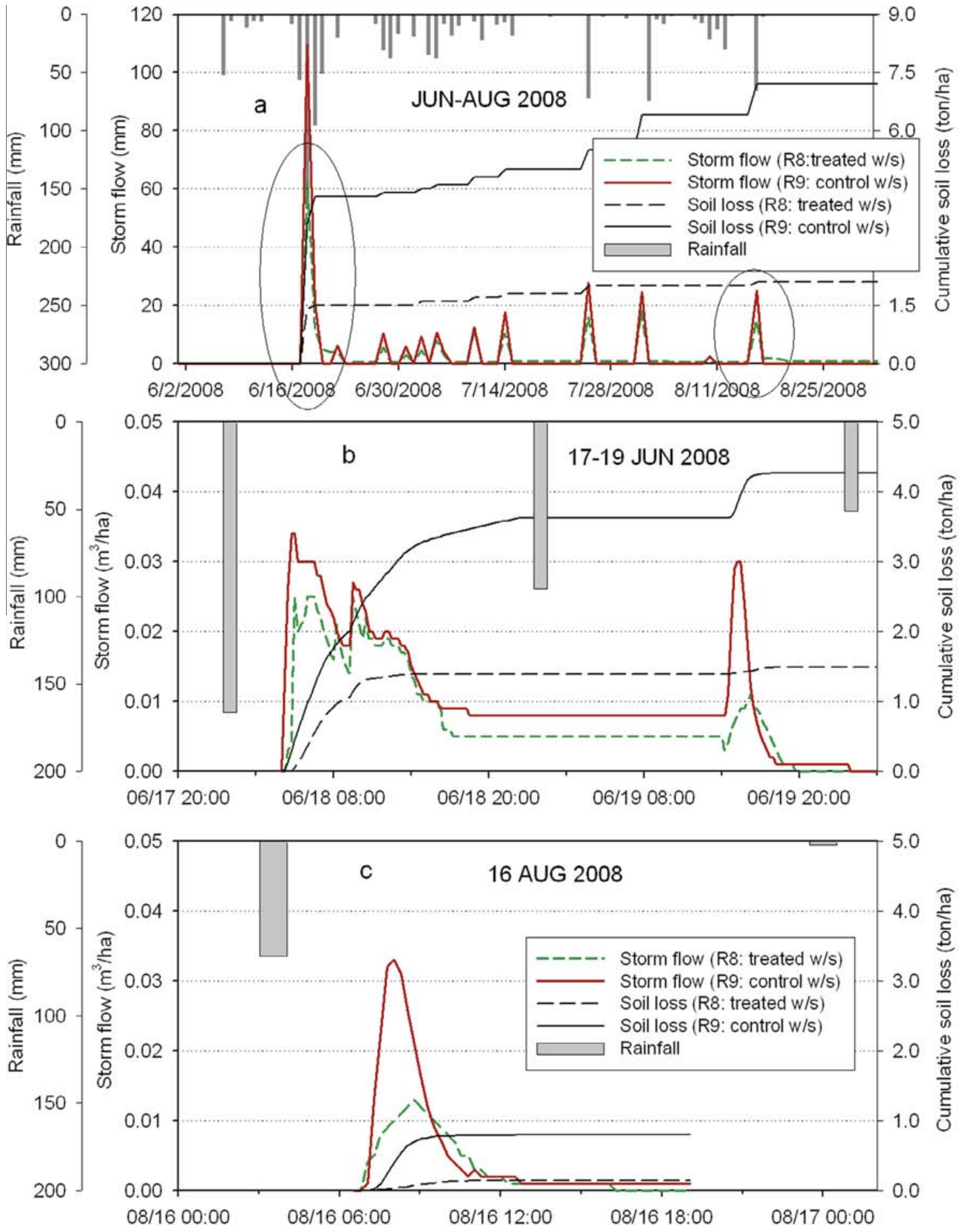

Fig. 8. (a) A comparison of storm flow and cumulative soil loss measured at outlet of treated watershed (R8) and control watershed (R9) in year 2008; (b and c) zoomed-in figure (s) shows hydrograph and soil loss of selected events.

ET was largest among all the water balance components. Nearly 60% of total rainfall was partitioned into ET in dry years and 45% in wet years during the monsoon season in control watershed. On the other hand, ET in treated watershed was 68% and 55% of total rainfall during dry and wet years, respectively. ET increased with increasing rainfall amount both in control and treated watersheds. High soil moisture availability and more irrigation application enhanced ET on average from 470 mm (58%) to 520 mm (64%) between June and October months in treated watershed compared to the control watershed (Table 2).

