Impact of agriculture water management interventions on hydrological processes in a fragile watershed of Western India

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Abstract

Water management interventions play an important role in ensuring sustainable food production and mitigating climate risks. This study was carried out in a watershed located in low rainfall (400-600 mm) region of western India. The paper analyses the changes in hydrological processes with the implementation of various rainwater harvesting (RWH) interventions using field measurements and SWAT simulation. The model was calibrated using the runoff gauging, storage levels, soil loss and groundwater measurements between 2000 and 2006. Various agricultural water management interventions have helped to enhance groundwater recharge from 30 mm to 80 mm, reduced surface runoff from 250 mm to 100 mm and enhanced base flow. The structures were filled 2 to 3 times depending on rainfall variability and total precipitation. The RWH interventions were found to build system resilience by enhancing groundwater availability even in dry years, which was the main reason for crop intensification and protected the landscape from heavy erosion. Sediment erosion reduced more than 75 percent compared to non-intervention stage. Moreover, 100-150 ha fallow land was brought under cultivation with high value crops such as horticulture, vegetables and fodder. The household income increased manifolds compared to non-intervention stage. The study showed about 50 percent reduction in downstream water availability, which could be the major concern. However, there are number of ecosystem trade-offs such as improved base flow and reduction in soil loss. The study is useful for larger scale decision making about optimal water harvesting for achieving sustainable development goals.

1. Introduction

Globally, agriculture is the source of livelihoods for about 60 percent of the population. An area of about 51 million sq km is under agriculture and pastures, which is about 50 percent of global habitable land, to feed increasing population with changing food habits (Ellis*et al* ., 2010). This has ensured food security but at the same time negatively affected the associated ecosystem services resulting in climate change and crossing safe operating boundaries at planetary scale (Rockstrom *et al* ., 2009). With changing face of economic development, pressure on fresh water availability has increased. As a result, number of river basins are facing severe water scarcity and rising transboundary issues and intra sectoral conflicts (Heksotra*et al* ., 2012).

India is one of the fastest growing economies prompting changes in food habits and life styles, which requires more resources. The per capita fresh water availability in India has declined from 5177 m^3 in 1951 to 1545 m^3 in 2011 due to increased population from 361 million in 1951 to 1250 million in 2011. There is limited scope of expanding surface irrigation system as most of the river basins in India are already harvesting more than 75 percent of the probable flow (GoI, 2019). In addition, groundwater resource is also significantly supporting agriculture in dry lands. Currently, India is withdrawing about 250 km^3 of fresh water annually from groundwater aquifers, which is the highest in the world (Shah, 2009). Groundwater resource is contributing $2/3^{rd}$ of the total irrigated area in the country. A large portion of cultivated area in the country is rainfed and the productivity is less than 1-1.5 t ha^{-1} as these areas face frequent droughts and witness acute moisture stress during critical crop growth stage making agriculture vulnerable to production risks (Wani *et al* . 2011). However, there exists a large scope to enhance productivity in the rainfed system through suitable technological interventions.

In this context, water management interventions have gained enormous attention to address risks in small scale production systems (de Fraiture *et al* ., 2010; Gordon *et al* ., 2010; Garg *et al* ., 2011; Kadyampakeni *et al* ., 2015; Anantha and Wani, 2016). Adopting a holistic resource management approach through integrated watershed development has paid rich dividends in rainfed areas and proved that this approach is capable of addressing many technological, natural, social and environmental issues in the dryland ecosystems (Wani*et al* ., 2003, 2011a, 2011b; Rockstrom *et al* ., 2010; Garg*et al* ., 2011, 2012; Garg and Wani, 2012; Anantha and Wani, 2016). Therefore, the Government of India, with support from several funding agencies, has invested more than US$ 14 billion since 1990 on Integrated Watershed Management Program (IWMP) (Mondal, *et al* ., 2020). This program has helped to enhance resource conservation to benefit a wide range of stakeholders in terms of ensuring food, income and livelihoods (Barron *et al* ., 2015). However, there is a poor documentation of impact of these interventions despite huge investments made over four decades, mostly due to lack of focus on data generation on key indicators such as hydrology, biophysical and socio-economic changes to understand the hydrological process in different agro-ecological regions. Most of the hydrological data are available at river basin/large-scale catchment area, which has limited scope to downscale for meso scale understanding due to complex hydrological processes (Glendenning *et al* ., 2012). There is almost no information on meso scale (500-5000 ha). With this background, this paper describes the journey of an integrated watershed approach in one of the degraded landscapes of Bundi district of Rajasthan state in western India and its impact on watershed hydrology, land degradation, land use, crop yield and economics from 2000 onwards. The study findings are critical for refining interventions and improving investments in agricultural water management and sustaining different ecosystem services.

2. Materials and methods

2.1 Description of study area

This study was focused on a fragile watershed with undulated topography in Bundi district (25.58° N; 75.41° E) of Rajasthan state, western India. This watershed drains from 4800 ha area with a population of 1800 (**Figure 1**). About one-third of total geographical area in the region is under degraded landscape. Rainfall of the region ranges between 400 mm and 600 mm annually and the potential evaporation demand is 1800-2000 mm. Agriculture and allied sectors are the main sources of livelihood and are largely dependent on locally harvested surface runoff and groundwater resources for domestic and agricultural use.

The soil water holding capacity was medium to low and the soil organic carbon content was poor ($< 0.5\%$). The landscape is undulating at upstream locations, which was under the range land having 2-5 percent slope whereas the valley portion of the watershed is mainly covered with farming. Sorghum, pearl millet, maize and pigeonpea are the major crops grown during monsoon (*kharif)* season; mustard, chickpea and wheat are grown with supplemental irrigation during the post-monsoon (*rabi*) season. In addition, livestock is also playing an important role in the livelihood system of the watershed.

ICRISAT and its partners together have developed this watershed as a site of learning between 1999 and 2005. Prior to this, there were several issues ranging from acute water shortage, land degradation, poor agricultural and livestock productivity. More than 90 percent of total agricultural land in the watershed was rainfed with mono-cropping system. Crops suffered from water scarcity and experienced moisture stress even during monsoon season due to long dry spells (5 to 7-day dry spells) usually occurring 5 to 7 times in a season. Average crop productivity ranges between 1,000-1,500 kg ha^{-1} of sorghum/maize/pearl millet and 200-300 kg ha^{-1} of pigeonpea.

A wide range of water management interventions have been implemented both at community and individual field scale. The most common *in situ* interventions are contour and graded bunds in the fields, which reduced travel distance and minimized the velocity of runoff and allowed more water to percolate into the fields. A number of *ex-situ*interventions such as renovation of village tanks, check dams, check walls, percolation ponds, etc., harvest significant amount of surface runoff from upland and facilitated groundwater recharge. In addition to the interventions implemented by ICRISAT and its partners, a number of other state and central government schemes were converged between 2006 and 2010 creating altogether 1.5 million m^3 water storage capacity. **Figure 1** shows the location of different RWH structures developed from 2000 onwards.

The total harvesting capacity of existing RWH structures is equivalent to 320 m^3 ha^{-1} (which is equivalent to 32 mm of the storage capacity) in the watershed. Out of 13 RWH structures, there were 3 major structures with a combined capacity to harvest 1.35 MCM and an earthen embankment of width 3-5 meter was constructed across the slope to harvest surface runoff from upstream sites and masonry outlet was given for safe disposal of excess water. These structures together have a water spread area of 90 ha. Farmers store water during the monsoon period and cultivate crops in the tank beds during post-monsoon period using residual soil moisture along with supplemental irrigation from wells. In addition to these structures, other small to medium size storage structures were also constructed following ridge-to-valley approach. In addition to RWH interventions, emphasis was also given to integrated crop management practices including soil-test-based fertilizer application, introduction of improved crop cultivars, integrated pest, disease and weed management through farmer participatory demonstrations and capacity building. The adopted research methodology of this study is summarized in**Figure 2** .

