Research Paper/

# Impact of rainwater harvesting on hydrological processes in a fragile watershed of South Asia

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## Conflict of Interest

The authors declare no conflict of interest.

**Key words**: SWAT, soil erosion, water management, integrated watershed management, water balance component, upstream-downstream trade-offs

**Article Impact Statement:**

*Agricultural water management interventions helped to build groundwater resilience and strengthened ecosystem services in the drylands*


## Abstract

Agricultural water management (AWM) interventions play an important role in ensuring sustainable food production and mitigating climate risks. This study was carried out in a watershed located in a low rainfall (400-600 mm) region of western India. The SWAT model was calibrated using surface runoff, soil loss and reservoir storage levels, between the year 2000 and 2006. The investigation indicated that the various AWM interventions increased groundwater recharge from 30 mm/year to 80 mm/year and reduced surface runoff from 250 mm/year to 100 mm/year. The intervention structures were refilled 2 to 3 times during the monsoon season depending on rainfall intensity and duration. The interventions have the advantage of building a resilient system by enhancing groundwater availability even in dry years, stimulating crop intensification and protecting the landscape from severe erosion. The results indicate that soil erosion has been reduced by more than 75% compared to the non-intervention situation. Moreover, the AWM interventions led to the cultivation of 100-150 ha of fallow land with high value crops (horticulture, vegetables and fodder). Household income increased by several-folds compared to the non-intervention situation. The study showed about 50% reduction in downstream water availability, which could be a major concern. However, there are a number of ecosystem trade-offs such as improved base flow to the stream and reduction in soil loss that should be considered. The study is of great importance to stakeholders to decide on the optimum design for AWM interventions to achieve sustainable development goals.

## Introduction

Globally, agriculture and its allied sectors are a source of livelihood for about 60% of the population (FAO, 2020; de Janvry and Sadoulet, 2020). About 51 million sq kms are under agriculture and pastures, comprising nearly 50% of global habitable land, to feed an increasing population with changing food habits (Duro *et al.*, 2020). In addition, there are the negative effects of climate change on the environment and ecosystem services (Rockstrom *et al*., 2009; Bahar *et al*., 2020; Gerten *et al.*, 2020). The pressure on freshwater resources has increased to keep pace with economic development. As a result, a number of river basins are facing severe water scarcity and rising transboundary and intra-sectoral conflicts (Hoekstra and Mekonnen, 2012; Garg and Azad, 2019; Omer *et al*., 2020; Abraham and Ramachandran, 2020).

India is one of the fastest growing economies prompting changes in food habits and lifestyles, which require more resources (Michler, 2020). Per capita freshwater availability in India has declined from 5177 $m^3$ in 1951 to 1545 $m^3$ in 2011 due to the increase in population from 361 million in 1951 to 1250 million in 2011 (Wani *et al*., 2014) . There is limited scope to expand irrigable land with declined water resource availability (Mukherjee *et al*., 2018; Ali *et al*., 2019). Agriculture in the drylands is largely supported by groundwater resources (Garg et al., 2020a,b). Currently, India withdraws about 250 $km^3$ of freshwater annually from groundwater sources, which is the highest in the world (Gleeson *et al*., 2016; GoI, 2019). Groundwater constitutes 2/3rd of the total irrigated area in the country (Green *et al*., 2020). A large portion of cultivated area in the country is rainfed with low productivity of 1-1.5 t/ha (Rao *et al*., 2015). 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; Singh *et al*., 2014; Garg *et al*., 2020a). Despite these challenges, there is considerable scope to enhance productivity in rainfed agriculture through suitable technological interventions (Gerten *et al*, 2020; Anantha et al., 2021a).

In this context, agricultural water management (AWM) interventions have attracted attention in addressing risks in small scale production systems in Asia and Africa (de Fraiture *et al*., 2010; Gordon *et al*., 2010; Garg *et al*., 2011; Kadyampakeni *et al*., 2015; Anantha and Wani, 2016; Adimassu *et al*., 2017; Abera *et al*., 2019). The focus has been on landscape restoration through the constructing of water infiltration structures as well as biological measures (Adimassu *et al*, 2017; Abera *et al*., 2019; Kato *et al*, 2019; FAO, 2020; Anantha et al., 2021b). Adopting a holistic resource management approach through integrated watershed development has paid generous dividends in rainfed areas and proved capable of solving and positively addressing many technological, natural, social and environmental issues in dryland ecosystems (Wani *et al*., 2011; Rockström *et al*., 2010; Garg *et al*., 2011 and 2012a; Garg and Wani, 2012; Singh *et al*., 2014; Anantha and Wani, 2016; Garg *et al*., 2020a).

Since 1990, the Government of India, with support from several funding agencies, has invested more than US$ 14 billion on its Integrated Watershed Management Program (Mondal *et al*., 2020; Anantha et al., 2021b). The program has helped enhance resource conservation to benefit a wide range of stakeholders in terms of ensuring food, income and improving livelihoods (Barron *et al*., 2015). However, there is a poor documentation of the impacts of these interventions on the environment despite the huge investments made over three decades. This has been largely due to a lack of focus on data generation on key indicators such as hydrology, biophysical and socio-economic changes to understand the hydrological processes in different agro-ecological regions.

Most of the hydrological data is available at river basin/large-scale catchment area, which is difficult to downscale to smaller areas (Glendenning *et al*., 2012) as there is almost no information available at the mesoscale (500-5000 ha) landscape. Moreover, there is a poor understanding of the impact of upstream landscape development on downstream ecosystem services and its trade-offs.

Against this background, this study describes an integrated watershed approach adopted in one of the degraded landscapes of Bundi district of Rajasthan State in western India and quantifies its impact on watershed hydrology, land degradation, land use, crop yield and economics between the years 2000 and 2006. Intensive field data on various biophysical, hydrological and land use parameters were collected. Further, a Soil and Water Assessment Tool (SWAT) was applied to compute water balance components. The study's findings are critical to refine interventions and improve investments in agricultural water management and to sustain different ecosystem services. The objectives of the study are to: (i) analyze the impact of various AWM interventions on groundwater recharge, land use change and crop productivity at uplands; and (ii) assess freshwater availability and sediment load at downstream locations.

## Materials and methods

### Description of the study area

This study was conducted on a fragile watershed (Govardhanapura-Thana watershed) with undulating topography in Bundi district (25.58° N; 75.41° E) of Rajasthan state, western India (Pathak *et al*. 2013). The study watershed covers 4800 ha and a population of 1800 (**Figure 1**). About a third of the total geographical area in the region is under degraded landscapes (Pathak *et al*. 2007, 2013). Rainfall in the region ranges between 400 mm and 600 mm annually and potential evaporation demand is 1800-2000 mm (Sharma *et al.* 2018). 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 (Pathak *et al*. 2013).

The water holding capacity of the soil is medium to low and its soil organic carbon is poor (< 0.5%). The landscape is undulating at upstream locations which are rangelands with a 2-5% slope whereas the valley of the watershed consists mainly of farm lands (Pathak *et al*. 2013). Sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), maize (*Zea mays*) and pigeonpea (*Cajanus cajan*) are the major crops grown during the rainy season (*kharif*, June to October); and mustard (*Brassica nigra*), chickpea (*Cicer arietinum*) and wheat (*Triticum aestivum L.*) are grown with supplemental irrigation during the post-rainy season (*rabi*, November to March). In addition, livestock plays an important role in the livelihood system of the watershed (Wani *et al.* 2014).

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and its partners developed this watershed as a study site between 1999 and 2005. Prior to this, the site was beset with acute water shortage, land degradation, and poor agricultural and livestock productivity (Pathak *et al*. 2013). More than 90% of total agricultural land in the watershed was rainfed with mono-cropping. Crops suffered from water scarcity and experienced moisture stress even during the rainy season due to long dry spells (5 to 7-day dry spells), usually occurring 5 to 7 times in a season. Average crop productivity ranged between 1,000 kg/ha and 1,500 kg/ha in sorghum/maize/pearl millet and between 200 kg/ha and 300 kg/ha in pigeonpea (Pathak *et al*. 2013; Wani *et al*. 2014).

A wide range of AWM interventions have been implemented both at community and individual field scales. The most common *in-situ* interventions are contour and graded bunds in the fields, which reduce travel distance, minimize the velocity of runoff and allow more water to percolate into the fields (Garg *et al.* 2011). *Ex-situ* interventions such as the renovation of village tanks, check dams, check walls, percolation ponds, etc., harvest significant amount of surface runoff from uplands and facilitate groundwater recharge (Singh *et al.* 2014; Garg et al. 2020a). 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, altogether creating 1.5 million $m^3$ (MCM) of water storage capacity (Pathak *et al*., 2013). **Figure 1** shows the location of the different AWM storage structures developed from the year 2000 onwards.

The total water harvesting capacity of existing AWM interventions is equivalent to 320 $m^3$/ha (32 mm of the storage capacity) in the watershed. Out of the 13 water storage structures, there were 3 major structures with a combined capacity to harvest 1.35 MCM. An earthen embankment of 3-5 meters wide was constructed across the slope to harvest surface runoff from upstream sites and a masonry outlet spillway was constructed for the safe disposal of excess water (Pathak *et al*., 2013; refer **Figure 2**). These structures together have a water spread of 90 ha. Farmers store water during the rainy period and cultivate crops in the tank beds during the post-rainy period using residual soil moisture and supplemental irrigation from wells. In addition, small to medium sized storage structures were constructed following the ridge-to-valley approach. In addition to various *ex-situ* AWM interventions, there was emphasis on integrated crop management practices including soil test-based fertilizer application, introduction of improved crop cultivars and integrated pest, disease and weed management through farmer participatory demonstrations and capacity building (Pathak *et al*. 2013).

**Data monitoring**

A total of 36 agricultural fields were identified to characterize the soil's physical and chemical properties following a systematic random sampling method. The soil analysis was meant to ascertain soil fertility in the farmers' fields as well as their water holding capacity. Soil samples were collected at 0-15 cm, 15-30 cm and 30-60 cm depths from 36 locations in the watershed to analyze the texture, bulk density, field capacity and permanent wilting point. Another 36 samples across the watershed were collected to analyze the soil nutrient status from the top soil (0-15 cm). Information on soil depth was derived based on farmers' experience as indicated in the survey.

The location and storage capacity of structures constructed during different periods were recorded through a topography survey. The elevation of the landscape was measured through a "total station" survey instrument and a contour map developed, based on which the water harvesting capacity was measured through Simpson's rule (Biswadeep 2015; Takal *et al*. 2017). Runoff at one of the micro-watersheds was measured using an automatic gauge recorder between 2002 and 2006 (**Figure 1**). A mechanical type stage recorder was installed at the outlet of the micro-watershed receiving drainage from 27 ha; the stage recorder was programmed to measure data at 30-minute intervals. The unit does smart sampling by linking the runoff sampling intervals to the sediment load (Black and Luce 2013; Pathak *et al*. 2016). During the runoff, water flowing at hourly intervals was pumped automatically and stored in separate containers. To measure soil loss, water samples collected during runoff events were analyzed in a laboratory for sediment concentration. Each runoff event hydrograph was divided into 60-minute time segments and sediment concentration data was superimposed on the runoff hydrograph to estimate soil loss. This was computed by multiplying the volume of segment runoff by sediment concentration (Pathak *et al*. 2016). Water levels in one of the check dams (S11) was monitored manually on a daily time scale during the rainy season between 2002 and 2005.

The water table in 10 wells in the treated watershed (where AWM interventions were implemented) and 10 wells in the nearby control watershed (without treatment) was monitored between 2003 and 2005. The location of the wells in the treated watershed are shown in **Figure 1**. In addition, data on the number of pumping hours, crop yield and cost of cultivation were recorded from selected farmers' fields for different crops between 2002 and 2006. To estimate crop yields, crop cutting studies were undertaken on a 5 m x 5 m area and grain yield was estimated during the crop harvest (Tek *et al*. 2016).

## Hydrological modeling

### *Model set up and parameterization*

Soil and Water Assessment Tool (SWAT) is a semi-process based hydrological model that has been widely used for water resource assessment, and to study the impact of changes in land use and agriculture water management interventions at catchment and basin scales (Arnold *et al*. 2012; Dile *et al*., 2016a and 2016 b; Worku *et al*., 2017; Mekonnen *et al*., 2018; Woldesenbet *et al*., 2017 and 2018; Berihun *et al*., 2020; Horan *et al*., 2021). The model's flexibility enables to parameterize local scale agricultural water management interventions along with land topography, soil types and land use details. A digital elevation model (DEM) was downloaded from the global database (Aster 30 m resolution). A soil map was created based on the measurements obtained from 36 samples collected from the watershed and provided as input to the model (**Table 1**). A land use map of 2010 was classified using remote sensing techniques. The total 4800 ha area was divided into 37 sub-basins and 85 Hydrological Response Units (HRUs). A total of 13 reservoir nodes were added into the model, which represented the actual *ex-situ* interventions, their storage capacity and submergence area based on actual measurements. Eleven years' rainfall (1999-2010) and other meteorological parameters (maximum and minimum temperature, relative humidity, wind speed and solar radiation) were provided to the model on a daily time scale.

The total landscape of the watershed was divided into three categories - agriculture, rangeland and settlements. Information on agriculture management practices was provided as an input to the management files. Maize was grown as a rainy season crop under rainfed conditions and winter wheat was chosen in the post-rainy season. Tillage operations, date of sowing and harvesting and fertilizer application data were provided according to the survey details. For the wheat crop, five irrigations were given using a shallow aquifer as a source of water. The model was run between 1999 and 2010. Model calibration was done based on observed surface runoff, soil loss measured from a micro-watershed, water level in one of the check dam sites and water table data. The model was run with and without the structural interventions. To simulate a non-intervention scenario, the reservoirs were removed from the model simulation and the model was run for the same period (1999-2010).