Surface runoff estimated for control and treated watershed is found as 35% and 25% (of total rainfall), respectively. IWD interventions however, reduced storm flow but enhanced base flow from 1.2% to 4.3% of total rainfall (Fig. 6). Base flow (base flow) usually was recorded at watershed outlet and around drainage network during and after the monsoon season for more number of days

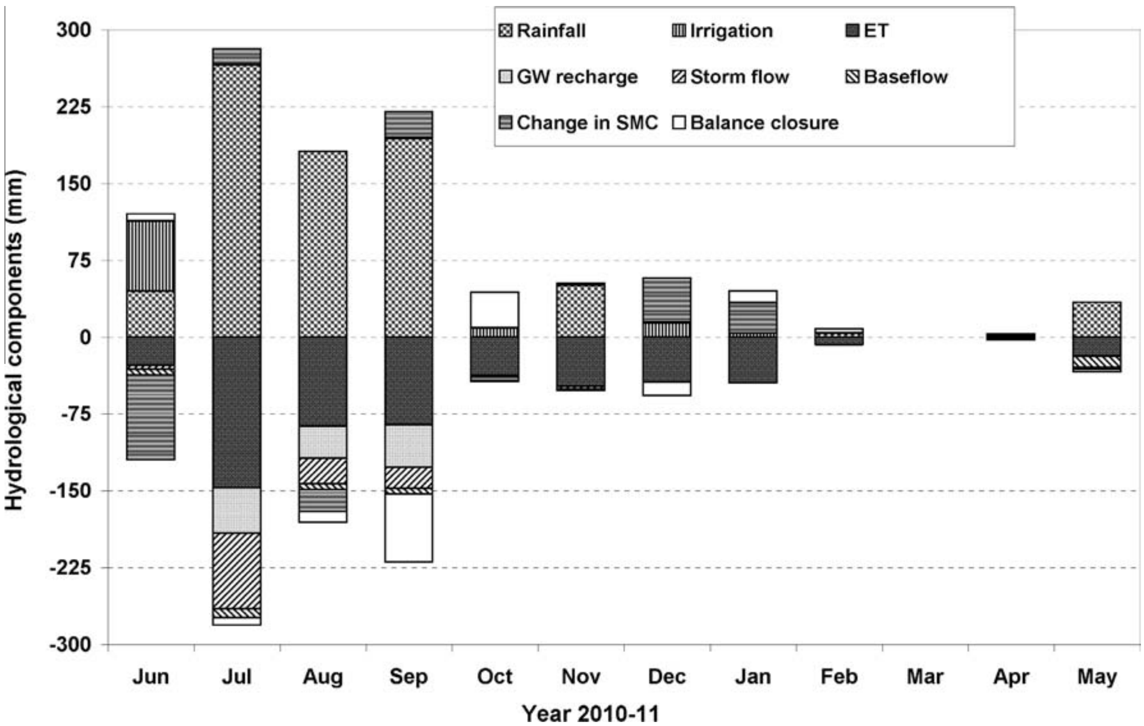

Fig. 9. Month-wise water balance components of Garhkundar watershed (treated watershed) during year 2010–11.

(increased from 35 to 110 days on average) in treated watershed compared to control watershed.

Impact of IWD interventions on runoff-hydrograph was analyzed and presented for two selected locations: (i) at reservoir no-1 (R1) of treated watershed and (ii) outlet of control watershed (R9), in year 2007 (Fig. 7a). Total catchment area of R1 and R9 were 261 ha and 298 ha, respectively. As the catchment areas of R1 and R9 were nearly same, the influence of their size (scale) on runoff-hydrograph should be minimal. During 2007, total rainfall received between June and September was 378 mm classified as dry year and no runoff was observed at the outlet of treated watershed (R8) throughout the monsoon season. On the other hand, runoff at given two locations (R1 at treated watershed and R9 at control watershed) was observed four times in the 2007 monsoon season (Fig. 7a) which all together generated 30 mm and 36 mm surface runoff, respectively.

Fig. 7b depicts hydrograph for one of selected rainfall event measured at R1 and R9 reservoir locations. Amount of rainfall received in 40 min was 18 mm on 27th August 2007. Total runoff produced from catchment R1 and R9 was recorded as 5.5 mm and 6.5 mm, respectively. Difference in total runoff amount between catchment R1 and R9 however, is not much higher but the temporal variability in terms of magnitude was significantly different. Peak discharge at R1 and R9 was observed at 60 and 30 min after the occurrence of the rainfall, respectively. Magnitude of peak runoff was found relatively higher in control watershed compared