2.2 Data monitoring

Profile soil samples from 0-15, 15-30, 30-60 cm were collected from 34 locations in the watershed and analysed for characterizing soil physical properties - texture, field capacity and permanent field capacity. Bulk density of different soil layers was also collected by core cutter. Another 36 samples were collected for analyzing soil nutrient status from top soil (0-15 cm) from across the watershed. Information on soil depth was elucidated based on farmers' experience by undertaking a survey.

The location and storage capacity of RWH structures constructed during different periods were also recorded through topography survey. Storage capacity and water spread area at full capacity was estimated. Runoff at one of the micro watersheds was measured using automatic gauge recorder between 2002 and 2006 (**Figure 1**). A mechanical type stage recorder was installed at the outlet of the micro watershed, which is draining from 27 ha area, and was programmed to record data at every 30 min interval. The designed unit does smart sampling by linking the runoff sampling intervals to the sediment load (Pathak *et al* ., 2016). During the runoff event, flowing water at every one-hour interval is pumped automatically and stored in separate containers throughout the runoff events. These samples were analyzed to estimate total soil loss from the micro-watershed.

Water depth in one of the check dams (S11) was monitored manually on daily time scale during the monsoon season between 2002 and 2005. Groundwater data from 10 locations in treated watershed area and 10 in nearby control watershed, those mainly located in agricultural area, was monitored between 2002 and 2006. Data on number of pumping hours, crop yield, cost of cultivation were also recorded from selected farmers' fields between 2002 and 2006.

2.3 Hydrological modeling

Model set up and parameterization

Soil and water Assessment Tool (SWAT)

SWAT is one of the semi-process based hydrological models, which has been widely used for water resource assessment, studying impact of change in land use and various agriculture water management interventions at catchment and basin scales (Arnold *et al* ., 2012). This model is flexible to build local scale agriculture water management interventions along with land topography, soil types and land use details. A digital elevation model (DEM) was downloaded from the global data base (Aster 30 m resolution). A soil map was created based on the actual data (36 samples) collected from the watershed and was given as an input to the model (**Table 1**). A land use map of 2010 was classified using RS techniques. The total 4800 ha area was divided in to 37 sub basins and 85 Hydrological Response Units (HRUs). A total of 13 reservoir nodes were added into the model set up, which represented the actual *ex-situ* water harvesting interventions; their storage capacity, submergence and other details were given based on actual measurements. Eleven years' daily rainfall (1999-2010) data was provided as an input and other meteorological parameters were provided to the model on daily time scale.

The total landscape of the watershed is divided into three main categories viz., agriculture, range-land and settlements. Information on agriculture management practices was provided as an input to the management files. Maize was grown as a *kharif* crop (July-Oct) under rainfed condition and winter wheat was chosen in post-monsoon period (Nov-Feb). Tillage operation, date of sowing and harvesting, fertilizer application data was provided as per the survey details. For the wheat crop, 5 irrigations were given using shallow aquifer as a source of water. The model was run between 1999 and 2010. Model calibration was done based on the actual surface runoff and soil loss measured from a micro watershed, water level in one of the check dam sites and groundwater table data. For simulating non-intervention stage, the reservoirs were removed from the model simulation and the model was run for the same period (1999-2010). **Table 1** and **Table 2** show the parameter values assigned while doing model calibration.

3. Results

3.1 Rainfall characterization

The long term rainfall data of Bundi district between 1985 and 2010 shows that annual average rainfall of the district was 562 mm with a huge temporal variability. Average number of rainy days in a year were 35 (with more than 2.5 mm rainfall/ day). Out of that, 18 days received rainfall less than 10 mm, 13 days had rainfall between 10 and 30 mm and 3 days received 30-50 mm and minimum one rainfall of more than 50 mm/ day (**Figure 3a**). With this distribution, 118 mm of rainfall amount received from low intensity events (< 10 mm); 230 mm from medium intensity (10-30 mm) and 125 mm from high intensity events (30-50 mm). Moreover, 90 mm amount of rainfall is received through very high intensity events of greater than 50 mm (**Figure 3b**).

3.2 Model performance

Figure 4a shows the simulated hydrograph of a micro watershed (27 ha, refer **Figure 1** for gauging location) and observed surface runoff on daily time scale. Rainfall values were also plotted along with the surface runoff between 2002 and 2006. Model simulated surface runoff was in agreement with observed data for both low and high intensity rainfall. **Figure 4b** shows observed and simulated runoff on 1:1 line. RMSE and R^2 of simulated and observed values were 9 mm and 0.68, respectively. However, there are number of missing data (shown in red cross) during the monitoring period due to various field related constraints.

Similarly, **Figure 5** compares the simulated reservoir storage (m^3) of structure number S11 with observed data. Both simulated and observed data followed a similar pattern. However, for some of the events, the simulated values were a little under estimated but the overall performance of the model in predicting reservoir volume was in close agreement with the observed value. Data recorded for most of the events are found to be in agreement with the simulated results.**Table 2** shows the calibrated model parameters bringing the simulated value close to observed data.

The simulated groundwater recharge was also compared with observed groundwater table data (**Figure 6**). The change in pressure head in respective monsoonal months were compared with simulated groundwater recharge for 3 years (i.e., 2003, 2004, 2005). As both are different parameters are presented on different Y axis. It can be seen in the figure that simulated groundwater recharge is following the trends in the observed water table increase.

The model performance of predicting soil loss was found satisfactory.**Figure 7a** and **Figure 7b** compare simulated soil loss with measured values between 2003 and 2006. Out of the total 23 events, average soil loss measured from micro-watershed was found to be 0.4 ton/ha compared to 0.6 ton/ha in simulated model and R^2 was found to be 0.62. It was very difficult to match the simulation with that of the measured data perfectly as sediment transport is a very complex phenomenon. However, the model was able to simulate soil loss with high runoff events but is overpredicted during small and medium rainfall intensity events.

3.3 Water balance components

Major water balance components (groundwater recharge, base-flow, outflow and ET) of before and after interventions is presented for dry, normal and wet years (**Figure 8**). Out of eleven years, five were normal, three wet and three dry years. The rainfall in normal year was 500 mm whereas it was 350 mm in dry years and 630 mm in wet years. The simulation results suggested that the evapotranspiration was the major consumer of the monsoonal water balance in all the years. In dry years, out of 350 mm, 250 mm was consumed as ET and the rest of the water was generated as outflow (80 mm) and approximately 20 mm is recharged as groundwater during before project interventions. After the intervention, the generated runoff was harvested in the RWH structures; the outflow was found negligible. *In-situ* interventions also enhanced soil moisture availability and flow towards actual ET increased within the monsoon period (increased by 50 mm). During normal year, about 60 percent of rainfall received was converted into ET within the monsoon period. Out of 150 mm of surface runoff, which was leaving from the watershed boundary before the intervention, about 100 mm was harvested by *ex-situ* interventions and enhanced the groundwater recharge while about 50 mm is spilled out. Whereas in wet years, 50 percent of the total rainfall received was partitioned as ET, 40 percent as outflow and 10 percent as groundwater recharge before the project interventions. This has also altered as 25 percent of total runoff is generated as outflow, which was leaving out from the watershed boundary and the rest 25 percent contributed to groundwater recharge after the project interventions.