***Analysis of water balance components***

As rainfall is the only source of water, it was partitioned into different water balance components. Rainfall data was analyzed on a daily, monthly and yearly time scale for the study period. To understand the intensity of rainfall distribution, daily data was classified into four major categories (low = < 10 mm; medium = 10-30 mm; high = 30-50 mm and very high = > 50 mm) (Rao *et al.* 2013). Major water balance components (runoff/outflow, groundwater recharge, base flow and evapotranspiration) were computed from the calibrated SWAT model. The result was summarized and classified as per the India Meteorological Department's specification (Rao *et al.* 2013) for a dry year (rainfall < 20% of long term average); normal year (rainfall ±20% of long term average) and wet year (rainfall > 20% of long term average).

## Results

### Soil properties and climate

*Soil properties*

**Table 1** describes layer-wise physical properties of the soil in the study watershed. Soils were characterized by their high sand content ranging from 56% to 70%. The percentage of sand increased from the 0-15 cm layer to 30-60 cm layer. Gravel content ranged from 5% to 30% and its fraction increased with depth. Field capacity and permanent wilting point were found to be 0.18-0.21% and 0.09-0.11 % (volume basis), respectively, indicating that water holding capacity is 0.10 m per meter of soil.

**Table 1**: Biophysical properties of the soil in the watershed (all these values were assigned to the model as input).

| Soil layer depth (cm) | Gravel (%) | Coarse sand (%) | Fine sand (%) | Silt (%) | Clay (%) | Available Water Content (m/m) | Field capacity ($m^3$ water / $m^3$ soil) | Permanent wilting point ($m^3$ water / $m^3$ 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 (0.020) |
| 15-30 | 5 (5) | 14 (10) | 37 (8) | 31 (8) | 18 (6) | 0.10 | 0.210 (0.040) | 0.11 (0.020) |
| 30-60 | 30 (4) | 48 (9) | 22 (8) | 21 (8) | 9 (5) | 0.09 | 0.180 (0.020) | 0.090 (0.010) |

Sample size for each layer (n= 3).

Figures in parentheses show standard deviation from mean.

*Rainfall characterization*

The long term rainfall data of Bundi district between 1985 and 2010 shows that annual average rainfall in the district was 562 mm with a significant year to year variability (**Figure 3a**). The average number of rainy days in a year was 35 (with more than 2.5 mm rainfall/ day). Of these 35 days, 18 days received rainfall of less than 10 mm, 13 days had rainfall between 10 mm and 30 mm and 3 days received between 30 mm and 50 mm and one event that received more than 50 mm. With this distribution, a total of 118 mm of rainfall was 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 rainfall was received through very high intensity events of greater than 50 mm.

**Figure 3b** explains the variability in maximum and minimum air temperature, relative humidity and rainfall for the selected year (2000). The study area was characterized by three predominant seasons: (i) rainy season from June to October which is hot and humid; (ii) winter season from November to March which is cold and dry and (iii) summer season from March to June which is hot and dry. The highest temperature reached was 45$^{O}$C in May while the minimum temperature of 6$^{O}$C was recorded during December and January. August was the most humid month with relative humidity > 80% while it was less than 20% during March to May. Data also showed that more than 85% of the rainfall in 2000 was concentrated in July and August.

**Model performance**

**Table 2** shows the calibrated parameter values to capture the mesoscale hydrology of the study watershed. Organic carbon ranged between 0.2% and 0.6% with a mean of 0.4%. The average soil depth of the landscape was 0.5 m, which varied from 0.1 m to 0.8 m. Saturated hydraulic conductivity which was derived using pedo-transfer function, ranged from 2-8 mm/hour. **Table 2**

shows the other calibrated parameters (CN, GW_REVAP, RES_K, REVAP_MN) controlling hydrological processes and those that control soil dynamics (CH_EROD, CH-COV and USLE_P). Hydraulic conductivity of the reservoir's bottom and curve number was found sensitive towards runoff generation.

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

| Variable (unit) | Parameter in SWAT | Initial value | Final value | Source |
|---|---|---|---|---|
| Organic carbon (%) | SOL_CBN | - | 0.4 (0.2-0.6) | Measured |
| Soil depth (m) | SOL_Z | - | 0.5 (0.1-0.8) | Surveyed |
| Saturated hydraulic conductivity (mm/hr) | SOL_K | - | 2.0-8.0 | Estimated by Pedo-transfer function (Schaap *et al*. 2001) |
| Curve number (-) | CN | 70 | 65-75 | Calibrated |
| Hydraulic conductivity of the reservoir's bottom (mm/hr) | RES_K | 8.0 | 12.5 | Calibrated |
| Groundwater upward flux to the root zone (revap coefficient) (-) for shallow aquifer | GW_REVAP | 0.02 | 0.2 | Calibrated |
| Threshold depth of upward water flux to the root zone ( revap) in shallow aquifer (mm water) | REVAP_MN | 1 | 0.3 | Calibrated |
| Channel erodability factor (-) | CH_EROD | 0.0 | 0.5 | Calibrated |
| Channel cover factor (-) | CH_COV | 0.0 | 0.5 | Calibrated |
| USLE equation support practice factor (-) | USLE_P | 1.0 | 0.5 | Calibrated |

* Data in parentheses show minimum to maximum range of parameter value.

**Figure 4a** compares the simulated surface runoff of a micro-watershed (27 ha, refer to **Figure 1** for gauging location) with observed daily surface runoff between 2002 and 2006. The model simulated surface runoff was in agreement with observed data for both low and high intensity rainfall. RMSE and $R^2$ of simulated and observed values were 9 mm and 0.68, respectively. However, there was missing data (indicated by a red X) during the monitoring period due to field related constraints.

**Figure 4b** compares simulated soil loss with measured values between 2003 and 2006. Out of the 23 events, average soil loss measured from the micro-watershed was 0.4 t/ha compared to 0.6 t/ha in the simulated model, and $R^2$ was found to be 0.62. It was very difficult to perfectly match the simulation with the measured data as sediment transport is a very complex phenomenon. However, the model was able to simulate soil loss with high runoff events but was overestimating during small and medium rainfall intensity events.

**Figure 5 a-d** compares the simulated daily reservoir storage ($m^3$) of structure number S11 during 2002, 2003, 2004, and 2005 with observed data. Both simulated and observed data followed a similar pattern. However, for some of the events, the simulated values were slightly underestimated 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 were in agreement with the simulated results.

**Water balance components**

Major water balance components (groundwater recharge, base flow, outflow and ET) for the two scenarios, with and without interventions, are presented for dry, normal and wet years (**Figure 6**). Of the 11 years, 5 were normal years, 3 were wet and 3 were dry. The rainfall in normal years was 500 mm while it was 350 mm in dry years and 630 mm in wet years. The simulation results suggested that ET was the major consumer of monsoonal water balance in all the years. In the absence of an intervention, in dry years, of the 350 mm, 250 mm was utilized as ET and the rest of the water generated outflow (80 mm) and approximately 20 mm was recharged in the groundwater. After the intervention, the runoff generated was harvested in the storage structures and the outflow was found to be negligible. *In-situ* interventions also enhanced soil moisture availability and flow towards actual ET increased within the monsoon period (50 mm increase). During normal years, about 60% of rainfall received was utilized as ET within the monsoon period. Of the 150 mm of surface runoff which left the watershed boundary before the intervention, about 100 mm was harvested by *ex-situ* interventions and enhanced groundwater recharge while about 50 mm spilled out. In wet years in the absence of interventions, total rainfall received was split into 50% ET, 40% outflow and 10% towards groundwater recharge, which saw a change to 55% ET, 20% outflow and 25% as groundwater recharge following project interventions.

**Figure 7** shows the relationship between rainfall and outflow, base flow and groundwater recharge in both intervention and non-intervention scenarios. A positive relationship between outflow and groundwater recharge was evident. While outflow reduced significantly, groundwater recharge increased, implying that the AWM interventions have a positive impact on groundwater recharge. While there was about 50-70 mm of groundwater recharge during wet years under a non-intervention scenario, recharge was in the range of 150 mm to 200 mm with interventions. The base flow duration, which used to be 10-15 days before the intervention, increased to 30-40 days after the project interventions.

**Figure 8** shows clear evidence of groundwater availability from measured water table data collected from the treated watershed and the control watershed. Both watersheds, however, showed a similar pattern during the monsoon. There was remarkable 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 during the driest month of May. Similar observations were made in 2005. During the post-rainy season, most of the wells, which were either drying or had little water (1-3 m) were rejuvenated with surplus amount as the average water table increased by 5-8 meters. Interestingly, nearly 30% of the wells, which were functioning during the monsoon period, turned into perennial sources of water for both domestic and agriculture use.

With increased water availability in the watershed, farmers were able to pump groundwater between 7-11 hours/day compared to 1-4 hours/day before the interventions during the rainy and post-rainy seasons, respectively. Due to increased recharge capacity, a decline was observed in the well recovery time after pumping, from 14 hours to 10 hours during the rainy season. A similar pattern was observed during the post-rainy and summer seasons; the recovery period fell by 5 hours and 9 hours, respectively (**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 the non-intervention stage.

**Table 3**. Impact of interventions on groundwater yield in the watershed (data based on field observation).

| | Pumping duration (hrs/day) | | Recharge recovery period (hrs) | | Avg. area irrigated by well (ha) | |
|---|---|---|---|---|---|---|
| Season | Before Int*. | After Int. | Before Int. | After Int. | Before Int. | After Int. |
| Rainy | 4 | 11 | 13.5 | 10 | 1 | 2.5 |
| Post-rainy | 1.5 | 6.5 | 21 | 16 | 0.5 | 1.5 |
| Summer | 0 | 1 | 30 | 21 | 0 | 0.2 |

*Int = intervention.

The total storage capacity of storage structures was equivalent to 32 mm of water depth. **Figure 9** shows that the number of fillings varied from 1-10 depending on their location and storage capacity. The storage structures were categorized into five groups based on the number of fillings. Structures with smaller capacity generally got filled more often  and the amount of inflow was several times more than that of bigger structures. The runoff generated from low intensity rainfall was sufficient to fill small structures. Structures located downstream of  the bigger structure had less opportunity to receive inflows (e.g., S10). On an average, these structures filled up 3-3.5 times in wet years and 1-2.5 times in dry and normal years.

**Figure 10a** shows the runoff generated at the outlet of the watershed between 2000 and 2010 and the monthly rainfall under both intervention and non-intervention conditions. There was a significant reduction in the outflow due to upstream AWM interventions. A reduction of about 30-40% in outflow during wet and normal years and more than 70% during dry years was observed. Outflow was found proportional to rainfall received.

**Figure 10b** shows simulated cumulative sediment load between 2000 and 2011 at the outlet of the watershed under non-intervention and intervention condition. AWM interventions were found very effective in controlling soil loss. Cumulative soil loss at the outlet with no intervention was estimated to be about 17,000 t in a 10-year period while it was only about 4,000 t after the intervention. In other words, soil loss came down from about 3.4 t/ha to 0.8 t/ha (76%) due to various AWM interventions.

**Figure 11** shows spatial variability in the runoff coefficient from upstream to downstream areas in relation to the reservoir locations during dry, normal and wet years. The runoff coefficient varied from 0.1 to 0.4. In general, runoff from the first order (upper most channels in a drainage network) streams/upstream locations (e.g., S7, S11, S12) was relatively higher than those from the downstream locations (e.g., S6, S9, S10, S13) due to upstream harvesting. Upstream sites are characterized by greater land slope and have shallow soil depth. The runoff generated from such HRUs were found to be 30-40% of the rainfall received. The runoff coefficients were found high in wet years compared to normal and dry years. Of the 13 structure sites, the runoff coefficient for 3 structures was over 0.4; 5 structures had a runoff coefficient between 0.2 and 0.4; and the rest had a runoff coefficient of less than 0.2. The overall runoff coefficient of the watershed (S13) was between 0.1 and 0.2 in all years.

**Uncertainties in the model results**

Efforts were made to collect a good amount of data on the physical properties of soils (texture, water holding capacity and soil depth), and the model was successfully calibrated. However, a number of uncertainties exist due to complex interactions between land use, land cover, topography and soil type. Moreover, the percolation behavior of different reservoir sites also influenced inflow and outflow, which may lead to uncertainty in water balance analysis. It may be noted that the model takes into account the constant infiltration rate of the storage structures while it varies within the monsoon period; this could lead to inaccurate estimation of deep percolation and groundwater recharge. The study assumed default parameters of shrub/rangelands (crop parameters) during model development. Moreover, while developing the model, we considered maize/wheat as a dominant cropping system whereas the project area is characterized by a wider range of cropping systems and management practices.

**Impact on crop intensification and crop yield**

AWM interventions in the treated watershed recorded increased water availability, which translates to intensifying cropping systems during both rainy and post-rainy seasons. **Figure 12a** and **b** show the area under different crops before (1999) and after the interventions (2004), both during rainy and post-rainy seasons, respectively. A significant amount of cultivable fallow land (nearly 25-30% both in rainy and post-rainy seasons) was converted into productive agricultural land. About 10% of fallow land has been used for horticulture crops during the monsoon and the rest has been utilized for vegetable cultivation during the post-rainy season. During the summer season, about 40-50 ha was also used for green fodder production.

**Figure 13** shows the increase in crop yields before and after the interventions during rainy and post-rainy seasons. Crop yields increased from 40% to 300% over several crops -- from 1050 kg/ha to 3200 kg/ha in maize (rainy); 3000 kg/ha to 5600 kg/ha in wheat (post-rainy); 1500 kg/ha to 2300 kg/ha in mustard (post-rainy) and 950 kg/ha to 1500 kg/ha in chickpea (post-rainy) after project interventions. With increased water availability, the area grown to vegetables as well as yields nearly doubled (4000 kg/ha to 7500 kg/ha). With increased cropping intensity and productivity, the net income from the agriculture sector increased manifold. Average household income from agriculture was US$ 300/year before the intervention and increased to US$ 1200/year after the intervention.