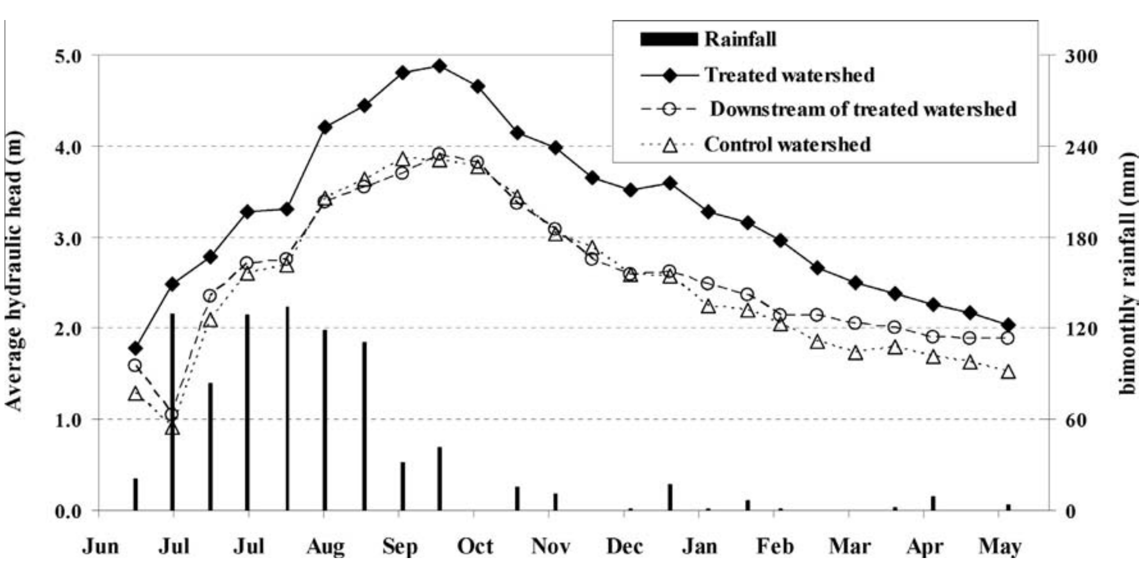

Fig. 10a. Fluctuation of hydraulic head in relation to rainfall received on a fortnightly time scale in control, treated watershed and downstream villages of Garhkundar watershed.

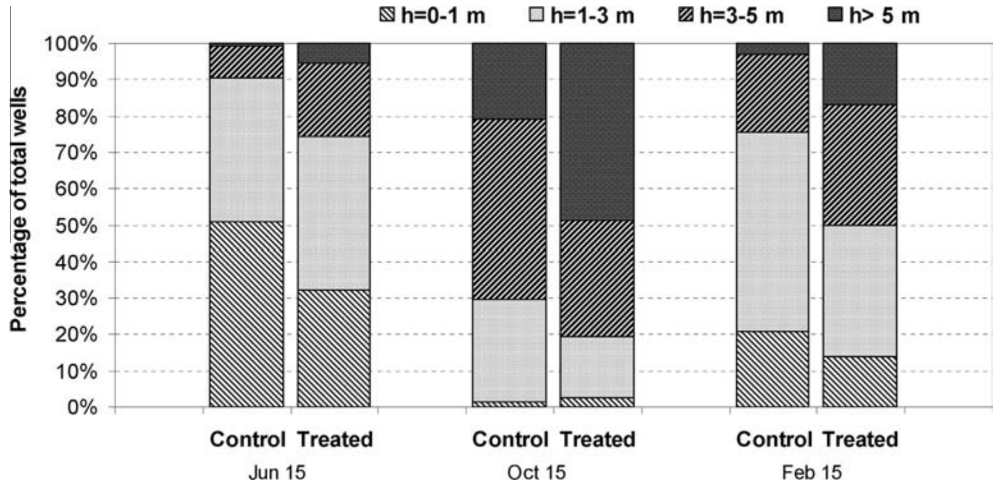

Fig. 10b. Total number of wells (percentage of total well) with different head status before monsoon (June 15th), post monsoon (October 15th) and before starting the summer (February 15th) at control and treated watersheds (data from 2007 to 2012).

to treated region. A long recession limb (lean flow) at R1 continued even after 12 h of the rainfall event whereas inflow at R9 reduced to zero after four hours of the rainfall event.

Similarly storm flow (hydrograph) measured at outlets of both the watersheds (R8 in control and R9 at treated watershed) are presented for year 2008 along with daily rainfall (Fig. 8). The 2008 was categorized as wet year (surplus) as total rainfall during monsoon (June–September) was recorded 1225 mm. Total 16 rain events those were equal or greater than 25–30 mm produced storm flow. Total amount of storm flow generated from catchment R8 (treated) was 280 mm compared with 395 mm from R9 (control) indicates significant reduction in surface runoff due to IWD interventions.

For understanding runoff characteristics between treated and control watersheds, two rainfall events (17–19th Jun and 16th Aug) were selected from 2008. Shape and magnitude of selected hydrographs (shown by circle in Fig. 8) are depicted along with rainfall intensity in Fig. 8b and Fig. 8c. Total 261 mm (166 + 95 mm) rainfall was recorded on 17–18th Jun 2008 in GKD watershed. Rain events higher than 100–150 mm on daily time scale are rare in Bundelkhand region. Total runoff produced from catchment R8 was 62 mm (24% of rainfall) and R9 was 110 mm (42% of rainfall). Magnitude of storm flow observed from treated watershed was found relatively lower compared to control watershed in initial hours but due to high intensity of rainfall, response from both watersheds was found similar at later stage (Fig. 8b). Generated runoff volume was relatively higher compared to storage capacity of the storage structures. After filling check dams and gully control structures, all the inflow spilled-out and joined into the main course of stream as storm flow. On the other hand, total 66 mm of rainfall was recorded on 16th Aug. Total runoff produced from catchment R8 was 15 mm and from R9 was 25 mm. Magnitude of peak and total amount was found relatively less from treated watershed compared to control watershed (Fig. 8c). Moreover 90 min time lag was also observed in attending peak runoff in treated watershed due to various IWD interventions compared to control watershed.