Figure 9 further shows the relationship between rainfall and the outflow, base flow and groundwater recharge for no-intervention and with intervention stage. There was a positive relationship found between outflow and groundwater recharge, as expected. While the outflow has reduced significantly the groundwater recharge has increased implying that the AWM interventions have influenced groundwater recharge. About 50-70 mm groundwater recharge was taking place during wet years under no-intervention stage whereas the equivalent amount of recharge was found even in the 300 – 400 mm rainfall condition after the project intervention. The base flow, which used to be 10-15 days before the intervention has now increased to 30-40 days after the project interventions.

Figure 10 shows a clear evidence of groundwater availability from measured groundwater table data collected from treated watershed and nearby control watershed. Both the watersheds, however, show similar pattern during the monsoon. However, there is a significant difference in water availability after the post-monsoon period. For example, in January 2004, there was a 10-meter difference in water table between treated and control watersheds. This difference was found to be 3 meters even in driest month of May. Similar observations were also found in 2005. During post-rainy season, most of the wells, which were either drying or had little water (1-3 mts) have rejuvenated with surplus amount as average water table increased by 5-8 meters. Interestingly, nearly 30 percent of the wells, which were functioning during monsoon period have turned into perennial sources both for domestic as well as agriculture use.

With increased water availability in the watershed, farmers are able to pump groundwater between 7 and 11 hours compared to 1 and 4 hours before interventions during rainy and post-rainy seasons, respectively. Due to increased recharge capacity, the well recovery time after the pumping has reduced from 14 hours to 10 hours during rainy season. Similar pattern was observed during post-rainy and summer seasons as recovery period has shortened by 6 to 9 hours (**Table 3**). Increased water availability has facilitated supplemental irrigation at critical stages and the average area supported by a well for supplemental irrigation increased by three times compared to non-intervention stage.

The total storage capacity of RWH structures was equivalent to 32 mm.**Figure 11** shows the relationship between cumulative rainfall and number of fillings of these structures. As expected, with increasing rainfall the number of fillings of the RWH structures has increased. These structures were found to be filled 3 to 3.5 times with maximum rainfall amount in wet years. Whereas these fillings, in dry and normal years, are simulated to be 1 to 2.5 times. The variability is due to rainfall intensity and its amount.

Figure 12 further shows that variability in number of fillings from location to location varied from 1-10 depending on location and storage capacity. The RWH structures were categorized into five groups based on the number of fillings. Structures those with smaller capacity generally got filled more number of times and the amount of inflow is multiple times more than the bigger structures. The runoff generated from low intensity rainfall also is sufficient to fill the small structures. Structures located downstream to the bigger structure got less opportunity to receive inflow (e.g., S10).

Figure 13 shows the generated runoff from the outlet of the watershed between 2000 and 2010 along with monthly rainfall for both no-intervention and with-intervention condition. There is a significant reduction in the outflow due to upstream water harvesting interventions. About 30-40 percent reduction in the outflow during wet and normal years and more than 70 percent reduction was simulated during dry years. Outflow was found sensitive with rainfall received in the current and previous months. **Figure 14** further shows spatial variability in runoff coefficient from upstream to downstream reservoir locations for dry, normal and wet years. Runoff coefficient varied from 0.1 to 0.4. In general, the runoff from first order streams/upstream locations (e.g., S7, S11, S12) were relatively more compared to downstream (e.g., S6, S9, S10, S13) due to upstream harvesting. Upstream sites are characterized by high land slope and have shallow soil depth. The generated runoff from such HRUs were found to be 30-40 percent of total rainfall received. The runoff coefficients were found high in wet years compared to normal and dry years as expected. Out of 13 structure sites, runoff coefficient for 3 structures was more than 0.4; 5 structures had between 0.2 and 0.4; and rest were less than 0.2. The overall runoff coefficient of the watershed (S13) was between 0.1 and 0.2 in all the years.

Figure 15 shows total simulated cumulative sediment loading between 2000 and 2011 from the outlet of the watershed under no-intervention and with intervention condition. The RWH interventions were found very effective in controlling soil loss. Total soil loss from the outlet under the no intervention stage was estimated to be about 17,000 tons in 10-year period whereas it was found to be only about 4000 tons after the project intervention. In other words, about 3.4 tons of soil loss was reduced to 0.8 ton/ha due to RWH interventions (i.e., 76% reduction in soil loss).

3.4 Uncertainty about the results

Efforts were made to collect a good amount of data on soil physical properties (texture, water holding capacity and soil depth) and efforts were also made on hydrological monitoring at the selected micro watershed. Based on this, the model was calibrated. However, there are a number of uncertainties existing due to complex interactions of land use, land cover, topography and soil type. Moreover, the percolation behavior of different reservoir sites also influenced inflow and outflow characteristics, which may lead to uncertainty in water balance analysis. It may be noted that the model considers constant infiltration rate of the storage structures whereas it varies within the monsoon period, which may overestimate the deep percolation and groundwater recharge. We have assumed default parameters of shrub/range lands during model development. Moreover, maize/wheat cropping system was considered while developing model whereas the project area is characterized by a wide range of cropping systems and management practices.

3.5 Impact on crop intensification and crop yield

Rainwater harvesting interventions at Gokulpura-Thana watershed recorded increased water availability, which has translated into intensifying cropping system both during rainy and post-rainy seasons. **Figure 16a** and **Figure 16b** show the area under different crops cultivated before (1999) and after (2004) the interventions, both during rainy and post rainy seasons, respectively. A significant cultivable fallow land (nearly 25-30% both in rainy and post-rainy season) was converted into productive agriculture land. About 10 percent of fallow land has been used for horticulture crops during monsoon and the rest of the fallow land has been utilized for vegetable cultivation during post-rainy season. During summer season, about 40-50 ha area was also used for green fodder production.

Figure 17 shows the increase in crop yield before and after project interventions during rainy and post-rainy seasons. The crop yield increased from 40 to 300 percent in different crops; Maize yield increased from 1050 kg ha^{-1} to 3200 kg ha^{-1}; wheat yield in post rainy season increased from 3000 kg ha^{-1} to 5600 kg ha^{-1}; mustard yield increased from 1500 kg ha^{-1} to 2300 kg ha^{-1}; chickpea yield from 950 kg ha^{-1} to 1500 kg ha^{-1} after the project interventions. With increased water availability, not only vegetable area but also the yields nearly doubled (from 4000 kg ha^{-1} to 7500 kg ha^{-1}). With increased cropping intensity and productivity, the net income from agriculture sector has increased many folds. Average household income from agriculture was US$ 300/year before the project interventions, which increased to US$ 1200/year after the project.

4. Discussion

It is evident that the rainwater harvesting interventions in Govardhanapura-Thana watershed have altered the hydrological processes. About 40 percent of total rainfall was generated as surface runoff before watershed interventions, which was leaving to the downstream area. There was little (less than 5%) groundwater recharge. With the implementation of large scale water harvesting interventions, this situation has reversed as, out of total generated runoff, more than 50 percent is harvested within the watershed and rest of the amount is left out to downstream. This has impacted the groundwater recharge and has contributed towards crop intensification. Results show that altogether 150 mm additional water is now being harvested and utilized as consumptive water in agriculture. With such additional water harvesting, the total production from agriculture has increased multiple times. In this watershed, a large scale upstream landscape (range land) was the major source for generating freshwater in valley areas (agriculture). As the soil depth and water holding capacity of the range land is relatively less, more than 50 percent of rainfall is generated as runoff. Upstream to downstream water harvesting has given opportunity to harvest the generated runoff in decentralized manner and given opportunity to farmers to cultivate nearby fields with supplemental irrigation. More than 150 ha area was brought under productive cultivation with assured groundwater availability. A good amount of surface runoff was generated even in dry years. However, the downstream release was most affected due to upstream water harvesting.