## Discussion

### Opportunity for sustainable crop intensification

It is evident that the AWM interventions in the study watershed have altered hydrological processes. About 40% of the total rainfall was generated as surface runoff before watershed interventions, which was flowing to the downstream area. There was little (less than 5%) groundwater recharge. Following AWM interventions, the situation was reversed. Out of the total runoff generated, more than 50% was harvested within the watershed and the rest flowed downstream. This has had a positive impact on groundwater recharge and has contributed to crop intensification. The results showed that altogether 150 mm of additional water is now being harvested and consumed for agriculture. The additional water harvesting increased total production from agriculture significantly. In this watershed, a large scale upstream landscape (rangeland) was the major source of freshwater in the valley. As the soil depth and water holding capacity of the rangeland is relatively poor, more than 50% of rainfall is generated as runoff. AWM interventions provided the opportunity to harvest the runoff and allowed farmers to cultivate nearby fields using supplemental irrigation. Over 150 ha was brought under productive cultivation with assured groundwater availability. A good amount of surface runoff was generated even in dry years. However, downstream release was most affected by upstream water harvesting.

### Upstream-downstream trade-offs

The findings of the study raise concerns about downstream water availability, as the upstream area was the main beneficiary. There could be trade-offs between development of upstream ecosystems and downstream water availability. AWM interventions in upstream enhance productivity, control flooding, enhance base flow and control erosion and land degradation. The results clearly showed more than 75% reduction in soil loss with AWM interventions. Heavy sedimentation is one of the major concerns for downstream stakeholders (e.g., reservoir operators and managers) as the storage capacity of most of the reservoirs in India (e.g., dams) has fallen by 20% compared to the last three to four decades (Durbude, 2014; Shukla *et al.*, 2017). Heavy sedimentation transports important nutrients such as nitrogen, phosphorus and other minerals from agriculture fields and pollutes downstream water bodies, which result in eutrophication and poor water quality (Haregeweyn *et al*., 2019). In surface water irrigation projects located at downstream areas (*i.e.*, large dams) in ecologies (arid/ semi-arid tropics) where evaporation rates are very high, nearly 20-30% of the stored water is lost due to evaporation losses (Mittal *et al*., 2017; Ates *et al*., 2020). AWM interventions at upstream locations provide opportunities to enhance groundwater recharge and reduce such losses to improve system-level efficiency.

Blue water (groundwater and surface runoff) is most sensitive to rainfall variability. Inevitably, a large portion of rainfall received goes towards ET. The remaining amount generates blue water, which again depends on landscape management. Before the intervention, surplus water was observed in the form of surface runoff, whereas it was partitioned into surface runoff and groundwater recharge after the intervention. About 80-120 mm of surplus water that is stored as groundwater (a reliable source) is available to various stakeholders. AWM interventions seem to have built a resilient groundwater system. A given amount of surplus water, if available as groundwater, can stay longer and is readily available. Field data shows that if it is recharged once in a year, it is sufficient for subsequent years (Garg et al., 2020a). Groundwater carried over from the previous year alleviates stress conditions in subsequent dry years and serves as an important resilience building strategy against drought.

The study also quantifies the number of times a structure is filled during the monsoon period. The high level of percolation in this watershed repeatedly provided opportunities to harvest surface runoff within the monsoon period. A few structures filled up more than 10 times in a year while some filled up a fewer number of times, all depending on their location and storage capacity. For example, 3 out of 13 structures had storage capacity of more than 0.3 MCM though the amount of inflow was not of the same magnitude. Therefore, these structures were filled less than once whereas a few of the structures with storage capacity between 3,000-10,000 $m^3$ and inflow was several folds higher, providing the opportunity to fill up frequently. However, the steep topography was one of the important factors keeping the hydraulic gradient high, affecting the spatial level of infiltration across the landscape. On an average, these structures were filled 2-3 times in a normal year.

**Comparison with other studies**

The findings of this watershed are different from those on agriculture-dominant watersheds. The latter are relatively flatter, intensively cultivated and have limited scope to generate surplus water, with only the wet years providing the opportunity for water harvesting (Garg *et al*., 2020a). There are a number of studies on regional scale water balance but very few attempt to understand mesoscale water balance components. Analyzing the water balance components of AWM interventions in a similar ecological system of a fragile landscape in Udaipur, Rajasthan state, Dashora *et al*. (2019) found that AWM interventions were maximizing groundwater recharge and refilling four times their capacity in a wet year. Glendenning and Vervoort (2010) have reported that AWM interventions helped enhance groundwater availability and mitigate the risk of crop failure in *Arvari* catchment, Rajasthan. However, a significant decline in downstream water availability due to upstream AWM interventions was the major concern. They also found that there is a limited scope of groundwater recharge after crossing a threshold as increasing the size of various structures does not always contribute to groundwater recharge (Glendenning and Vervoort, 2010). Rather, it negatively impacts downstream flow, contrary to the current study in which large scale harvesting did not limit groundwater recharge due to the higher slope gradient.

**Future scope**

Adequate moisture availability is required for crop intensification in drylands. AWM interventions has ensured the availability of supplemental irrigation. The additional resources required for ensuring moisture availability are generated within the landscape. This study shows both upstream benefits and the consequences on downstream communities. The study will be useful to understand hydrological processes and take informed decisions on optimizing available resources in a fragile landscape. Though landscape hydrology is complex to model due to the heterogeneity in the topography, soil types, rainfall, land use, and management practices, an effort was made to do so by using field measurements and simulation modeling. There is also scope to quantify the economic benefits generated due to various AWM interventions and do a cost-benefit analysis. With technological advancements in the areas of monitoring and evaluation, it has become possible to capture impact more accurately; a comparison could be done with and without interventions and also before and after the project interventions. Similar efforts are needed for different agro-ecological regions to bridge the knowledge gap and to facilitate informed decisions.

## Conclusion

The study analyzed the impact of decentralized AWM interventions in a fragile watershed in western India following a ridge-to-valley approach to construct storage structures. This watershed was monitored intensively and a number of parameters, including biophysical, meteorological, hydrological, crop productivity, land use change, soil loss and socio-economic characteristics were collected between 2000 and 2006. This data was used to calibrate a hydrological model and the results were simulated between 2000 and 2010 to capture rainfall variability. The impact of AWM interventions on watershed hydrology and different water balance components was analyzed. The key findings are:

- Water balance: Of the 500 mm rainfall received during a normal year, 300 mm (60%) was utilized as ET, 150 mm generated as surface runoff and the rest was recharging groundwater before the project interventions.
- AWM interventions have helped enhance groundwater recharge by more than double compared to non-intervention conditions. However, it did reduce surface runoff by more than 50%. The outflow from the watershed was reduced by over 70% in dry and normal years and by 50% in wet years. However, the AWM interventions reduced sediment loading by more than 75% compared to non-intervention conditions.
- Water storage structures were filled up an average of 2-3 times depending on rainfall and inflow generated. The number of fillings were largely dependent on the location of the structure in terms of toposequence and its size.
- Groundwater augmentation has helped enhance crop intensification, reduced the risk of crop failure and enhanced crop yields from 50% to 300%. The additional area was brought under cultivation with assured water availability. This enhanced farmers’ incomes by 3-5 times.

The findings of the study would be helpful to stakeholders in making informed decisions while planning AWM interventions by considering their consequences on downstream communities.

## Acknowledgements

The financial support provided by Sir Dorabji Tata Trust for the development of the Govardhanapura-Thana watershed at Bundi, Rajasthan, is gratefully acknowledged. The CGIAR Research Program – Water, Land and Ecosystems' (WLE) support for ICRISAT scientists' time to analyze historical data is duly acknowledged. The authors would also like to thank both the reviewers, Dr. Sreekanth Janardhanan and Dr. John McCray, for providing very insightful comments and suggestions to improve the manuscript.

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**Figure 2**: The village tank constructed for harvesting runoff using **a)** masonry and earthen embankments and **b)** check dam on a stream.

**Figure 3: a)** Temporal variability of rainfall between 1985 and 2010 along with intensity distribution; and **b)** variation in maximum and minimum temperature, relative humidity and rainfall on a daily scale for 2000.

**Figure 4**: Comparing daily simulated **a**) surface runoff and **b**) soil loss with measured data at the micro-watershed between 2002 and 2006. The red crosses indicate missing data from runoff measurements.

**Figure 5**: Comparing simulated reservoir volume with measured data for S11 on daily time scale for years **a)** 2002; **b)** 2003; **c)** 2004 and **d)** 2005.

**Figure 6:** Simulated water balance components (groundwater recharge, base flow, outflow and ET) with intervention and without interventions during dry, normal and wet years based on a 11-year model simulation.

**Figure 7**: Relationship between rainfall and outflow, base flow and groundwater recharge under intervention and non-intervention conditions, based on a 11-year model simulation.

**Figure 8**. Comparing fluctuations in the depth of the water table in the treated (Govardhanapura-Thana) watershed and control watershed between 2003 and 2005 (data based on 20 monitoring wells).

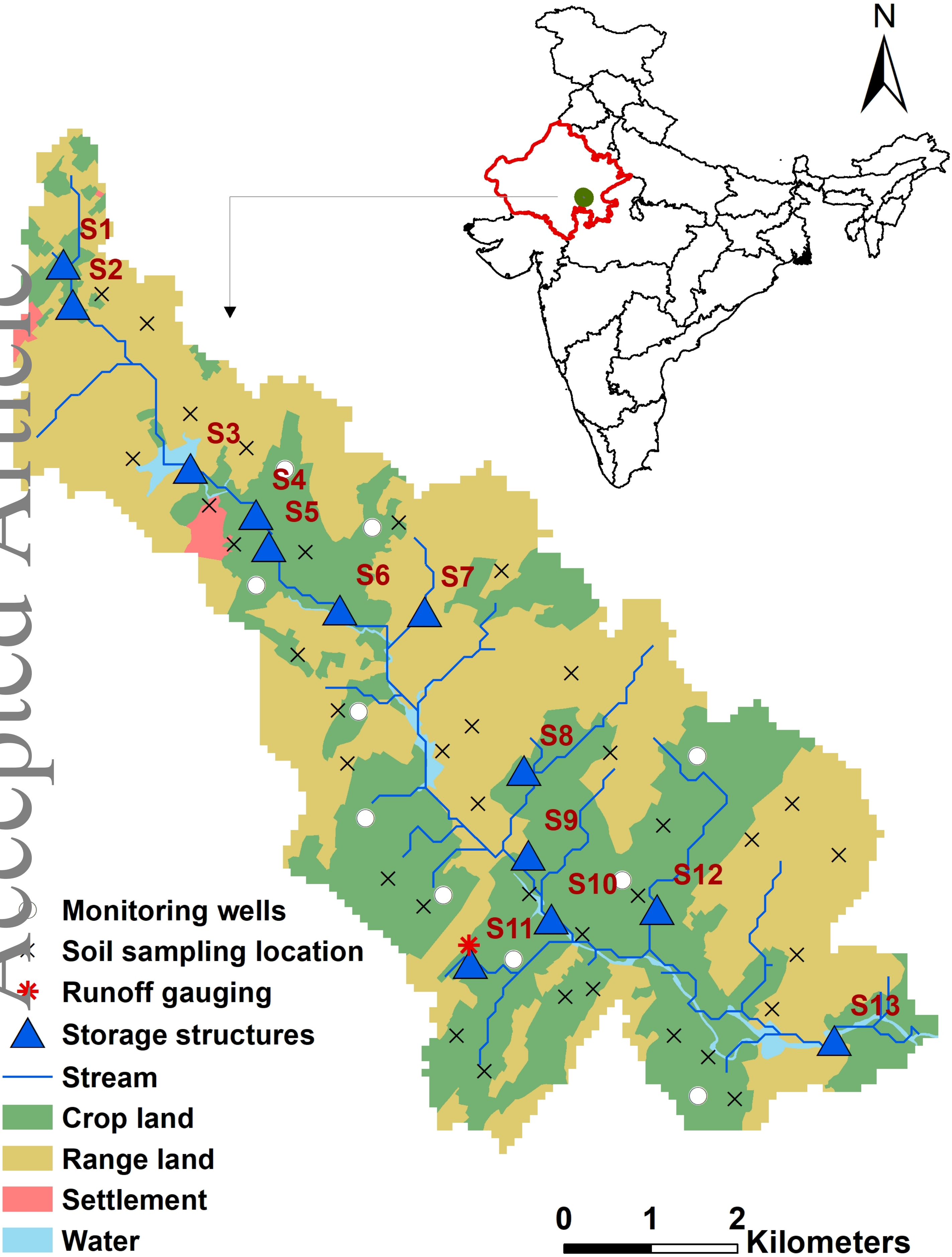
**Figure 9**: Variation in the number of fillings of storage structures at different locations during **a)** dry, **b)** normal and **c)** wet years.

**Figure 10 a)** Outflow generated from the watershed before and after the interventions (results based on a 11-year model simulation) and **b)** cumulative simulated sediment (t) transported at the watershed outlet with and without AWM interventions between 2000 and 2011.

**Figure 11**: Variability in runoff coefficients at upstream and downstream locations during **a)** dry, **b)** normal and **c)** wet years.

**Figure 12.** Area (%) under cultivation during the **a)** rainy season and **b)** post-rainy season before and after the interventions (data based on field records).

