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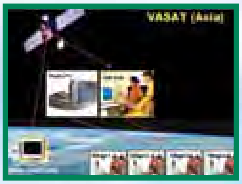

Use of High Science Tools in Integrated Watershed Management

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Hydrological Modeling of a Micro Watershed using GIS-based Model SWAT: A Case Study of Kothapally Watershed in Southern India

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Abstract

Rain-fed agriculture in arid or semi arid tropics is complex, diverse, risk prone, and characterized by low levels of productivity and low input usages. Kothapally, a micro watershed of 450 ha area is located approximately 25 km upstream of Osman Sagar in Musi catchment of Southern India. Rainfall in this region is highly erratic both in terms of total amount and its distribution over time. ICRISAT consortium with national partners (Central Research Institute for Dryland Agriculture (CRIDA), National Remote Sensing Agency (NRSA) now NRSC, and District Water Management Agency (DWMA), in Hyderabad, Andhra Pradesh,); and non-governmental organizations (NGOs) started community based watershed development program in Kothapally village in 1999. Since the on-set of the program, water flows and crop parameters in the area have been monitored, creating database of hydrological data and crop yield information. This data was analyzed with the Soil and Water Assessment Tool (SWAT) to study the water balance for different water management options. In addition, flow reduction and soil loss from the fields was evaluated to assess the downstream impacts on the Osman Sagar reservoir. It was found that different water management approaches significantly changes the water balance of the system. Check-dams increase groundwater recharge which can be used for supplementary irrigation of the monsoon crop, and especially the second crop when rainfall is almost nil. Both check-dams and in-situ soil water management reduces the outflow from the system. In-situ soil water management increases evapotranspiration, which can be expected when more water is infiltrated into the soil. Monsoonal analysis shows that watershed management practices reduced surface runoff from 27% to 11%, improved groundwater availability from 9% to 22%, increased ET flow from 53% to 66% of total rainfall, and reduced soil loss from 1.5 t ha^{-1} to 2.5 t ha^{-1} compared to pre-development stage. This program has built resilience in the agricultural systems, and has improved the livelihoods of the farmers.

Keywords: *Hydrological modeling, SWAT, water balance, sediment transport, resilience, watershed management.*

Introduction

Degradation of agro-ecosystems and declining sustainability are major concerns for agricultural development in many poor regions of India where livelihoods depend on exploitation of natural resources (Reddy et al. 2007). In recent years, it has been realized that rain-fed agriculture, which were almost neglected during the green revolution in the 1970s, also has remarkable scope for agricultural development. The International Crop Research Institute for the Semi Arid Tropics (ICRISAT), a non-profit, non-political, international organization, consortium with national partners (Central Research Institute for Dryland Agriculture (CRIDA); National Remote Sensing Agency (NRSA) now NRSC; and District Water Management Agency (DWMA) in Hyderabad, Andhra Pradesh,); and non-government organizations (NGOs) started a community-based integrated watershed development program in Kothapally village as a benchmark study from 1999. This concept ties together the biophysical notion of a watershed as a hydrological unit with the social aspect of community and its institutions for building resilience in agriculture by sustainable management of land, water and other resources (Reddy et al. 2007).

We developed a modeling framework for the Kothapally watershed to represent its hydrology, soil and crop growth dynamics, using a hydrological modeling tool, the Soil and Water Assessment Tool (SWAT). The aim of the present study is to analyze the impact of agricultural water management on the local water balance and implications for downstream systems. More specifically, the objectives are to 1) parameterize, calibrate and validate a hydrological model (SWAT) on the Kothapally watershed, 2) compare the impact of four different agricultural water management scenarios (representing a degraded reference scenario and three watershed development program scenarios on the local water balance, soil loss and downstream impacts).

Study Area: Kothapally Watershed

The Kothapally watershed is located at 17°22’ N latitude, 78°07’ E longitude and about 550 meters AMSL altitude in Ranga Reddy district, Andhra Pradesh, India. This watershed is the part of the Musi sub-basin of the Krishna river basin, and situated approximately at 25 km upstream of the Osman Sagar reservoir (Fig. 1). Krishna is one of the largest rivers in Southern India and the basin lies within the states of Maharastra, Karnataka, and Andhra Pradesh (Immerzeel et al., 2008). Musi is one of the tributaries of the Krishna river and flows completely into state of Andhra Pradesh. There are three major reservoirs in the Musi catchment: Osman Sagar (OS), Himayat Sagar (HS), and Musi Medium (MM).