The findings of the study raise a number of concerns toward downstream water availability, although the upstream is benefited. There are trade-offs between development of upstream ecosystems and downstream water availability. Rainwater harvesting in the upstream, on one hand enhances the productivity and also controls the flooding, enhances the base flow and controls the land degradation. The results clearly showed that there was more than 75 percent reduction in soil loss with implementation of rainwater harvesting interventions. Heavy sedimentation is one of the biggest concerns for the downstream authorities (e.g., reservoir operators and managers) as storage capacity of most of the reservoirs in India (e.g., Dams) has reduced by 20 percent as compared to their original level in the last three to four decades (Durbude, 2014; Shukla *et al* , 2017). Heavy sedimentation also transports important nutrients such as nitrogen, phosphorus and other minerals from agriculture fields and pollute downstream water bodies, which resulted into eutrophication and poor water quality (Wang*et al* ., 2013; Haregeweyn *et al* ., 2019).

Blue water (groundwater and surface runoff) is most sensitive with change in rainfall variability. A large portion of the rainfall received is being partitioned into ET as it is the first environmental allocation. The remaining amount generated in any form of blue water depends on the landscape management. Before the intervention, surplus water was in the form of surface runoff whereas it partitioned both in terms of surface runoff and groundwater recharge after the project intervention. About 80-120 mm of surplus water stored in the groundwater aquifers (which is one of the reliable source) is available for various stakeholders. Rainwater harvesting has built the groundwater resilience. A given amount of surplus water, if available in groundwater aquifer, can stay longer and is readily available. Measured field data also shows, if it is recharged once in a year it is available for the subsequent years. Carry over groundwater availability from the previous year alleviates the stress condition in follow up dry years, which is an important resilience building strategy against drought.

The study also discusses the number of times a structure is filling during the monsoon period. In this watershed, due to high percolation, there was a repetitive opportunity to harvest surface runoff within the monsoon period. It was found that few of the structures were filled more than 10 times in a year, but few had filled less number of times. This is mainly dependent on location (catchment) and storage capacity of the structures. For example, 3 out of 13 structures had storage capacity of more than 0.3 MCM though the amount of inflow was not in the same magnitude. Therefore, these structures were filled less than once whereas few of the structures had the storage capacity between 3000-10000 m^3 and inflow was many folds higher and had the opportunity to fill the structure frequently. However, the steep topography was also one of the important factors keeping the hydraulic gradient high for maintaining a high infiltration behavior of the study landscape. On an average, these structures were filled 2-3 times in a normal year.

The study results are a little different from the agricultural landscape watersheds, which are relatively flatter and intensively cultivated. There is limited scope to generate surplus water, especially in the agriculture dominated watersheds. Only the wet years provide opportunity to harvest. There are a number of studies that discuss the regional scale water balance but very few attempt to understand meso-scale water balance components. Dashora *et al* ., (2019) have analysed the water balance components of rainwater harvesting structures in the similar ecology of a fragile landscape (Udaipur, Rajasthan state). They found that RWH structures are contributing in terms of maximum groundwater recharge and fill four times their capacity in wet years. Similar to current study, Glendenning and Vervoort (2011a, b) have reported that RWH structures have helped to enhance groundwater availability and in mitigating the risk of crop failure in Arvari catchment, Rajasthan. However, a significant decline in downstream water availability due to upstream rainwater harvesting interventions was the major concern. They also found that there is a limited scope of groundwater recharge after crossing a threshold of RWH structures as increasing the size/density of RWH structures does not always contribute to groundwater recharge. Rather, it impacts downstream flow negatively whereas in the current study, due to higher slope gradient, the large scale harvesting also was not the limiting factor for groundwater recharge.

Crop intensification is the essence of the rainfed system but it requires supplemental support. The supplemental support has been created within the watershed by constructing rainwater harvesting structures. The additional resources required for sustainable development are generated within the landscape whereas downstream have to improve their use efficiency to keep the production sustainable. This study shows both upstream benefits and the downstream consequences. The study will be helpful for understanding site specific decision making on optimizing available resources. Similar efforts are needed towards data monitoring and system level analysis for different agro-ecological regions to bridge the knowledge gap and for facilitating informed decisions.

5. Conclusion

The paper has analysed the impact of decentralized rainwater harvesting interventions in a fragile watershed in western India. Ridge-to-valley approach was followed to construct rainwater harvesting structures between 1999 and 2004. This watershed was intensively monitored and number of parameters, including biophysical, meteorological, hydrological, crop productivity, land use change, soil loss and socio-economic characteristics were collected. The collected data was used to calibrate hydrological model (Soil and Water Assessment Tool) and the results were simulated between 2000 and 2010 to capture rainfall variability. The impact of rainwater harvesting intervention on watershed hydrology and different water balance components was analysed. It is proved that rainwater harvesting has helped to enhance groundwater recharge more than double compared to non-intervention stage; however, it reduced surface runoff by more than 50 percent. The outflow from the watershed reduced by over 70 percent in dry and normal years and reduced by 50 percent in wet years. However, the RWH interventions reduced the sediment loading by more than 75 percent compared to non-intervention stage.

Groundwater augmentation has helped to enhance crop intensification, reduced the risk of crop failure and enhanced crop yield from 50 to 300 percent. Additional area was brought under cultivation with assured water availability and the farmers' incomes were enhanced many folds (3-5 times). The paper also discusses the spatial and temporal variability of different water balance components. The findings of the study would be helpful for various stakeholders to take informed decisions while planning water harvesting interventions by considering downstream consequences.

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Table 1 : Soil biophysical properties of the watershed (All these values were assigned to model as input layers)

Depth	Gravel %	Coarse sand %	Fine Sand %	Silt %	Clay %	Available Water Content (mm H_2O/mm soil)	Field capacity (mm H_2O/mm soil)	Perman wilting point (mm H_2O/m soil)
	ROCK	SAND	SAND	SILT	CLAY	_		
0-15	9 (7)	15 (10)	41 (7)	30 (9)	14 (5)	0.090	0.190 (0.040)	0.10 (0.
15-30	5 (5)	14 (10)	37 (8)	32 (8)	18 (6)	0.10	0.210 (0.040)	0.11 (0.
30-60	30 (4)	48 (9)	22 (8)	20 (8)	9 (5)	0.09	0.180 (0.020)	0.090 (0.010)

Sample size for each layer (n= 36); Figures in parenthesis show standard deviation from mean

Table 2 : Model parameterization. Initial and final values given before and after calibration

Variable (unit)	Parameter in SWAT	Initial value	Final Value	So
Organic carbon (%)	_	-	0.4 (0.2-0.6)	M
Soil Depth (mm)	_Z	-	500 (100-800)	Su
Saturated Hydraulic conductivity (mm/hr)	_K	-	2.0-8.0	Es
Curve number (-)	CN	70	65-75	Ca
Hydraulic conductivity of the reservoir bottom (mm/hr)	_K	8.0	12.5	Ca
Groundwater revap coeff. (-)	GW_REVAP	0.02	0.2	Ca
Threshold depth of water for revap in shallow aquifer (mm H_2O)	REVAP_MN	1	0.3	Ca
Channel erodibility factor (-)	CH_EROD	0.0	0.5	Ca
Channel cover factor (-)	CH_COV	0.0	0.5	Ca
USLE equation support practice factor (-)	USLE_P	1.0	0.5	Ca

* Data in parenthesis show minimum to maximum range of parameter value

Table 3. Impact of watershed interventions on groundwater yield (Data based on field observation)

Season	Pumping duration (hrs.)	Pumping duration (hrs.)	Recharge recovery period (hrs.)	Recharge recovery per
	Before Int.	After Int.	Before Int.	After Int.
Rainy	4	11	13.5	10
Post-rainy	1.5	6.5	21	16
Summer	0	1	30	21

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Figure 2: Flow diagram on adopted methodology

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Figure 4a : Comparing simulated surface runoff with measured gauging data at micro watershed on daily scale between 2002 and 2006;**Figure 4b** : Measured versus simulated surface runoff on 1:1 line (on daily time scale)

Figure 5 : Comparing simulated reservoir volume with measured data for S11 on daily-time scale between 2002 and 2005

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Figure 9 : Relationship between rainfall and outflow, base flow and groundwater recharge with intervention (after) and no-intervention (before) stage at Govardhanapura-Thana watershed, Bundi, Rajasthan; results based on 11-year simulation model.