**Figure 13.** A comparison of yields of major crops before and after watershed interventions; crop yields were measured based on crop cutting studies from select farmer fields.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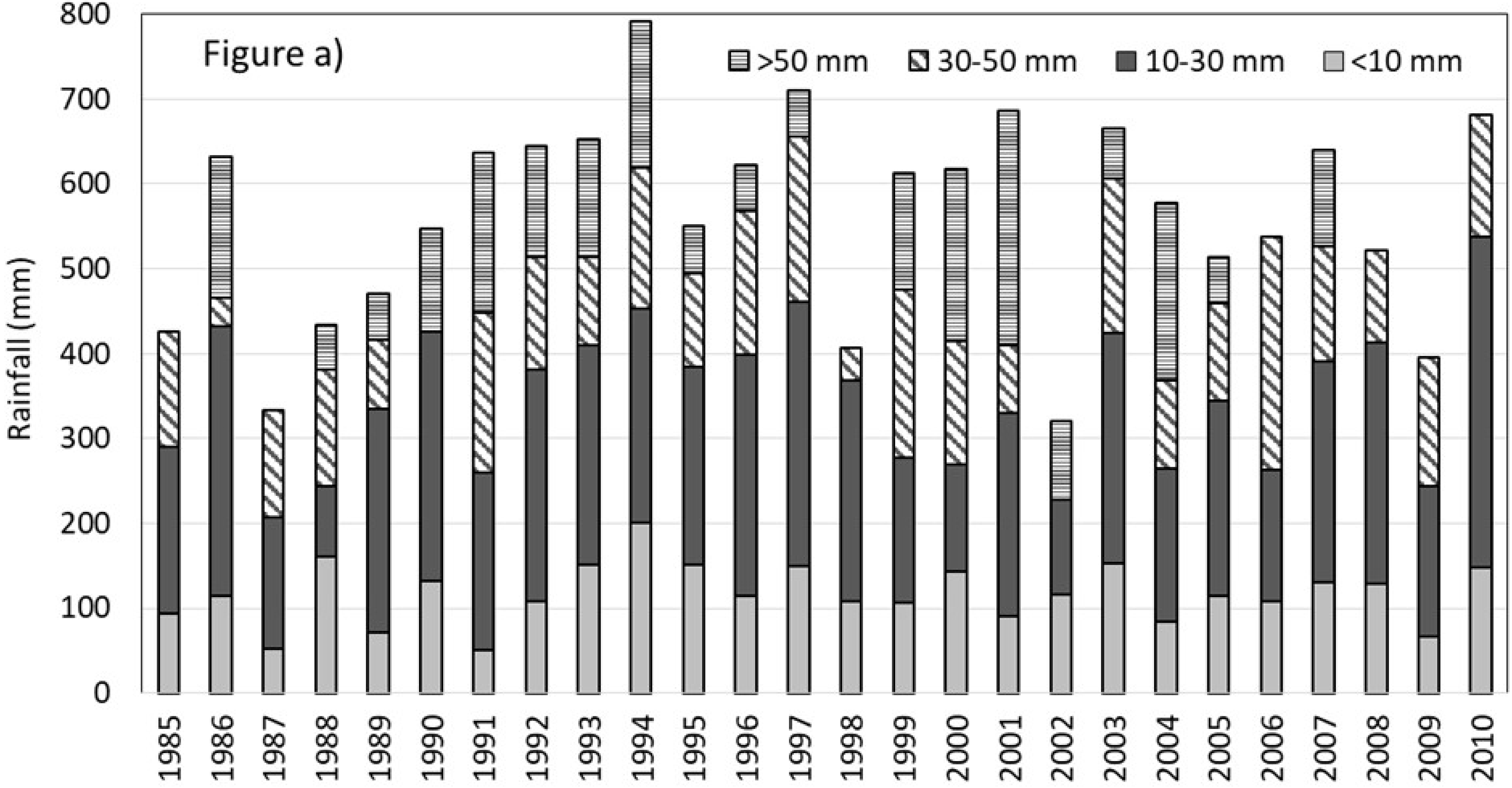

Figure a)
>50 mm
30-50 mm
10-30 mm
<10 mm
Rainfall (mm)
0
100
200
300
400
500
600
700
800
1985
1986
1987
1988
1989
1990
1991
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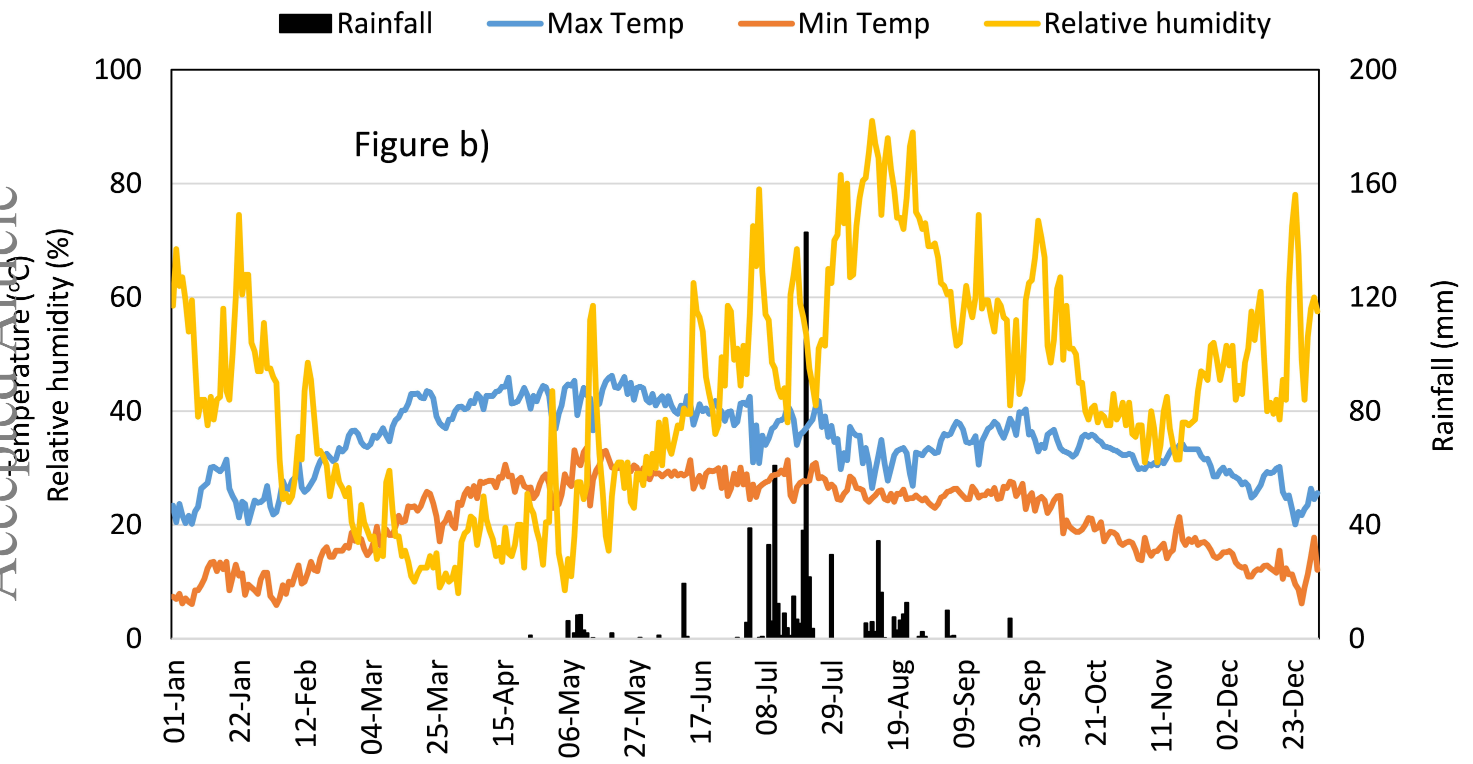

Rainfall
Max Temp
Min Temp
Relative humidity
Figure b)
Temperature (°C)
Relative humidity (%)
Rainfall (mm)
100
80
60
40
20
0
200
160
120
80
40
0
01-Jan
22-Jan
12-Feb
04-Mar
25-Mar
15-Apr
06-May
27-May
17-Jun
08-Jul
29-Jul
19-Aug
09-Sep
30-Sep
21-Oct
11-Nov
02-Dec
23-Dec

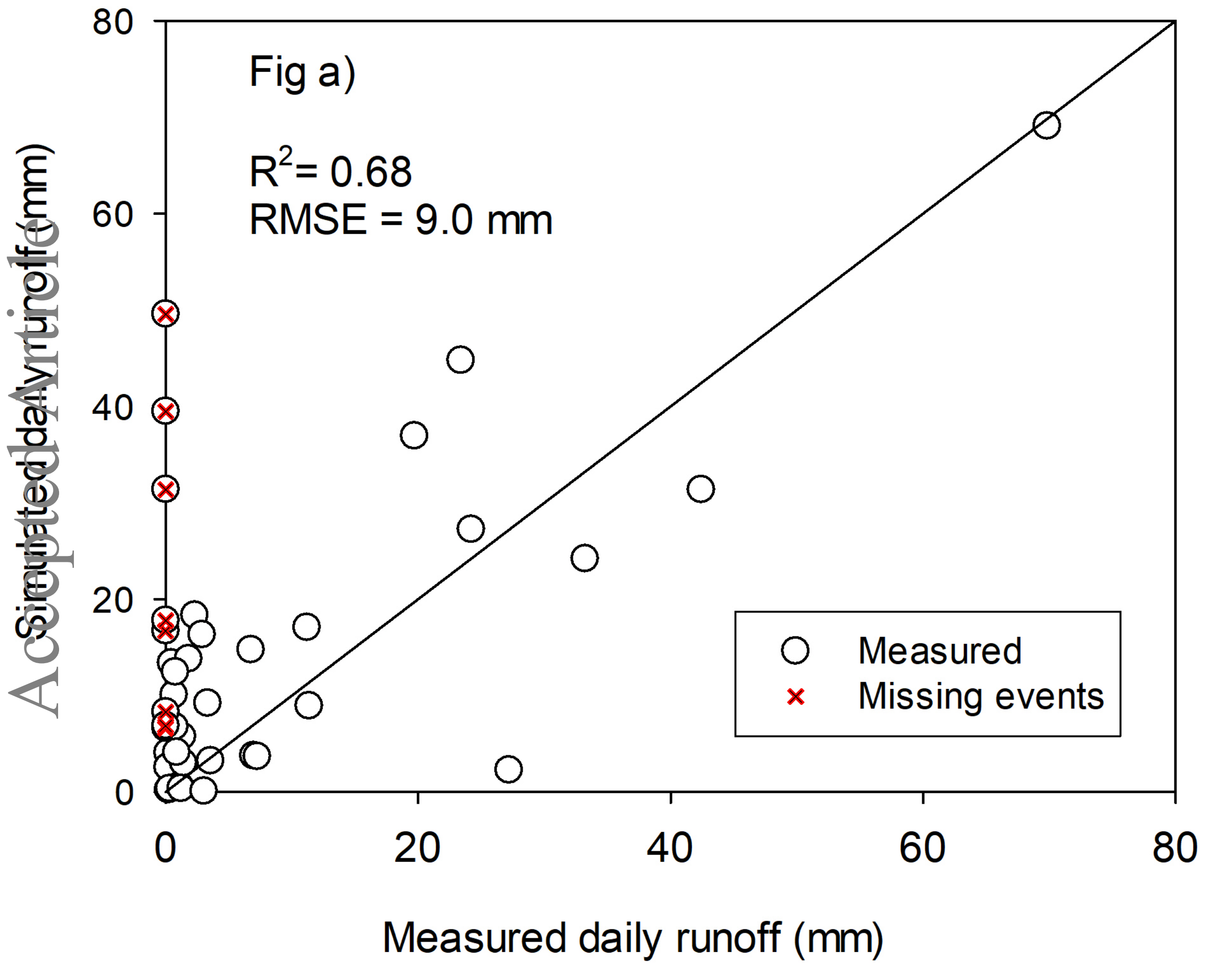
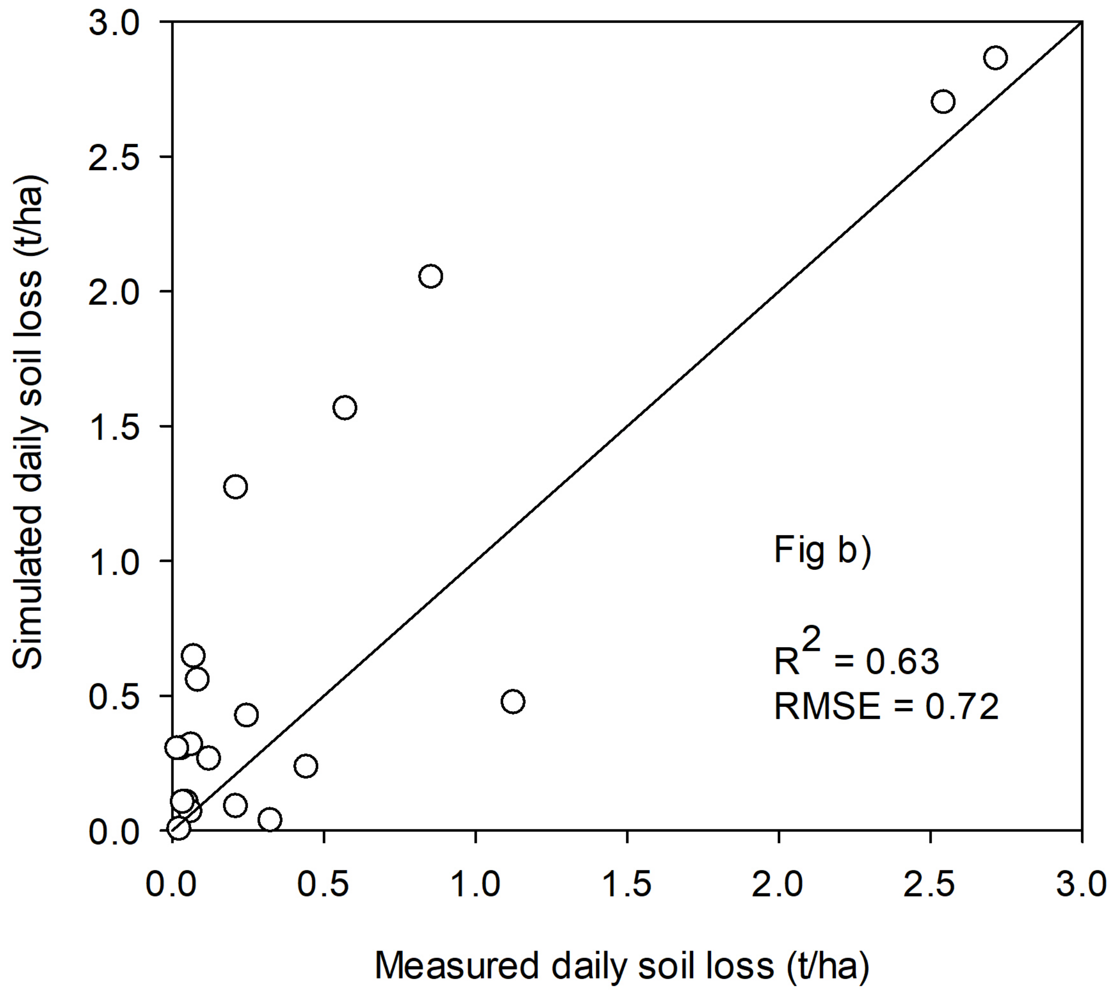