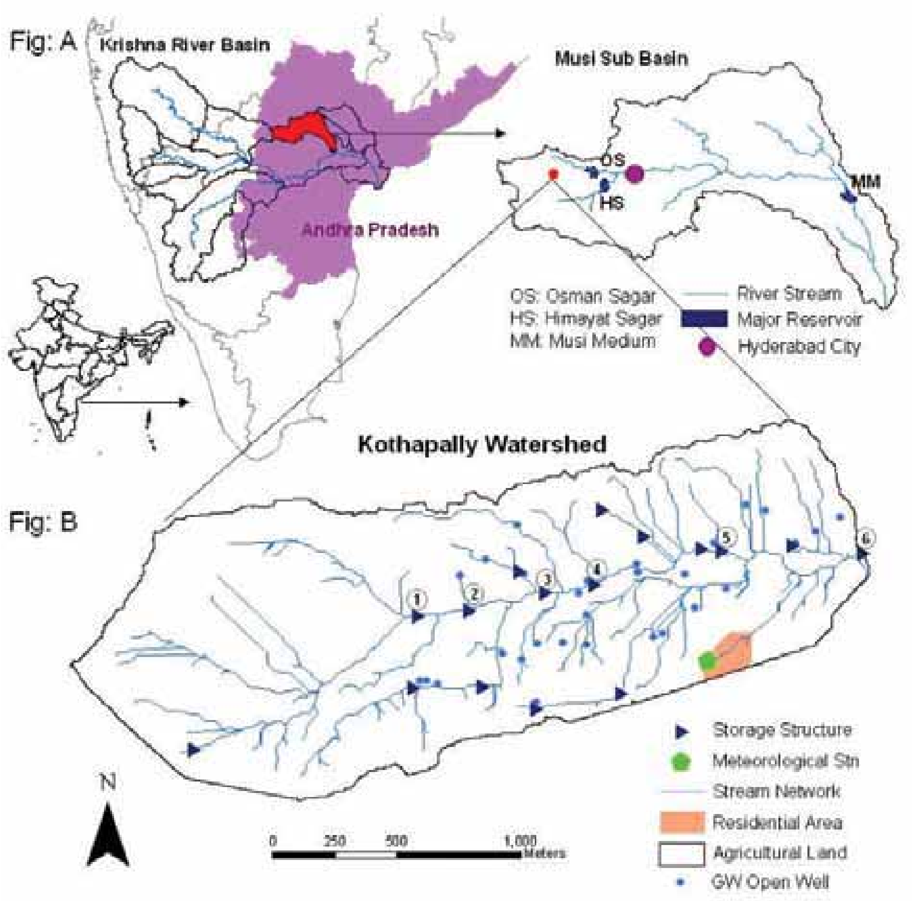

Figure 1. (A) Location of Kothapally watershed in Musi sub-basin of Krishna river basin, down stream reservoirs and Hyderabad city; (B) Stream network, location of storage structures, open wells, meteorological station, and residential area in Kothapally watershed.

The main criteria for selecting this watershed were: existence of a large proportion of cropland under rain-fed farming, low crop yields, non-existence of water harvesting structures and the potential for minimum interventions to conserve soil and water. The villagers have a positive attitude towards the watershed program and are willing to cooperate with the consortium partners to gain mutual benefit. The local leader (*Sarpanch*, Chief of *Panchayati Raj* Institution) has been actively involved in the watershed program. The consortium partners had several rounds of free and frank discussions before undertaking any activity. There is a visible mutual trust and a shared vision among partners. Easy access and timely advice to farmers are important drivers for the observed impressive impacts in this watershed. This has led to enhanced awareness of the farmers and facilitated their ability to consult with the right people when they faced problems (Sreedevi et al. 2004).

The watershed development program in Kothapally started from year 1999 onwards. Contour and graded bunds were built in the fields, and gully control structures, percolation tanks and check dams were constructed in the channels. Constructed bunds across the land slope reduce travel distance and minimize velocity of generated runoff and allow more water to percolate into the fields. This practice created opportunity to accumulate surface runoff along the contour line or disposes surface water safely outside the field and protects soil erosion. Check dams and other ex-situ practices reduce peak discharge in order to reclaim gully formation and harvest substantial amount of runoff, which increases groundwater recharge. Adoption of low-cost water storage and harvesting structures ensured water conservation benefits more equitably distributed in different parts of the watershed landscape.