3.2. Monthly water balance

To show a detailed description of mass balance, the monthly water balance of treated watershed is presented for selected one of the normal year (June 2010 to May 2011) in Fig. 9. Figure shows upper panel (with positive numbers) indicate source of water and the bottom panel (with negative numbers) indicate different hydrological components in respective months. Total rainfall received in 2010–2011 was 775 mm and out of that 685 mm (88%) received during monsoon. ET was generally large during the monsoon season, groundwater recharge and runoff occurred predominantly between July and September. Significant amount of *in situ* soil moisture stored in vadose zone was utilized in October. In post-monsoon season, rainfall during the non-monsoon period was small and *in situ* soil moisture and groundwater source had become primary source of water and largely partitioned into ET.

3.3. Impact of IWD interventions on water table depth

Data on hydraulic head in open wells recorded on fortnightly time scale between 2006 and 2012 both in control and treated watershed covered wide range of weather variability. Fig. 10a shows average hydraulic head in control, treated and downstream location at GKD watershed. On an average, 4.0 m difference in hydraulic head (difference in water table) was recorded in open wells before and after monsoon period. Measured hydraulic head in open wells shows that groundwater availability (water levels in well) differed from year to year depending on variability in rainfall intensity and distribution (not shown). Despite more pumping and groundwater use, hydraulic head in treated watershed was found approximately one meter higher compared to the control watershed through-out the year (Fig. 10a). Water table in downstream wells are found equal or relatively higher than control watershed but usually recorded lower as compared to the treated watershed.

Fig. 10b shows recharging and depleting stage of open wells in terms of hydraulic head at three different dates (before monsoon, after monsoon and before summer) in control and treated watersheds. Total 50% of wells were found drying or with less than one meter hydraulic head in control watershed on 15th June. Whereas, in treated watershed only 30% wells were observed with less than one meter hydraulic head, 60% wells had hydraulic head between 1 and 5 m and rest 10% wells had hydraulic head more than five meter on 15th June. IWD interventions enhanced groundwater recharge and nearly 50% wells showed hydraulic head more than 5 m in treated watershed at the end of monsoon period (Oct 15th). Water table in open wells depleted fast and hydraulic head depleted less than 3 m nearly in 80% wells by February 15th in control watershed. Whereas 50% of wells in treated watershed showed hydraulic head higher than 3 m.

Table 3
Amount of water harvested and its utilization in different check dams in treated watershed.

Year	Rainfall (mm)	Storage capacity of check dam (m^3)	Water pumped for agricultural use (m^3)	Water Evaporation (m^3)	Percolation estimated (m^3)	Net water harvested (m^3)	Harvesting ratio to total storage capacity (–)
2009–10	820	24,800	189300	11,700	34,400	235400	9.5
2010–11	755	24,800	171400	11,100	41,700	224200	9.0
2011–12	1053	24,800	139000	17,200	46,700	202900	8.2

3.4. Reservoir hydrology

Role of water harvesting structures such as checkdam was found very important in GKD watershed. Total eight check dams of 1000–6500 m^3 created nearly 24,800 m^3 of storage space in treated watershed. Water balance in selected three years from 2009 to 2011 showed that these structures could harvest more than eight times of the total storage capacity during monsoon period (Table 3). Water stored in structures was directly used for irrigation during monsoon and post-monsoon periods and structures were filled and refilled as per inflow received. The stored water in structures was also released slowly as base flow during monsoon and after the monsoon period. Amounts of evaporation and deep percolation were found on an average 6% and 18% of total harvested water, respectively.

3.5. Impact of IWD interventions on sediment transport and soil loss

The average annual soil loss measured from the treated watershed was 1.5 t ha^{-1} which was significantly lower than 5.5 t ha^{-1} in control watershed. Soil loss was strongly affected by rainfall intensity (Fig. 11). Rainfall intensity below 50 mm day^{-1} did not generate much soil loss but rainfall intensity more than 50 mm caused significant soil loss especially in control watershed (Fig. 11). Total amount of soil lost from watersheds boundaries is shown for 2007 and 2008 along with storm flow in Figs. 7 and 8, respectively. Year 2007 experienced deficit rainfall therefore amount of surface runoff and soil loss from treated and control watershed was found negligible. On the other hand, soil loss from treated and control watershed was measured as 2.0 t ha^{-1} and 7.2 t ha^{-1} during Jun-Aug 2008, respectively. Moreover, silt deposition in check dams at treated watershed was found less than 10% of their gross storage capacity by the end of year 2011. On the other hand, check dam at outlet of control watershed silted 70% to its gross storage capacity. Low-cost gully control structures constructed at upstream location (shown by black-filled triangles in Fig. 1) and field bunding in agricultural area in treated watershed acted as silt-traps resulting clean runoff at various check dam and downstream locations.

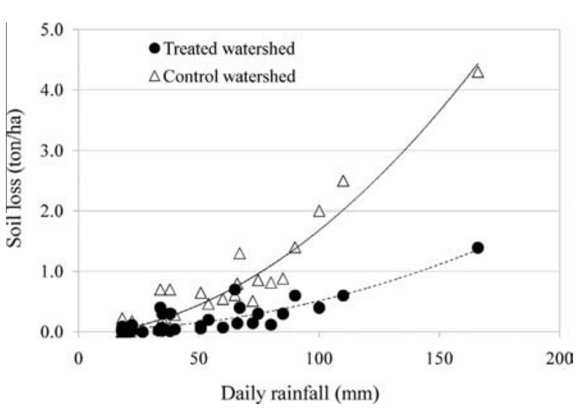

Fig. 11. Rainfall intensity vs. rate of soil loss in treated and control watershed.