Fig a)
$R^2$= 0.68
RMSE = 9.0 mm
Simulated daily runoff (mm)
Measured daily runoff (mm)
Measured
Missing events
0
20
40
60
80
0
20
40
60
80



3.0
2.5
2.0
1.5
1.0
0.5
0.0
Simulated daily soil loss (t/ha)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Measured daily soil loss (t/ha)
Fig b)
R2 = 0.63
RMSE = 0.72

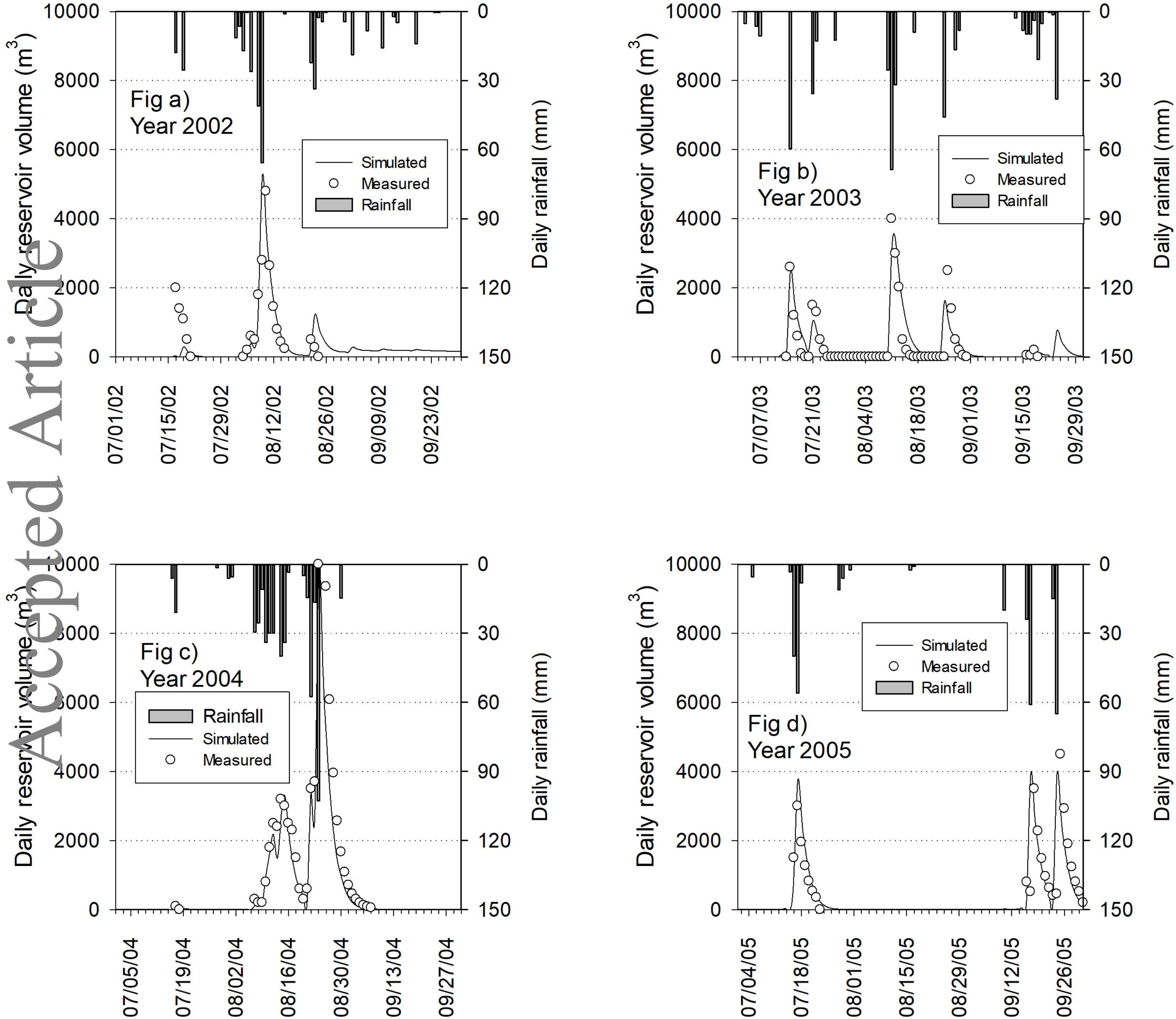
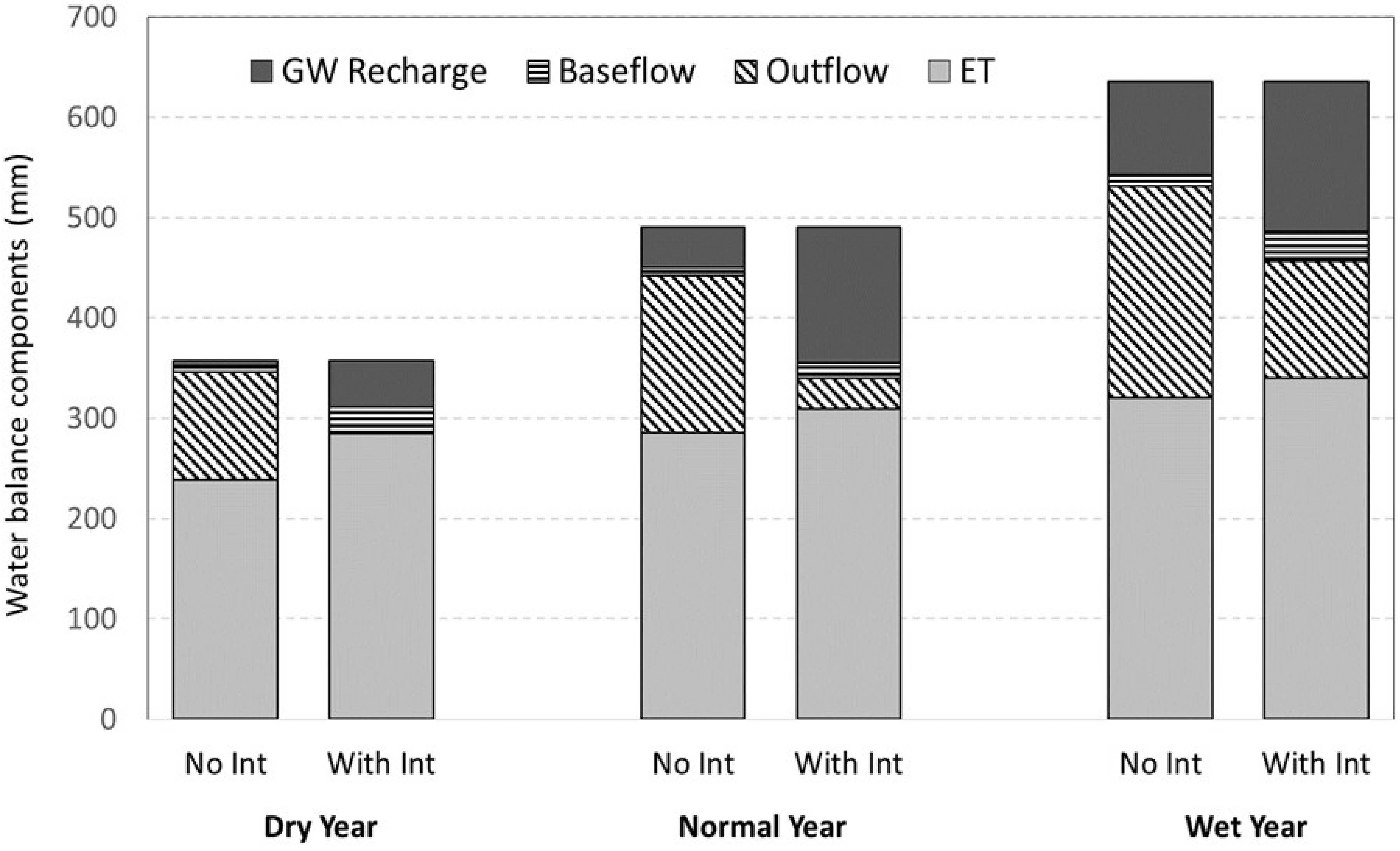
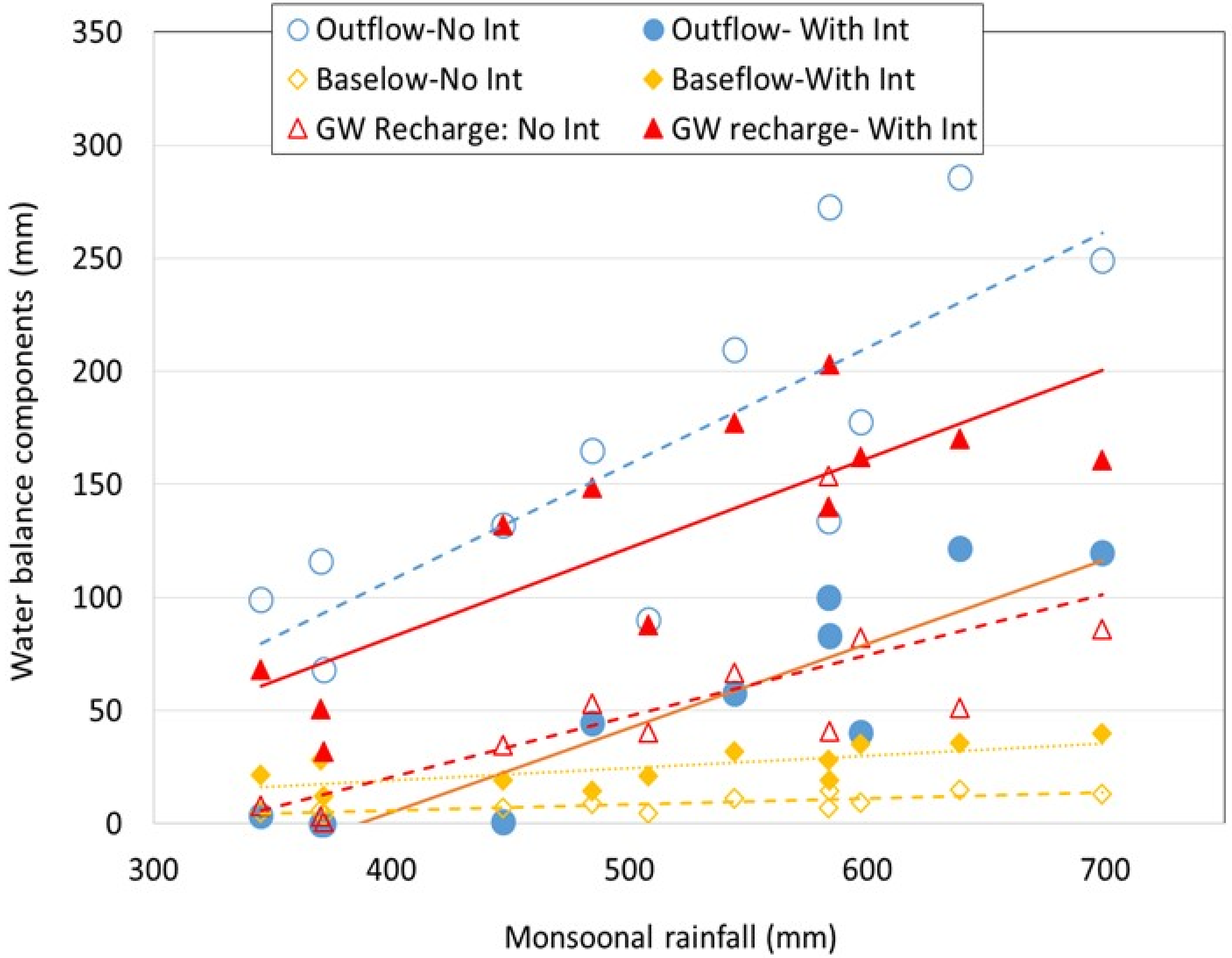


Fig a)
Year 2002
Fig b)
Year 2003
Fig c)
Year 2004
Fig d)
Year 2005
Simulated
Measured
Rainfall
Daily reservoir volume (m$^3$)
Daily rainfall (mm)
10000
8000
6000
4000
2000
0
0
30
60
90
120
150
07/01/02
07/15/02
07/29/02
08/12/02
08/26/02
09/09/02
09/23/02
07/07/03
07/21/03
08/04/03
08/18/03
09/01/03
09/15/03
09/29/03
07/05/04
07/19/04
08/02/04
08/16/04
08/30/04
09/13/04
09/27/04
07/04/05
07/18/05
08/01/05
08/15/05
08/29/05
09/12/05
09/26/05


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)
Monsoonal rainfall (mm)
350
300
250
200
150
100
50
0
300
400
500
600
700