Water availability and crop yield have substantially improved after the watershed development program was implemented (Sreedevi et al. 2004). For instance, many of the wells that were not functioning due to low groundwater levels have reverted into active well with good amounts of water yield. Moreover, the cropping pattern has changed in recent years. Farmers who used to be cultivating cotton of traditional varieties, sorghum, maize, paddy, onion, and chilly before the onset of the watershed development program, have started cultivating higher yielding cotton varieties (BT cotton) as irrigation water supply from the wells is now reliable. Those farmers who do not have wells for irrigation also started cultivating cotton as the soil moisture availability has improved after the in-situ conservation practices which allowed to crop to survive for another two to three months after monsoon without irrigation. Maize and paddy are now cultivated only in limited areas during monsoon and vegetables is being grown in irrigated area during summer.

An integrated nutrient and pest management approach was adopted along with the soil and water conservation measures. Detailed characterizations of soil chemical properties in agricultural fields suggested that Kothapally soils were deficient not only in major nutrients (N and P) but also had a poor status of zinc (Zn), boron (B) and sulphur (S) (Sreedevi et al. 2004). In addition to supplying chemical fertilizers, *Gliricidia* plantations along the field bunds started to generate N-rich organic matter in watershed. Vermi-composting was undertaken by self-help groups as a micro-enterprise to generate income and nutrient rich organic fertilizer.

The socio-economic status has improved after introducing IWM approach in the Kothapally village (Sreedevi et al., 2004). Most of the farmers were solely dependent on agriculture in 1999 and earlier. Farmers were motivated to do other job activities and services along with cultivating crops, which together with improved yields, led to a substantial change in their livelihood in recent years. Farmers started doing dairy farming, transport services, labor work for building roads and houses, nursery plantation and engaged with small scale business and local services (viz., running small café, saloon shop, stitching cloths in home, selling food and general materials in shops, selling coupons for recharging mobiles, etc.) locally. Approximately one fourth households in Kothapally watershed currently generate additional income other than agriculture. The average household income in the Kothapally watershed is about 50% higher compared to adjoining villages without watershed interventions (Sreedevi et al. 2004).

Methodology

Input Data and Model Setup

SWAT requires three basic files for delineating the watershed into sub-watersheds: Digital Elevation Model (DEM), Soil map and Land Use/Land Cover (LULC) map. A meteorological station (Figure 1) was installed in Kothapally watershed in 2000. Daily data of precipitation, wind speed, relative humidity, solar radiation and air temperature were monitored, and provided as input to the model. Check dam plays an important role in watershed hydrology; it captures excess surface runoff and prevents/reduces soil loss. We recorded exact location of storage structures using GPS and measured its surface area and storage volume. Structures that comprises storage capacity equal to or greater than 350 m^3 were exactly located as a reservoir into SWAT setup and smaller structures were all together lumped into single unit at every stream/channel. All together 14 reservoirs were created (Figure 1); their year of construction and other salient features (i.e., surface area and total storage capacity) were provided as inputs into model. Parameters concerned with management operation like tillage, plantation, fertilization, irrigation and harvesting were provided as input to the model. Cropping pattern in Kothapally is dominated by cotton as a major crop. Therefore, we assigned cotton plantation and its cultivation under the land management operation between June and December months.

Model Calibration

Calibration is required to characterize the system correctly before making any simulations for decision making. SWAT generates default values for each variable and allow user to modify parameter values during calibration process. In present study, model was calibrated based on (1) discharge at outlet, (2) reservoir stage-volume data, (3) sediment flow at outlet and (4) crop yield; and further model is validated using groundwater (water table) data.

Scenario Development

Impact of watershed management practices on water availability, sediment loss and crop yield was assessed. Four scenarios were developed with combination of (a) with or without In-situ land management practices and (b) with or without building storage structures in stream channel (called as ex-situ management). Thus scenarios are: 1) in-situ + ex-situ; 2) in-situ + no ex-situ; 3) no in-situ + ex-situ; 4) no in-situ + no ex-situ. ICRISAT meteorological data of 31 years from period 1978 to 2008 was used for scenario generation. Prior to this, Kothapally and ICRISAT rainfall data was compared for known period between year 2000 and 2008 and a good correlation (R^2=0.90) was found on monthly time scale.

Results

Water Balance of Different Water Intervention Scenarios

Different water interventions significantly change the water balance components in watershed (Figure 2). Before the introduction of the watershed development program (scenario four), approximately 60% of the rainfall became evaportranspirated (ET), while some 10% recharged the groundwater aquifer and 20% was lost from the watershed boundary as outflows, during the first cropping season. When the watershed development program was in place, the amount of water leaving the watershed as ET had increased to around 70%, groundwater recharge was also higher than previously, while outflows from the watershed was now less than 10% of the total water balance (scenario one). Constructing check-dams substantially increased groundwater recharge (scenario three), while in-situ practices resulted in a higher ET, since more water was available as soil moisture in the fields, and higher groundwater recharge (scenario two).