3.6. Impact of IWD interventions on land use change

Fig. 12 showed per cent agricultural area under different crops in treated and control watersheds between 2003 and 2011. Thirty to forty per cent of agricultural land was under cultivation and rest of the land was left fallow between 2003 and 2006. Farmers those cultivated land during monsoon were not taking second crop due to lack of residual soil moisture and non-availability of irrigation. Whereas, other farmers were keeping their land fallow during monsoon to harvest green water and cultivating post-monsoon crop (mustard, chickpea and peas) with residual soil moisture. Overall cropping intensity in project villages (treated and control) was recorded from 70% to 90% (maximum one crop per year) between 2003 and 2006. Project villages experienced severe drought between 2005 and 2007 (average rainfall < 460 mm). Year 2006 was worst drought hit as total rainfall received was mere 350 mm (65% less than the long term average) compared to 850 mm in normal year. Despite the IWD interventions in 2005–2006, there was no clear impact observed in terms of cropping intensity compared to base year due to physical water scarcity. IWD interventions were mostly done in 2006–2007. Due to consistent drought, cropping intensity did not show any enhance during this period.

Impact of IWD interventions were observed during and after 2007 in treated watershed. With increased availability of surface and groundwater resources, cropped area increased drastically. About 95% of agricultural land was cultivated largely with black gram and sesame during monsoon; and 70–90% with wheat during post-monsoon that resulted into 190 per cent cropping intensity (double compared to control) between 2009 and 2011 (Fig. 12). Areas under chickpea, mustard and non-edible oil seeds were predominately replaced by wheat in recent years in treated watershed, which however, is relatively more water demanding but economically remunerative and assured crop. On the other hand, no significant changes were found in cropping pattern and cropping intensity in control watershed compared to base year (2003).

3.7. Impact of IWD interventions on crop yield, water productivity and income

Impact of IWD interventions on crop yield, water productivity and income generated from treated and control watersheds are shown from year 2008–2009 to 2011–2012 (Table 4). Average crop yield in GKD watershed from treated and control watershed were recorded as 1.75 and 1.25 t ha^{-1} $season^{-1}$, respectively. In general, IWD interventions with improved crop management enhanced crop yield by 30% to 50% depending on crops, variety and cropping season. IWD interventions reduced crop water stress and significantly improved crop yields. For example, traditionally managed control watershed experienced water shortage by 15–25% than the required quantity in groundnut fields, whereas treated watershed experienced negligible (<10%) water stress (Table 4). *In situ* moisture availability and supplemental irrigation played an important role in supplying water in treated watershed. Crop water productivity was increased from 0.27 to 0.62 kg m^{-3} in treated watershed compared to control area. Interestingly the income generated from treated watershed was nearly double compared to traditionally managed watershed. Average annual income generated from treated watershed was 27,500 INR ha^{-1} compared to 11,500 INR ha^{-1} in control watershed which lagely helped in improving socio-economic status of the community. Economic water productivity in control and treated watershed was estimated as 2.5 and 5.0 INR m^{-3}, respectively.

3.8. Benefit–cost ratio

Economic returns obtained from initial two to three years were found negligible as it was project inception and development phase and during same period watershed experienced with the severe drought situation. Farmers in treated watershed started getting benefits from year 2008 onwards (Table 5). Benefit–cost (B:C) ratio in 2009 exceeded one (>1.0) indicating four years of payback period on invested capital. With increasing economic returns in subsequent years, B:C ratio was estimated to be 2.6 by end of 2011. Moreover B:C ratio without considering institutional cost was found 4.0. Similarly, benefits and costs were further projected up to year 2015 (10 years) using ex-ante analysis showed B:C ratio 3.3 with full project cost and 5.5 without institutional cost; indicating economic feasibility to scale-up IWD interventions to large areas of Bundelkhend region (Table 5).

4. Discussion

4.1. IWD interventions enhanced groundwater and socio-economic resilience

GKD watershed which suffered acute water shortage and land degradation before 2005 has been completely transformed by implementing IWD interventions. Consumptive water use in treated watershed increased from 65% to 75% of total rainfall after the IWD interventions annually. On the other hand, runoff was reduced from 35% to 25% of total rainfall (one third reduction in runoff) due to IWD interventions. Treated watershed however, utilized 10% additional rainwater compared to control watershed and crop production increased by two folds. Such increase in total yield and water productivity could be explained by "*vapour shift*" (Rockstrom, 2003). A large portion of non-productive evaporation from degraded stage is converted into the productive transpiration in recent years. Large fraction of green water was lost from fallow lands either in monsoon or post-monsoon season before the intervention. With increasing soil moisture and groundwater availability, risk of crop failure reduced and farmers could cultivate two crops in a year. IWD interventions including *in situ* and *ex situ* interventions significantly changed water resource availability in watershed. *In situ* interventions helped in enhancing infiltration rate and soil moisture availability and check dam and other structures enhanced groundwater recharge and base flow. This is particularly helpful during dry years when yields and income are very low. With increasing groundwater recharge, farmers were able to grow second crop with supplemental irrigation and cropping intensity doubled, which has made important contribution in household budget. In addition, *ex situ* interventions also captured large fraction of sediment loads within fields and watershed boundary.