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Figure 14 : Variability in runoff coefficients at upstream and downstream locations during dry, normal and wet years

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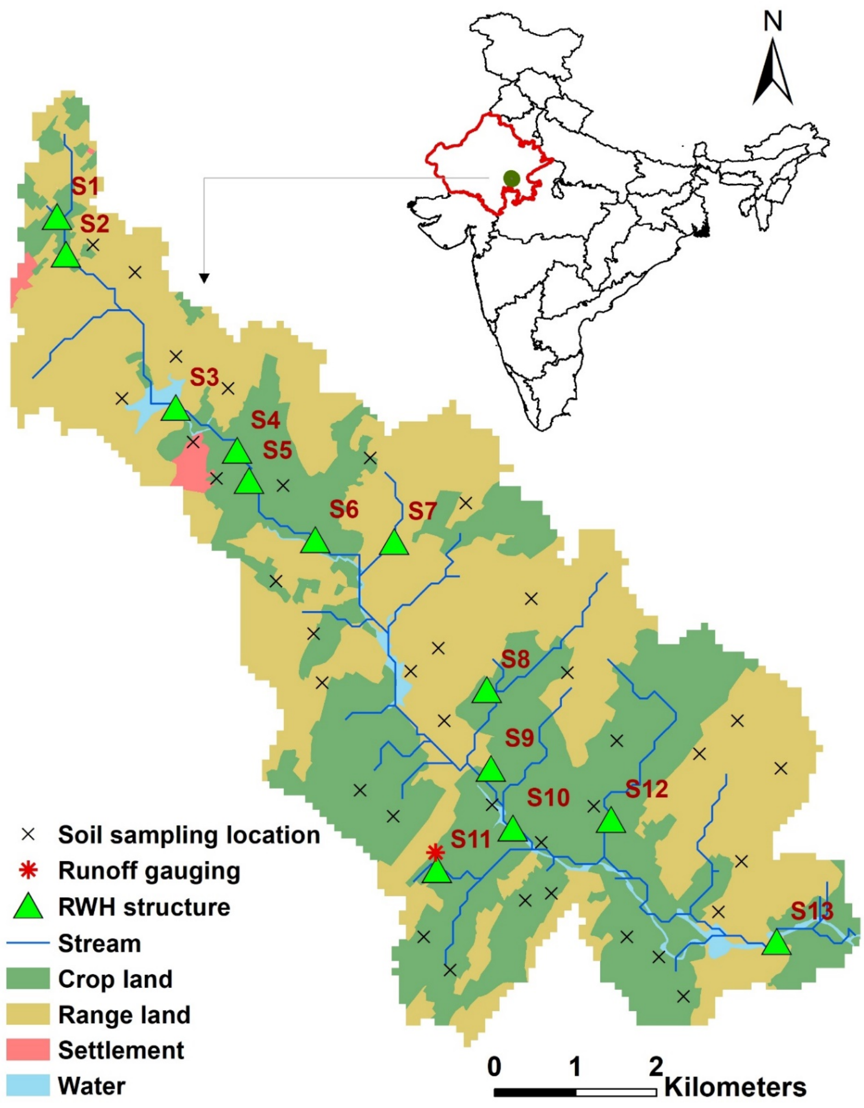
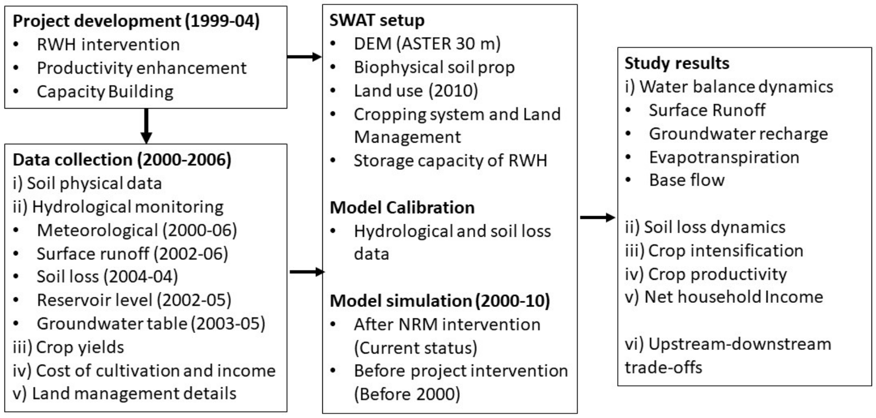
Figure 17. A comparison of yields of major crops before and after watershed interventions in Govardhanapura-Thana watershed, Bundi, Rajasthan

Hosted file

`Data Availability Statement.docx` available at https://authorea.com/users/333654/articles/459792-impact-of-agriculture-water-management-interventions-on-hydrological-processes-in-a-fragile-watershed-of-western-india




Project development (1999-04)
• RWH intervention
• Productivity enhancement
• Capacity Building
Data collection (2000-2006)
i) Soil physical data
ii) Hydrological monitoring
• Meteorological (2000-06)
• Surface runoff (2002-06)
• Soil loss (2004-04)
• Reservoir level (2002-05)
• Groundwater table (2003-05)
iii) Crop yields
iv) Cost of cultivation and income
v) Land management details
SWAT setup
• DEM (ASTER 30 m)
• Biophysical soil prop
• Land use (2010)
• Cropping system and Land Management
• Storage capacity of RWH
Model Calibration
• Hydrological and soil loss data
Model simulation (2000-10)
• After NRM intervention (Current status)
• Before project intervention (Before 2000)
Study results
i) Water balance dynamics
• Surface Runoff
• Groundwater recharge
• Evapotranspiration
• Base flow
ii) Soil loss dynamics
iii) Crop intensification
iv) Crop productivity
v) Net household Income
vi) Upstream-downstream trade-offs

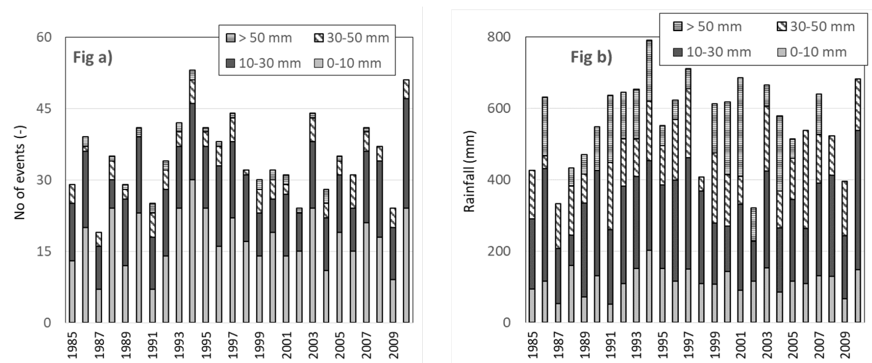


Fig a)
No of events (-)
> 50 mm
30-50 mm
10-30 mm
0-10 mm
Fig b)
Rainfall (mm)