Sediment Transport and Soil loss

The average soil loss from the watershed has been less than 3.0 t ha in all years except in 2000, when Kothapally experienced a heavy downpour of 303 mm within 24 hours in August, which created enormous

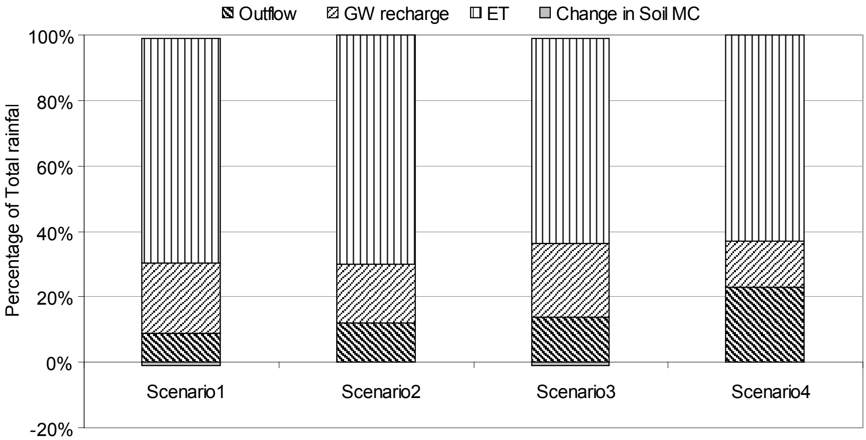

Figure 2. Water balance for the four different water management scenarios for the first cropping season (from June to Dec); scenario-1: in-situ + check-dams; scenario-2: in-situ + no check-dams; scenario-3: no in-situ + check-dams; scenario-4: no in-situ + no check-dams. GW recharge = groundwater recharge. ET = evapotranspiration.

amounts of runoff and soil loss from the watershed boundary. Simulations suggest that on average 7 mm of soil was lost from the entire watershed due to this extreme event. A soil loss map for 2000 shows that soil is lost from a large area of the watershed (Figure 3). Soils are deposited in those micro-watersheds where check dams were built, since the check

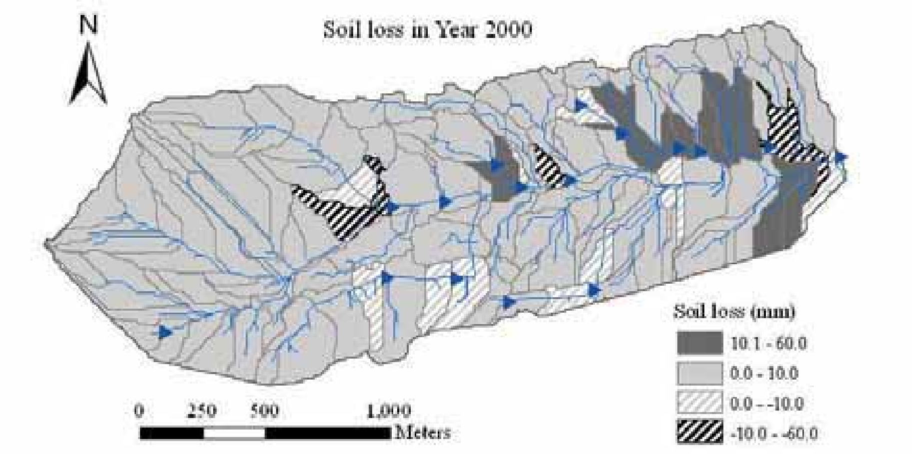

Figure 3. Soil loss in different micro-watersheds of Kothapally area in year 2000. Gray colour in map shows soil loss and crossed lines shows its deposition (also shown by negative numbers).