Under changing climatic conditions with slight lower annual rainfall, Bundelkhand is expected to experience upcoming future challenges of drought. Long-term weather data of Jhansi indicated that medium duration rainfall events decreased therefore annual rainfall reduced by 100 mm in last 30 years. If such trend continued further, Bundelkhand is expected to face frequent occurrence of dry years and longer duration dry-spells. Such climatic change may adversely affect hydrological cycle and water resources especially groundwater availability in Bundelkhend, which is the only source of water for domestic and agricultural use in the region. Our analysis showed that even from a dry year with 600 mm annual rainfall situation, 60 mm groundwater recharge was possible by implementing IWD interventions compared to mere 30 mm in control watershed. Due to hard rock geology of Bundelkhand region, maximum storage capacity of groundwater aquifer is mere 80 mm as found from current study. Thus, IWD interventions have potential to recharge groundwater aquifer up to 75% of the total aquifer capacity even in a dry year (25% deficit rainfall than normal) compared to mere 35% under the natural situation.

Dryland areas hold huge potential to meet current and future food demand. In order to achieve these targets, integrated watershed development is the promising framework for managing water and natural resource effectively as suggested by Wani et al., 2003, 2009, 2012; Joshi et al., 2008; Rockström et al., 2007; Rockstrom et al., 2010; Singh et al., 2010; Palsaniya et al., 2012. Traditionally, water management dealt with the irrigated agriculture, however, as showed by the comprehensive assessment of water for food and water for life (Molden et al., 2007) that agricultural water management is larger than the irrigation and vast untapped potential of rainfed system need to be harvested (Rockström et al., 2007; Wani et al., 2009, 2011a, 2011b). Therefore, a large portion of green water which is under utilized at present is required to be improved substantially.

4.2. Balancing water needs between upstream and downstream system

From ecosystem point of view, IWD interventions enhanced provisioning ecosystem services (*e.g.*, crop intensification and yield) and regulating ecosystem services (controlling flood, enhancing base flow, reducing siltation and enhancing groundwater availability) in targeted area. Gordon et al., 2010 described that agricultural water management is a central entry point for minimizing upstream–downstream trade-offs and finding synergies between food production and other ecosystem services. They identified three main strategies for maintaining ecosystem services: (i) by improving water management practices on agricultural lands, (ii) better linkage with management of downstream aquatic ecosystems, and (iii) paying more attention to how water can be managed to create multifunctional agro-ecosystems. This can only be done if watershed approach is adopted for managing natural resources and the values of ecosystem services other than food production are well recognized (Sreedevi et al., 2006; Gordon et al., 2010; Garg et al., 2012; Palsaniya et al., 2011).

Large scale IWD implementation however, is expected to improve green water use efficiency, groundwater recharge, income and livelihood of uplands farmers but at the same time it may cause reduction in water availability at downstream locations. Results from current study indicated 30% reduction in surface runoff after implementing IWD interventions. On the other hand IWD interventions also have potential implication for protecting flood and sediment loads to downstream areas. Semi-arid tropical areas are highly vulnerable not only to drought but frequent floods affecting agriculture and livelihood of marginal and smallholder farmers adversely. It is therefore not evident from current analysis whether IWD interventions will have an overall positive or negative impact on downstream systems. Region-specific analysis is needed to assess trade-offs for downstream areas along with onsite impact.

4.3. Comparison of results with other studies

Recently Garg et al., 2012a analyzed impact of IWD interventions on hydrology and soil loss in one of the micro-watershed

(Kothapally) of 500 ha area in southern India. In Kothapally, surface runoff, groundwater recharge and ET were partitioned as 8%, 20% and 72% of total rainfall after implementing IWD interventions, respectively. Despite similar climatic conditions (total rainfall and PET), hydrological response of GKD watershed in current study is found different from Kothapally watershed. Surface runoff from GKD watershed is found relatively higher and less groundwater recharge compared to Kothapally watershed. This difference may be attributed due to different land use, soil characteristics and geological conditions. GKD watershed holds shallow soil depth, surrounded by steep hillocks and also has diverse land use (*e.g.*, forest, scrub land and agricultural land). On the other hand, land use in Kothapally is largely dominated by agriculture and has flat terrain. Specific yield of groundwater aquifer is relatively poor in GKD watershed compared to Kothapally watershed. But commonality of both the watersheds is that IWD interventions addressed food security and land degradation issues and improved livelihood. Similarly Sreedevi et al., 2006 reported that rainwater harvesting through IWD interventions doubled the productivity of groundnut and other major crops, increased cropping intensity by 30% in Rajsamadhiyala watershed of Gujarat in Western India. Moreover due to IWD intervention, downstream villages (Aniyala and Katurba Dham) were also benefited in terms of increased groundwater availability, reduced siltation and flooding through the base flow seepage water and excess runoff.