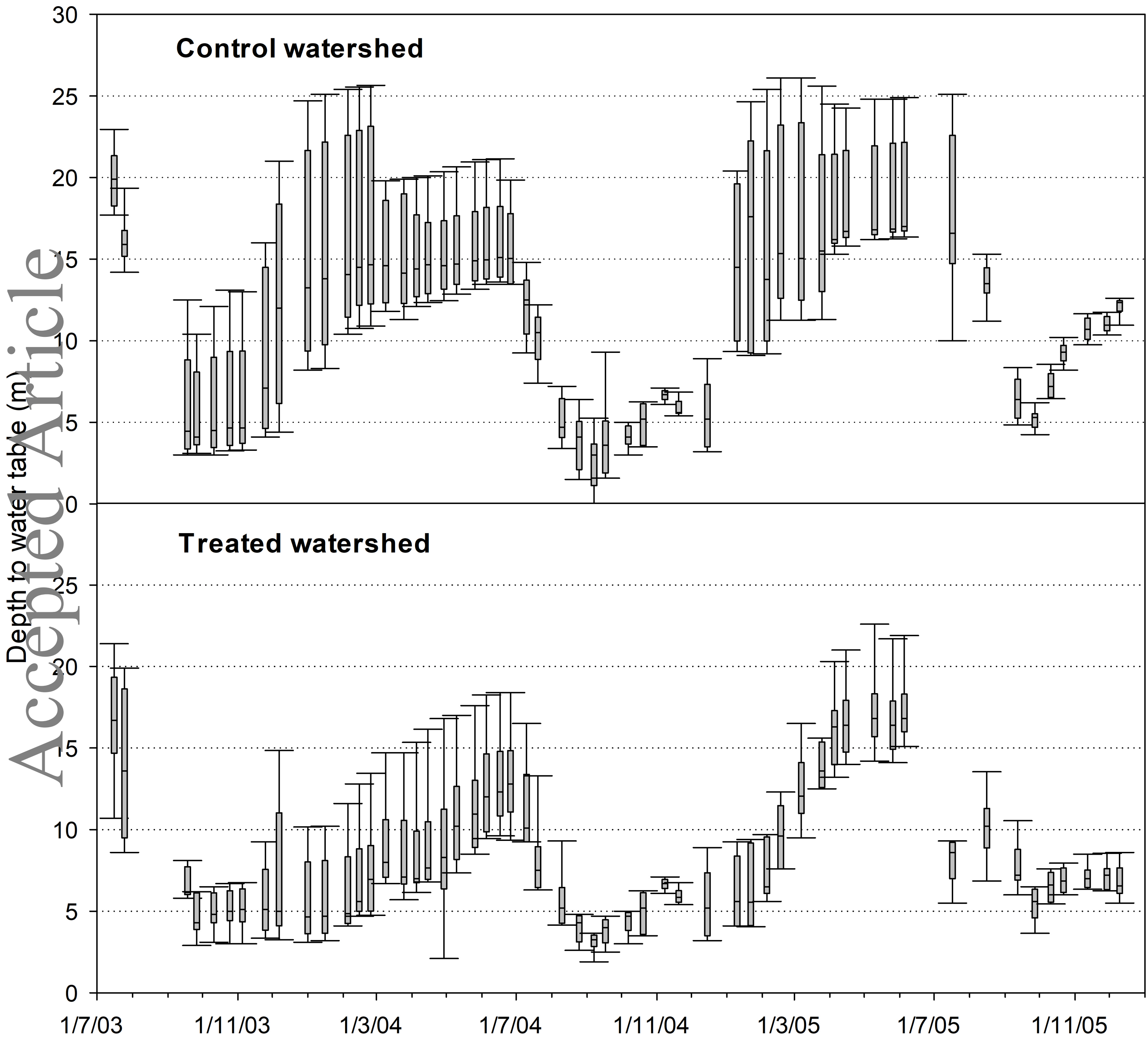
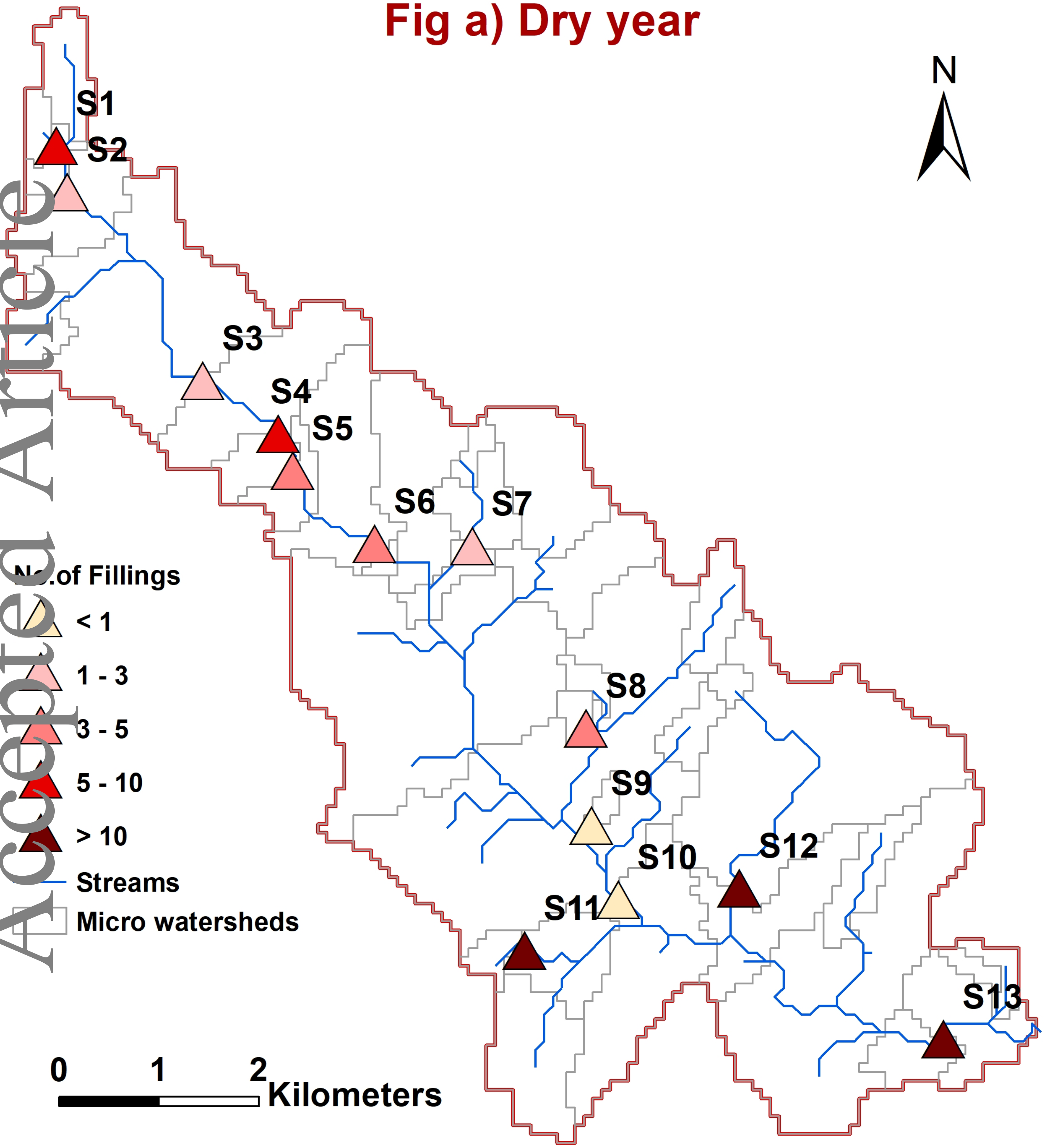

Control watershed
Treated watershed
Depth to water table (m)
30
25
20
15
10
5
0
1/7/03
1/11/03
1/3/04
1/7/04
1/11/04
1/3/05
1/7/05
1/11/05

Fig a) Dry year




| 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 |

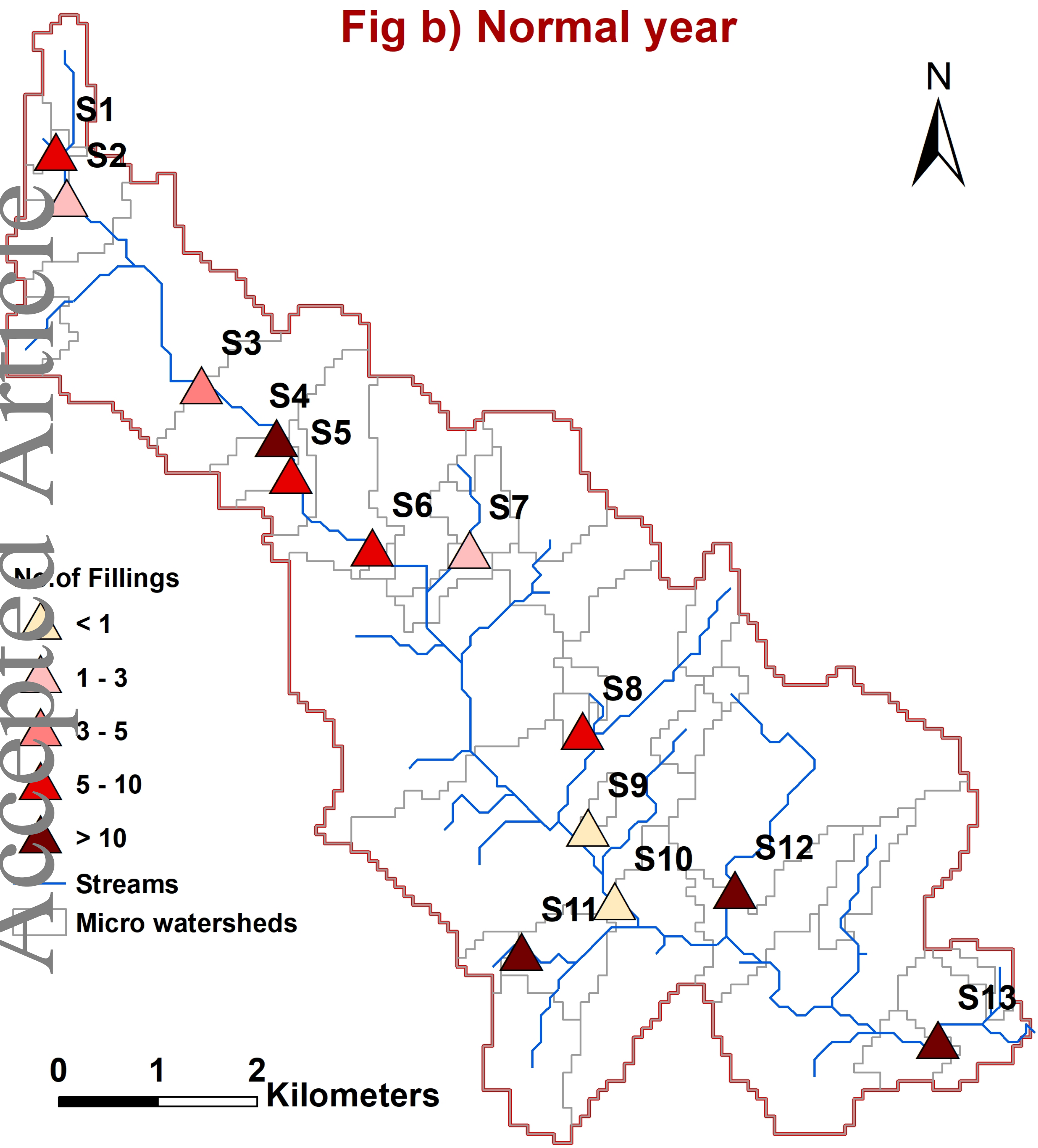
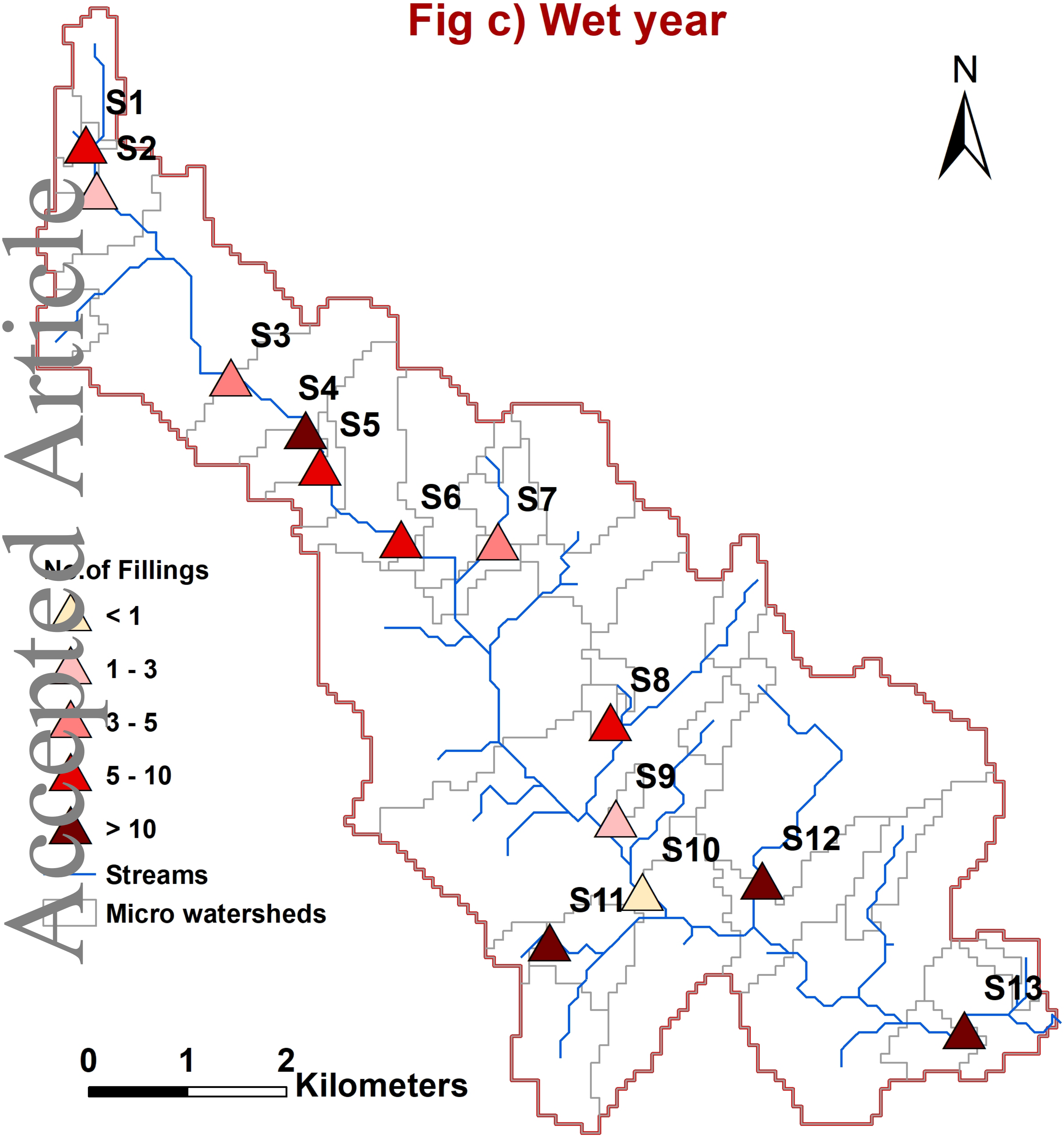