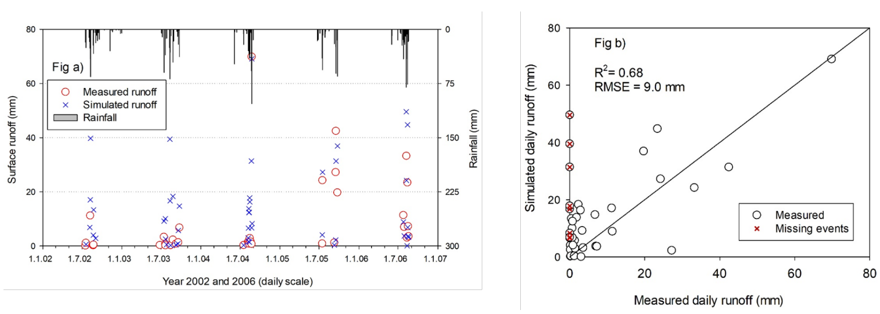


Fig a)
Measured runoff
Simulated runoff
Rainfall
Surface runoff (mm)
Rainfall (mm)
Year 2002 and 2006 (daily scale)
Fig b)
R^2= 0.68
RMSE = 9.0 mm
Measured
Missing events
Simulated daily runoff (mm)
Measured daily runoff (mm)

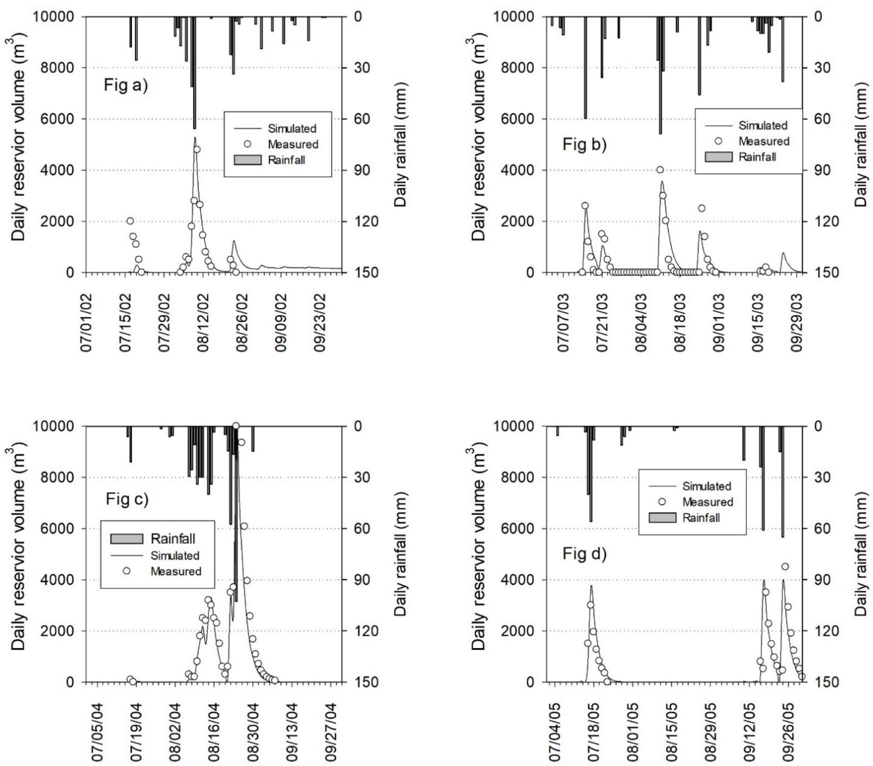


Fig a)
Fig b)
Fig c)
Fig d)
Daily reservior volume (m3)
Daily rainfall (mm)
Simulated
Measured
Rainfall
07/01/02
07/15/02
07/29/02
08/12/02
08/26/02
09/09/02
09/23/02
07/07/03
07/21/03
08/04/03
08/18/03
09/01/03
09/15/03
09/29/03
07/05/04
07/19/04
08/02/04
08/16/04
08/30/04
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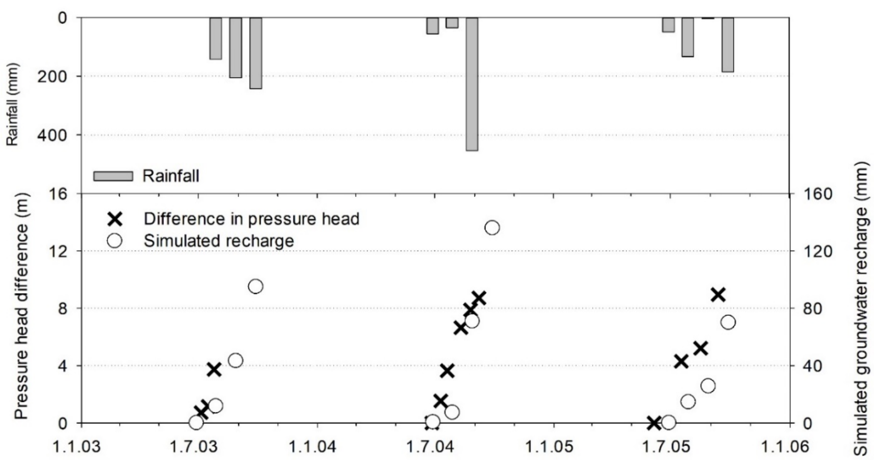
09/12/05
09/26/05


Rainfall (mm)
Rainfall
Difference in pressure head
Simulated recharge
Pressure head difference (m)
Simulated groundwater recharge (mm)
1.1.03
1.7.03
1.1.04
1.7.04
1.1.05
1.7.05
1.1.06