The benefit-cost analysis from current study indicated economic feasibility to scale up such interventions at large scale in Bundelkhand region. The systematic analysis summarizing multiple benefits derived from 636 watersheds by Joshi et al., 2008 also revealed that watershed programs are silently bringing about a

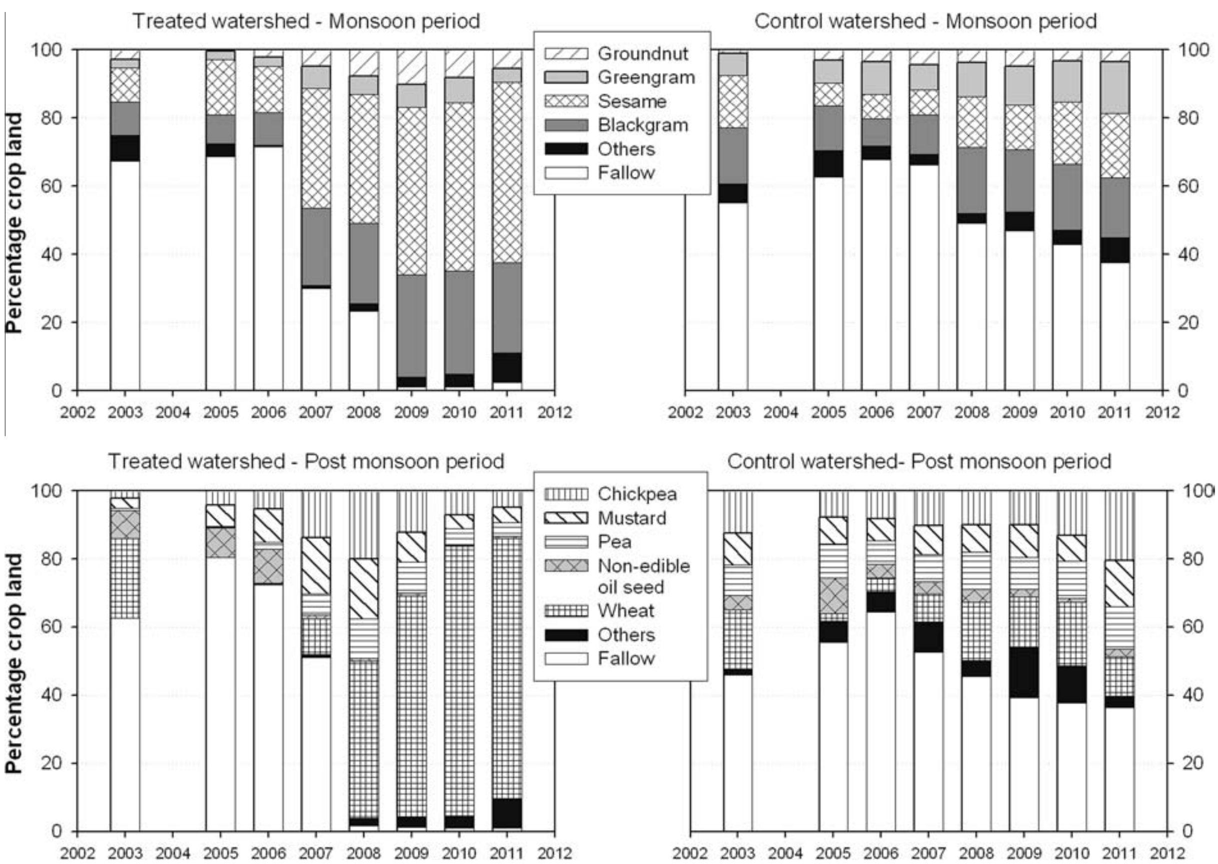

Fig. 12. Change in cropping pattern from year 2006 to 2012 during monsoon and post-monsoon period in treated and control watershed.

Table 4
Impact of integrated watershed development interventions on crop yield, water productivity, income and economic water productivity.

Indicators	2008–09		2009–10		2010–11		2011–12	
	Treated	Control	Treated	Control	Treated	Control	Treated	Control
Cultivable area (ha)	264	136	264	136	264	136	264	136
Gross cultivated area (ha)	448	128	504	124	502	140	470	154
Total annual production (t)	708	159	914	153	1025	179	999	177
ET (mm)	616	526	532	426	524	444	579	462
Average crop productivity (t/ha/season)	1.58	1.24	1.81	1.24	2.04	1.27	2.12	1.15
Water stress factor (–)[a]	0.05	0.15	0.10	0.25	0.06	0.18	0.07	0.22
WP (kg/m^3)	0.44	0.22	0.65	0.26	0.74	0.30	0.65	0.28
Net benefit (INR/ha/year)	23,000	10,600	30,000	10,400	33,200	12,200	32,300	13,000
EWP (INR/m^3)	3.7	2.0	5.6	2.4	6.3	2.8	5.6	2.8

[a] Shown for groundnut during monsoon.

Table 5
Impact of integrated watershed management interventions on benefit-cost ratio.