Fig b) Normal year
N
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
No.of Fillings
< 1
1 - 3
3 - 5
5 - 10
> 10
Streams
Micro watersheds
0
1
2
Kilometers

# Fig c) Wet year



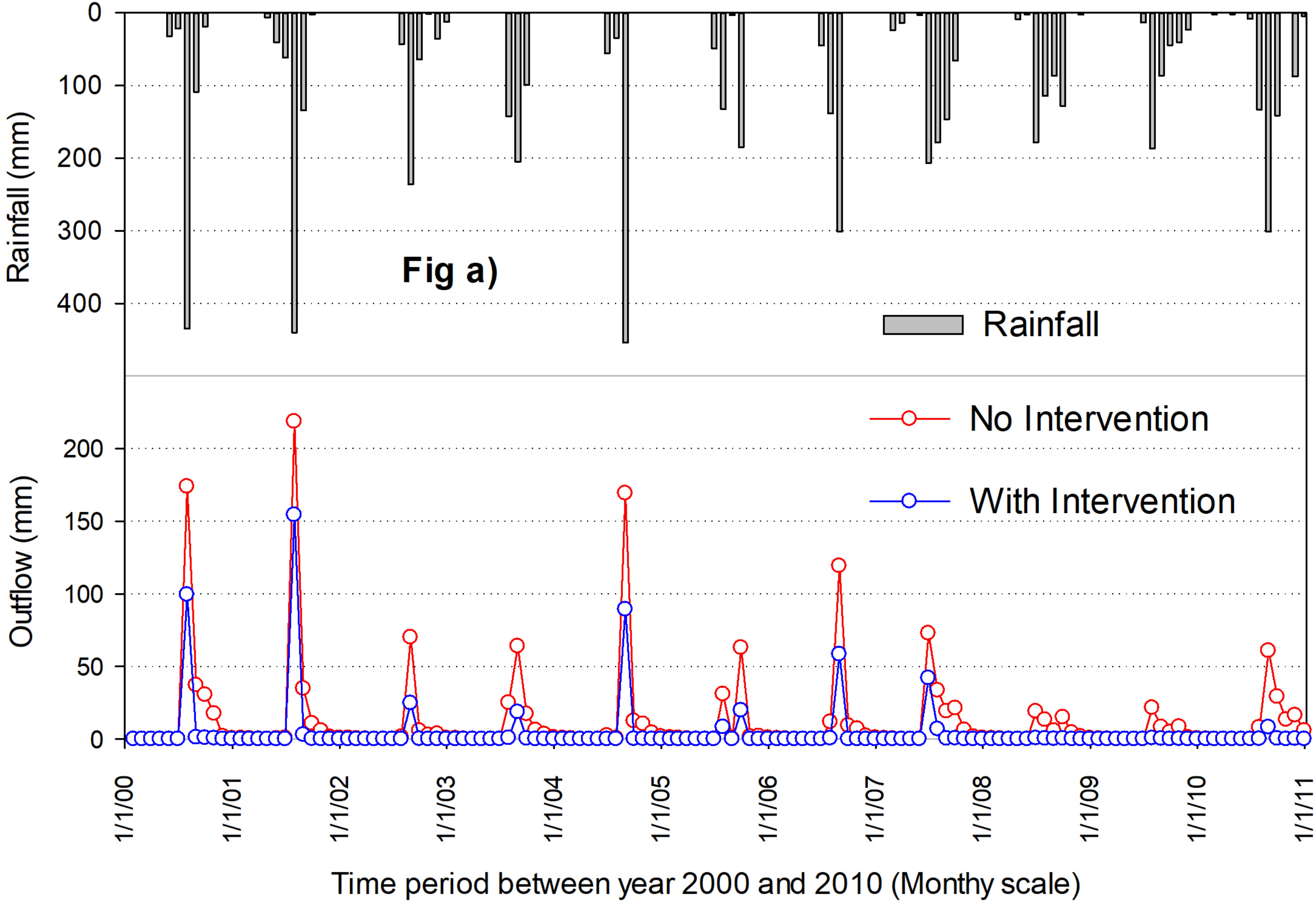


Fig a)
Rainfall (mm)
0
100
200
300
400
Rainfall
No Intervention
With Intervention
Outflow (mm)
200
150
100
50
0
1/1/00
1/1/01
1/1/02
1/1/03
1/1/04
1/1/05
1/1/06
1/1/07
1/1/08
1/1/09
1/1/10
1/1/11
Time period between year 2000 and 2010 (Monthy scale)

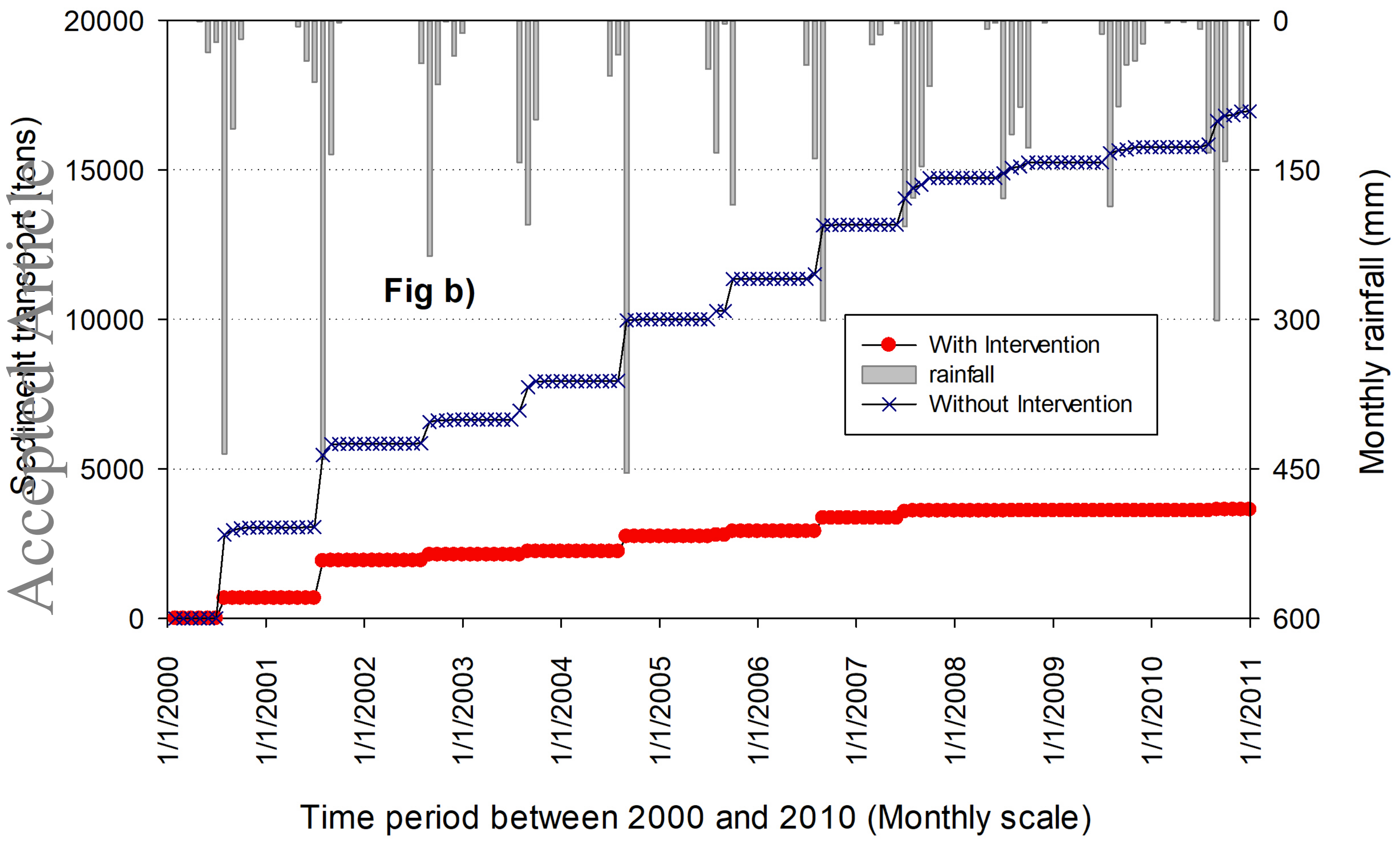
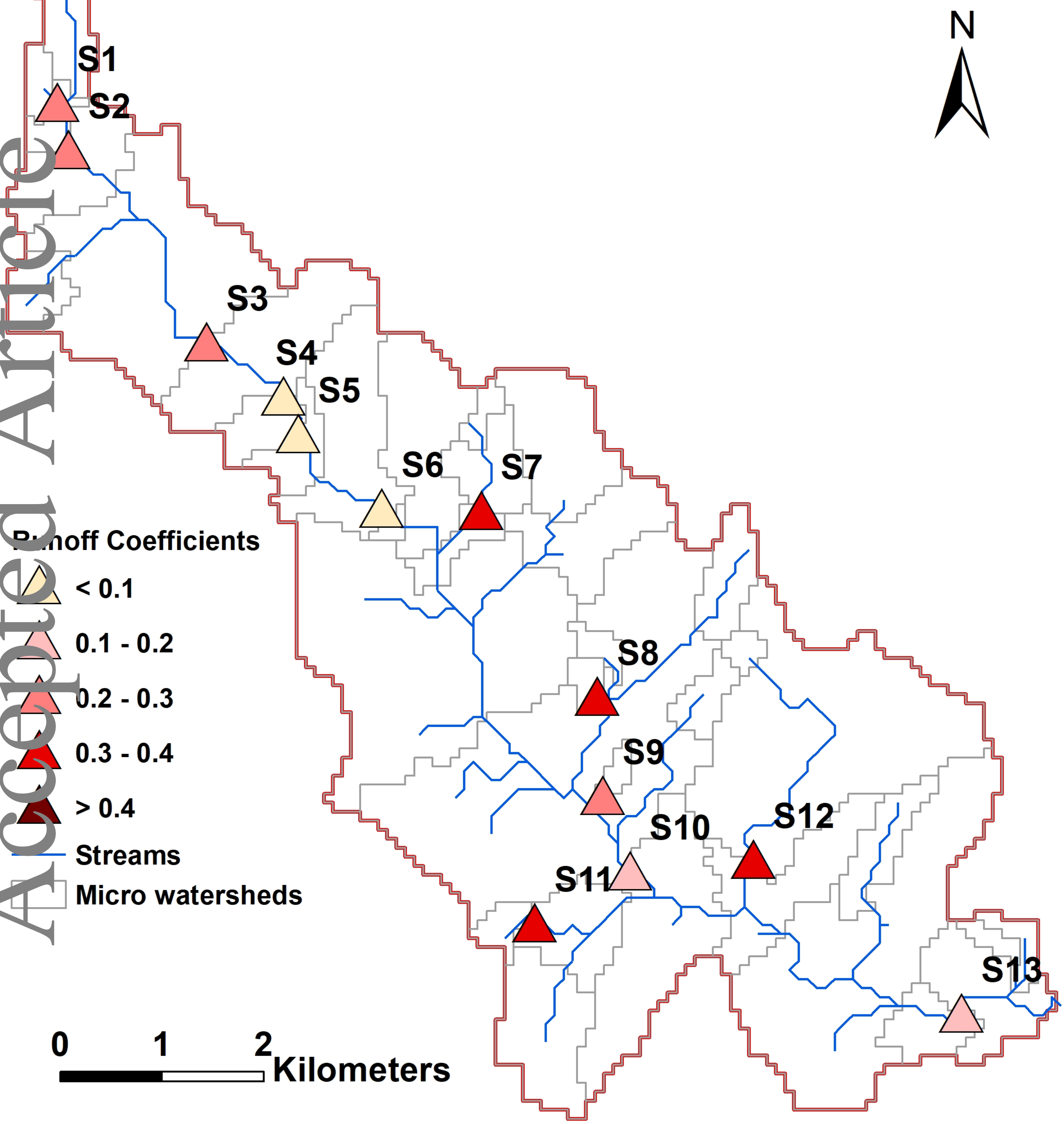


Fig b)
Sediment transport (tons)
Monthly rainfall (mm)
20000
15000
10000
5000
0
0
150
300
450
600
With Intervention
rainfall
Without Intervention
1/1/2000
1/1/2001
1/1/2002
1/1/2003
1/1/2004
1/1/2005
1/1/2006
1/1/2007
1/1/2008
1/1/2009
1/1/2010
1/1/2011
Time period between 2000 and 2010 (Monthly scale)