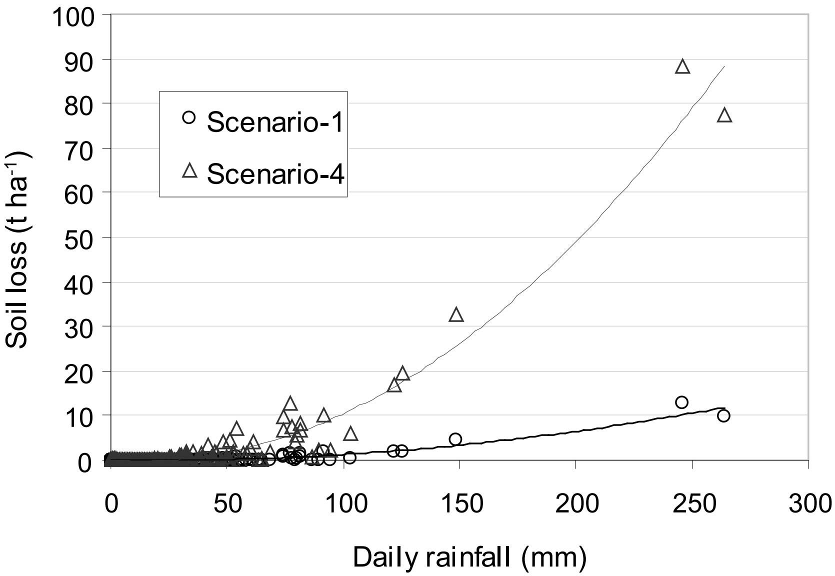

Figure 4. Rainfall vs. soil loss; scenario-1: in-situ + check-dams (post watershed development); scenario-4: no in-situ + no check-dams (no watershed development).

dams reduce the flow velocity of the water and allow silt particle to settle down.

Soil loss is strongly affected by rainfall intensity (Figure 4). Rainfall intensity below 50 mm/day did not generate much soil loss in any of the four management scenarios. However, a clear difference in soil loss can be seen between the situation before and after the implementation of the watershed development program at rainfall intensities above 50 mm/day, where more soil is lost from the system without water interventions. It is apparent that soil loss from the fields as rainfall intensities above 100 mm/day significantly impacts on downstream systems, in this case the sediment load to the Osman Sagar reservoir, without the watershed development programs. High rainfall intensities are expected to become more common with a changing climate, and soil loss from the fields can therefore be expected to increase in the future.

Discussion

Water Management Interventions Improve the Resilience of Small-scale Tropical Agricultural Systems

Because of the watershed development programs, the livelihoods of the farmers in the Kothapally village have improved. Agricultural yields are on the increase, and farmers are now able to save some of the incomes generated by the farm and to re-invest in the business. Because of diversification of sources of income due to more off-farm activities, their resilience to external shocks has been improved. More specifically, the water interventions have reduced the inherent risks in agriculture in the semi-arid zone posed by high rainfall variability and frequent dry-spells, thereby building resilience in tropical agriculture. With a more erratic precipitation under future climate change, water management interventions in tropical agriculture are likely to be of even greater importance.

The Choice of Water Management Intervention Depends on Hydro-ecological and Social Settings

Watershed management programs including in-situ water harvesting and check-dams, significantly change the water resources availability in watershed. Check-dams are helpful in storing water for groundwater recharge, which can be used for irrigation, as well for protecting soil loss. In-situ water management practices improve infiltration capacity and water holding capacity of the soil, which results in higher crop water availability.

The strategy of the watershed development program should be based on hydro-ecological zones and soil characteristics. In-situ management may be sufficient at higher rainfall amounts, while ex-situ water management for supplementary irrigation may be needed to complement the in-situ system at lower rainfall amounts (below 600 mm yr^{-1}) and to bridge dry-spells. However, practicing both in-situ and ex-situ management in low rainfall zones may not be economically viable because with in-situ management there may not be enough local run-off to collect in the ex-situ storage systems. At rainfall amounts above

600 mm yr^{-1}, both practices might be implemented without the risk of them competing with each other for water. In-situ practices in such areas would improve infiltration and at the same time check-dams can store surplus amounts of water and sediment. A common strategy cannot be implemented everywhere; it depends on topographic and soil characteristics, the location of the watershed and the objective of the development.

Ex-situ management is indeed helpful for storing water but it may create an unequal distribution if only some of the framers will be benefited but not entire community. In the Kothapally village, some farmers have wells on their properties which they use for irrigation of their own fields first, and, if there is water left after they have fulfilled their own irrigation requirements, they allow neighbouring farmers to use their water for a proportion of the income from that farm. Thus, in the case of Kothapally, the farmers with wells on their properties will benefit more by having the check-dams than the others.

Conclusions

Watershed interventions in agriculture in the form of in-situ and ex-situ water harvesting systems are important for building resilience in tropical agriculture, but may at the same time cause negative impacts to downstream systems because of reduced water flows. The watershed interventions in the Kothapally village resulted in higher infiltrability and waterholding capacity of the soil, as well as increased groundwater levels, which enabled supplementary irrigation of the monsoon crop to bridge dry-spells, and full irrigation of a second dry season crop on 30% of the fields. Soil loss has decreased by a factor ten because of the watershed development program, which is expected to have positive impacts on instream river ecology and the life-span of the reservoir downstream. Case study of Kothapally watershed has shown that integrated watershed management approach has built resilience in the agricultural systems, and has improved the livelihoods of the farmers.

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