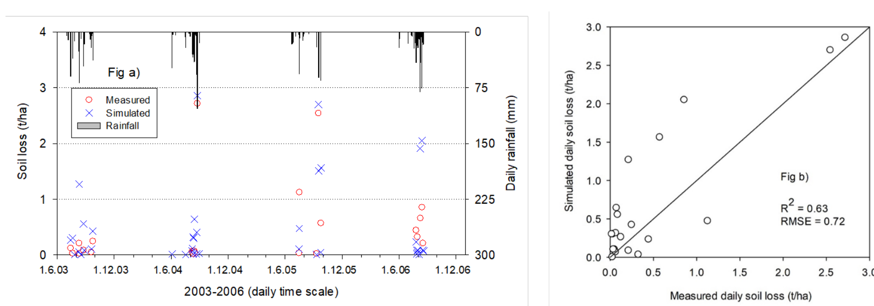
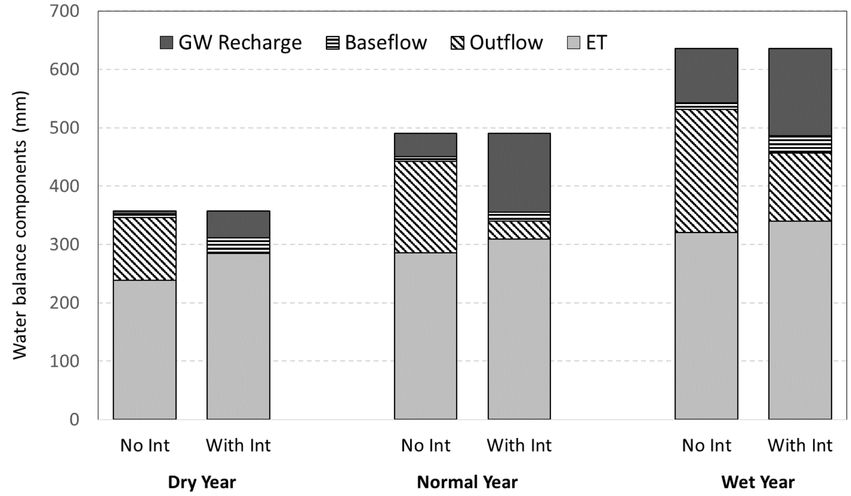
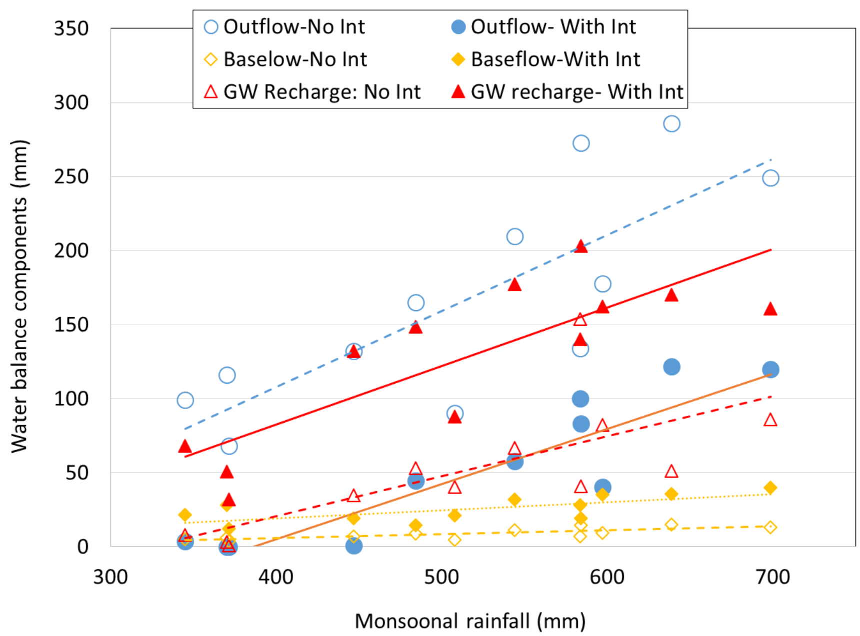
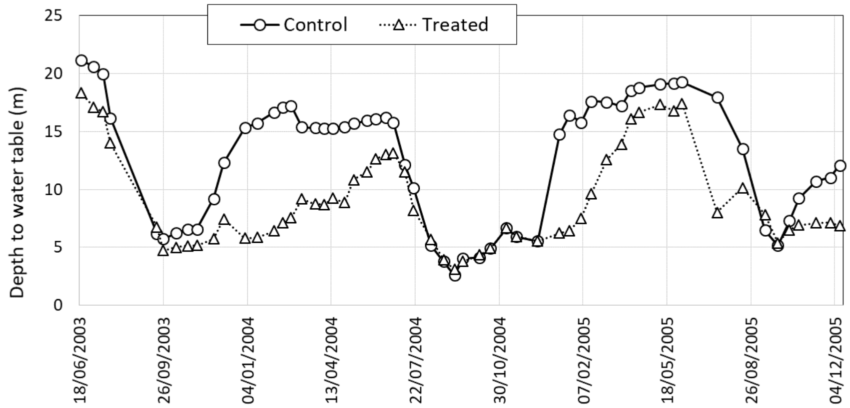
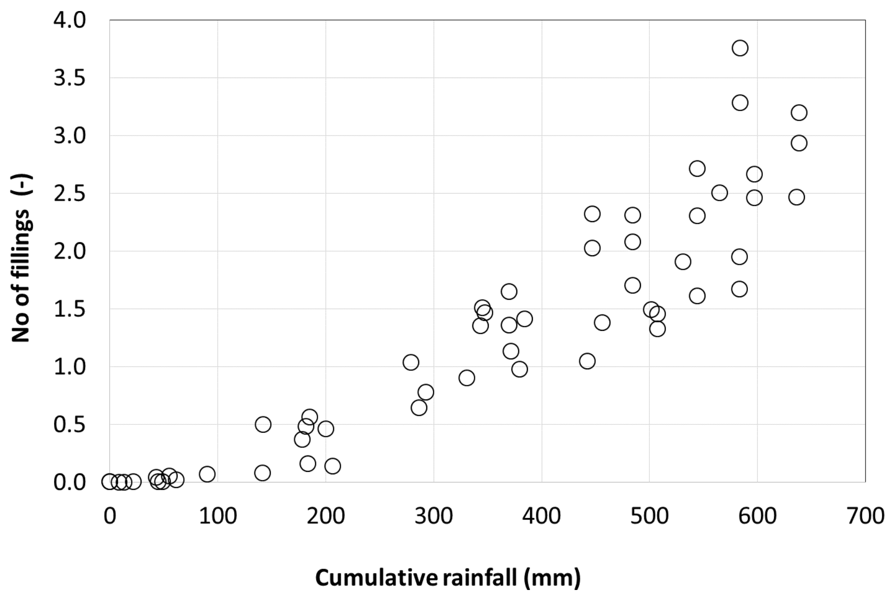


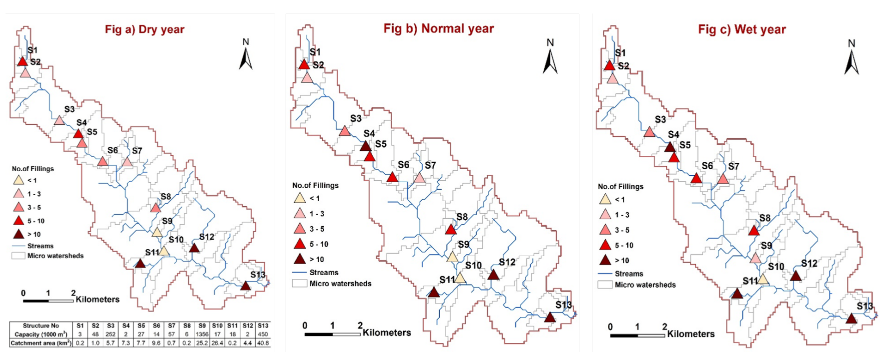
Fig a)
Measured
Simulated
Rainfall
Soil loss (t/ha)
Daily rainfall (mm)
1.6.03
1.12.03
1.6.04
1.12.04
1.6.05
1.12.05
1.6.06
1.12.06
2003-2006 (daily time scale)
Fig b)
R2 = 0.63
RMSE = 0.72
Simulated daily soil loss (t/ha)
Measured daily soil loss (t/ha)


GW Recharge
Baseflow
Outflow
ET
Water balance components (mm)
700
600
500
400
300
200
100
0
No Int
With Int
No Int
With Int
No Int
With Int
Dry Year
Normal Year
Wet Year