Source	Year	Development cost (1000 INR)	Institutional + data monitoring cost (1000 INR)	Principle amount + Interest @10% per annum (1000 INR)	Returns measured from treated watershed (1000 INR/ha/year)	Returns measured from control watershed (1000 INR/ha/year)	Benefit due to IWD interventions in Garhkundar watershed (1000 INR/ha/year)	Cumulative benefits (1000 INR/ha/year)	Cumulative project cost (1000 INR/ha/year)	B:C Ratio (With full project cost)	B:C Ratio (considering only development cost)
Measured	2006	2970	330.0	3300.0	–	–	0.0	0.0	12.5	0.0	0.0
	2007		560.0	4190.0	–	–	0.0	0.0	15.9	0.0	0.0
	2008		305.0	4914.0	23.0	10.6	12.5	12.5	18.6	0.7	0.9
	2009		212.0	5617.4	30.0	10.4	19.7	32.1	21.3	1.5	2.1
	2010		186.0	6365.1	33.2	12.2	21.0	53.1	24.1	2.2	3.2
	2011		375.0	7376.7	32.3	12.9	19.3	72.4	27.9	2.6	4.0
Projected	2012		200.0	8314.3	29.7	11.5	18.1	90.5	31.5	2.9	4.5
	2013		200.0	9345.8	29.7	11.5	18.1	108.7	35.4	3.1	4.9
	2014		200.0	10480.3	29.7	11.5	18.1	126.8	39.7	3.2	5.3
	2015		200.0	11728.4	29.7	11.5	18.1	144.9	44.4	3.3	5.5

revolution in rainfed areas with a mean benefit–cost (B/C) ratio of 2.0 with the benefits ranging from 0.82 to 7.30 and more than 99% of the projects were economically remunerative. About 18% of the watersheds generated a B/C ratio above 3, which is fairly modest. However, it also indicated a large scope to enhance the performance of 68% of watersheds that had an average B/C below 2.0. Merely 0.6% of the watersheds failed to commensurate with the cost of the project (Joshi et al., 2005, 2008). Recently, district-level analysis of rainfed crops in India by Sharma et al. (2010) described that harvesting a small portion of the available surplus runoff in rainfed areas and using it for supplemental irrigation at critical crop growth stages can enhance crop productivity by 50% without affecting much at downstream water availability as equivalent amount of water generally is lost through evaporation during transportation process.

4.4. Uncertainties in the analysis and scope for future study

Watershed hydrology is complex and governed by numbers of bio-physical and land management factors. Impact of IWD interventions on various hydrological components were analyzed using data from treated and control watershed by parallel comparison. Both the watersheds are located in same terrain and most of the biophysical and land use factors are same but uncertainties remain in results due to landscape heterogeneity. Scale is other important issue as treated watershed is relatively larger in size compared to control watershed, also bring uncertainty in current analysis. Other than water inputs, WIC which was used to estimate crop evapotranspiration does not consider nutrient and temperature stress could overestimate ET especially in control watershed.

Despite all such limitations, GKD watershed has been intensively monitored in terms of hydrology, soil loss and crop yield and provide a strong base for analyzing impact of IWD interventions and results could be further refined by modeling study. This framework further could be utilized for analyzing impact of land use and climate change on various ecosystem services and upstream–downstream trade-offs. Climate resilient adoption and mitigation strategies should be identified and well tested in advance for addressing food security and welfare of rural community at various scales (watershed to basin) in Bundelkhand region.

The economic analysis in current study consider only direct benefits in terms of crop yield due to IWD interventions compared to control watershed. There are other ecosystem services that have not been valued in this analysis, in particularly supporting and regulating services. Reduction in peak flows and soil loss will remediate sediment loading in downstream water bodies. Other non-valued aspects, which we did not account for in this benefit–cost analysis relate for example to the multiple benefits of improving productivity, income from livestock-based activities and livelihood of farmers in upland areas could be analyzed in future studies.

5. Conclusions

The watershed development program is identified as an adaptation strategy for increasing agricultural production and income under present and future climatic situations of dry lands and also Bundelkhand region of central India. In this study, impact of IWD interventions on water balance components and different ecosystem services were assessed using field and watershed scale monitoring in two different watersheds (with intervention and non-interventions). The key findings of this study are:

- Rainfall in the watershed ranged from 400 to 1100 mm with an average of 815 mm and the majority of which occurred during June to September. IWD interventions changed the hydrological components as ET increased from 58% to 64%, runoff reduced from 35% to 25%, and groundwater recharge enhanced from 7% to 11% of rainfall received in monsoon as compared to no intervention stage.
- Higher groundwater and surface water availability in treated watershed changed cropping pattern from less water demanding chickpea and mustard to high water demanding wheat and other high-value crops during *Rabi*. Cropping intensity increased from 110% to 180% after the interventions. Average economic water productivity and income in treated watershed increased from 2.5 to 5.0 INR m^{-3} and 11,500 to 27,500 INR ha^{-1} yr^{-1} after IWD interventions, respectively.
- IWD interventions however, reduced storm flow substantially but it enhanced base flow in terms of total quantity and duration during monsoon and post monsoon period. In result, check dams harvested more than eight times water than their storage capacity during monsoon season.
- Benefit-cost ratio of the project interventions is found 3.3 considering full project cost and four years of payback period, indicating economic feasibility of IWD interventions to scale-up at large scale areas of Bundelkhend region.

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