# Fig a) Dry year




| 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 |

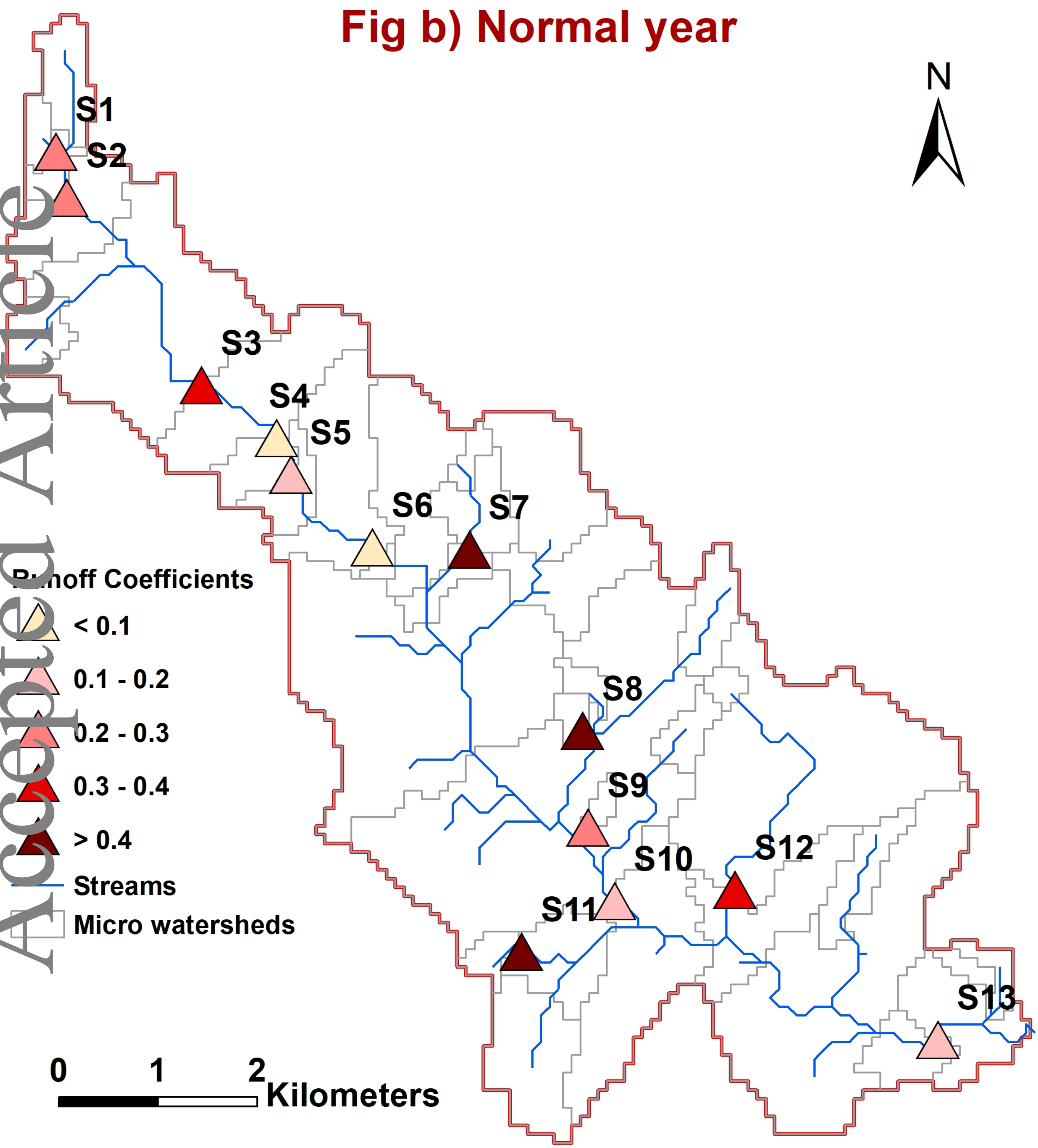


Fig b) Normal year
N
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
Runoff Coefficients
< 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
Streams
Micro watersheds
0
1
2
Kilometers

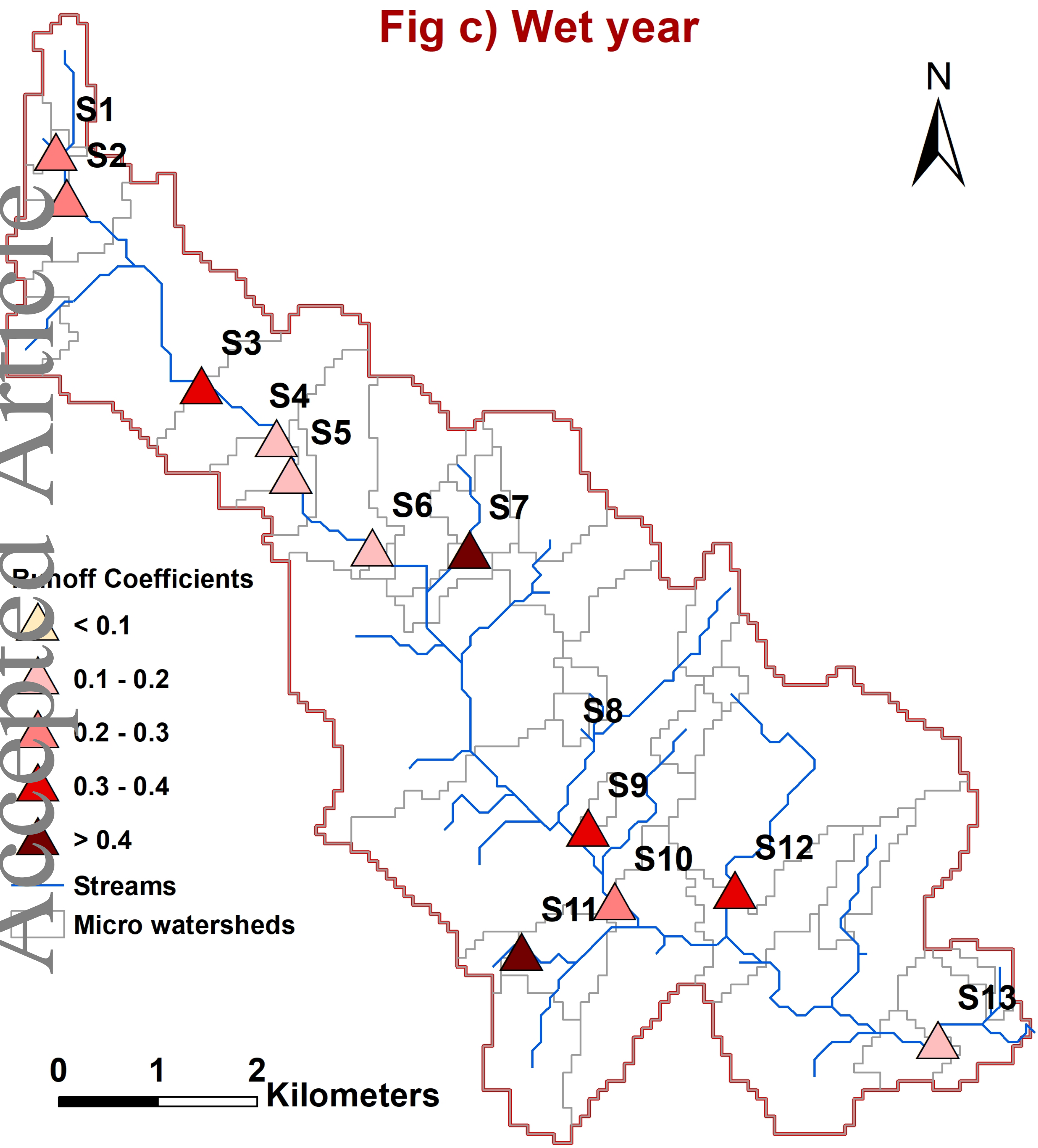


Fig c) Wet year
N
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
Runoff Coefficients
< 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
Streams
Micro watersheds
0
1
2
Kilometers

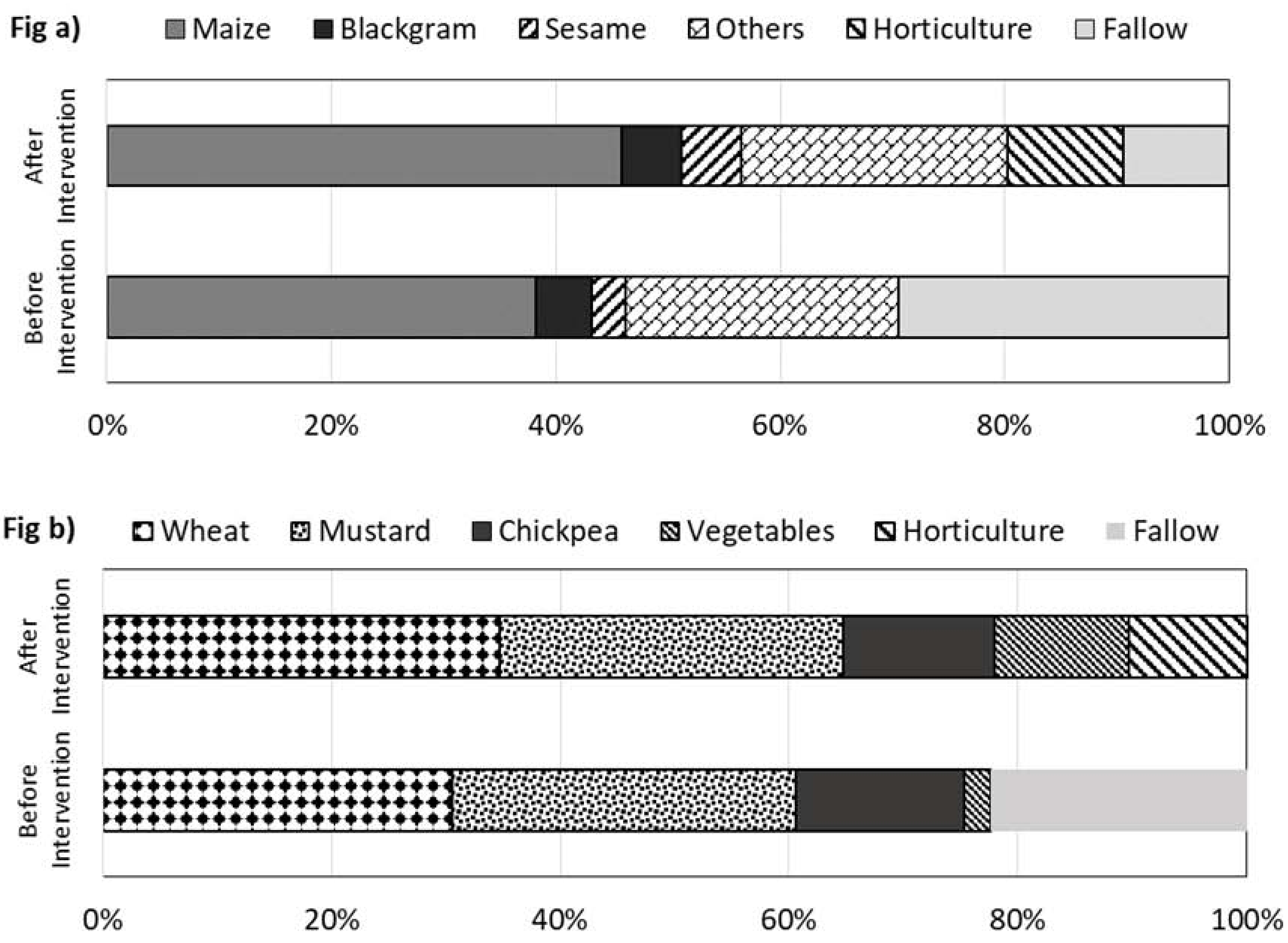
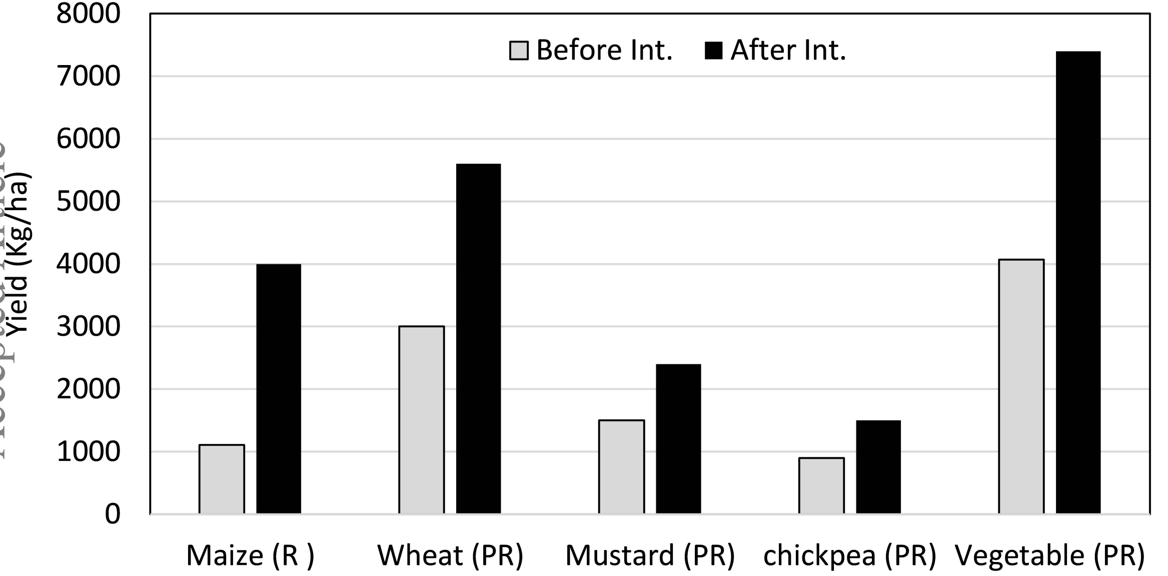


Fig a)
Maize
Blackgram
Sesame
Others
Horticulture
Fallow
After Intervention
Before Intervention
0%
20%
40%
60%
80%
100%
Fig b)
Wheat
Mustard
Chickpea
Vegetables
Horticulture
Fallow
After Intervention
Before Intervention
0%
20%
40%
60%
80%
100%


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