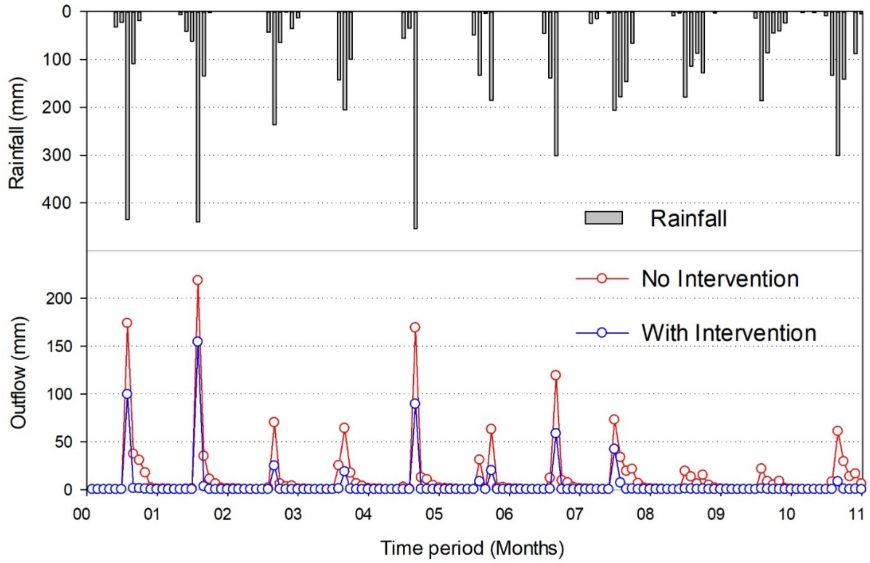

Outflow-No Int
Outflow- With Int
Baselow-No Int
Baseflow-With Int
GW Recharge: No Int
GW recharge- With Int
Water balance components (mm)
350
300
250
200
150
100
50
0
300
400
500
600
700
Monsoonal rainfall (mm)







Structure No	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
Capacity (1000 m^3)	3	48	252	2	27	14	57	6	1356	17	18	2	450
Catchment area (km^2)	0.2	1.0	5.7	7.3	7.7	9.6	0.7	0.2	25.2	26.4	0.2	4.4	40.8



Rainfall (mm)
Rainfall
Outflow (mm)
No Intervention
With Intervention
Time period (Months)

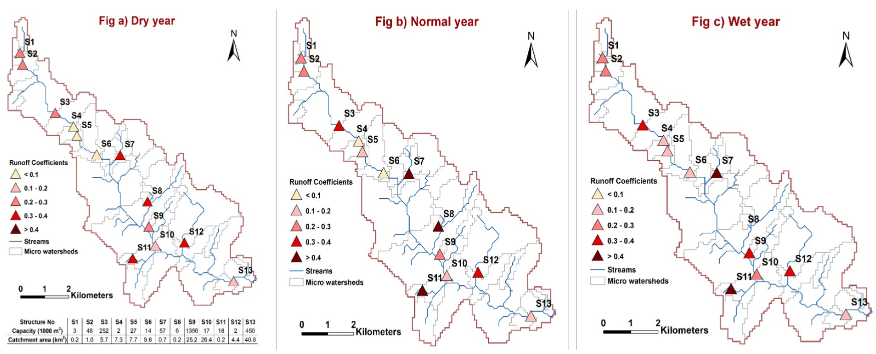
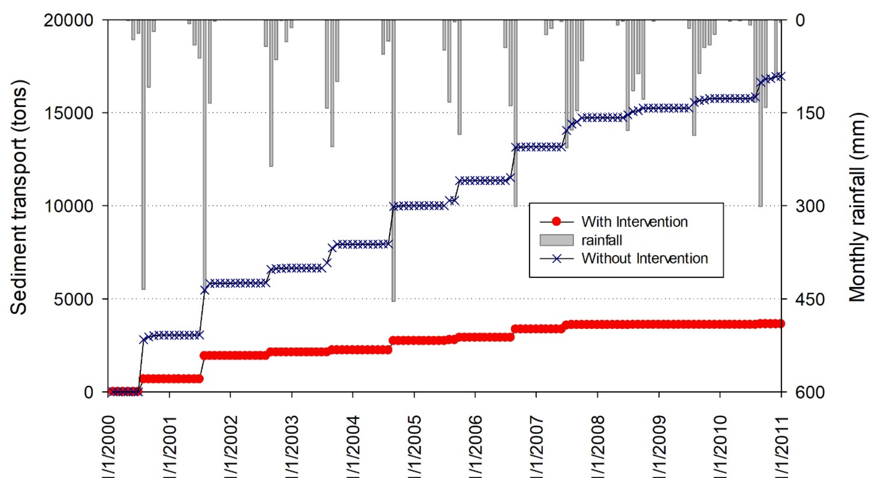


Fig a) Dry year
Fig b) Normal year
Fig c) Wet year
Runoff Coefficients
Streams
Micro watersheds
Kilometers



Sediment transport (tons)
Monthly rainfall (mm)
With Intervention
rainfall
Without Intervention

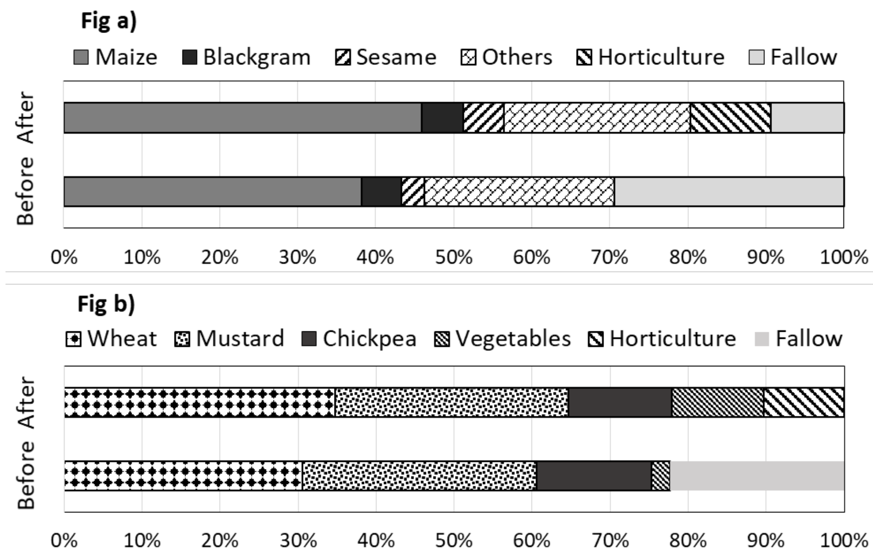
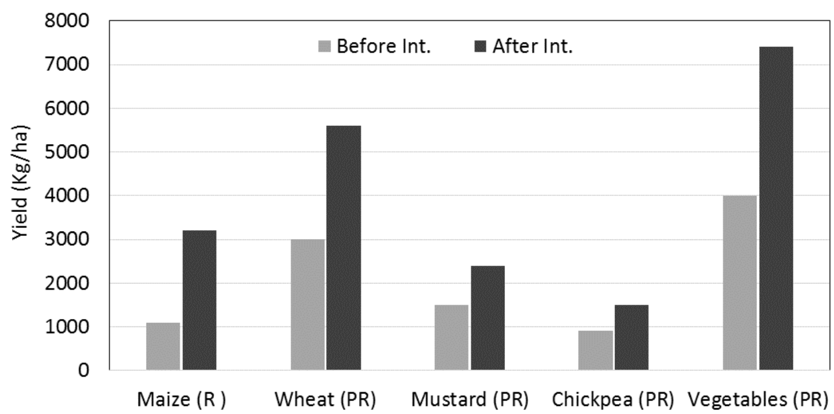


Fig a)
Maize
Blackgram
Sesame
Others
Horticulture
Fallow
Before
After
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Fig b)
Wheat
Mustard
Chickpea
Vegetables
Horticulture
Fallow
Before
After
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


Before Int.
After Int.
Yield (Kg/ha)
0
1000
2000
3000
4000
5000
6000
7000
8000
Maize (R)
Wheat (PR)
Mustard (PR)
Chickpea (PR)
Vegetables (PR)