Jatropha production on wastelands in India: opportunities and trade-offs for soil and water management at the watershed scale

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Abstract

Biofuel production from feedstocks grown on wastelands is considered as a means to address concerns about climate change and improve energy security while at the same time provide an additional source of income. Establishment of biomass plantations on wastelands is likely to affect local livelihoods and can affect surrounding ecosystems by influencing hydrologic flows and processes such as erosion. We present an assessment of *Jatropha plantation establishment on wastelands*, using the ArcSWAT modeling tool. The assessment was made for a wasteland located in the Velchal watershed, Andhra Pradesh, India, which recently was converted to a biofuel plantation with *Jatropha*. The previous land-use, in this case grazing, could continue in the *Jatropha* plantations. Several desirable effects occurred as a result of the land-use conversion: non-productive soil evaporation was reduced as a larger share of the precipitation was channeled to productive plant transpiration and groundwater recharge, and at the same time a more stable (less erosive) runoff resulted in reduced soil erosion and improved downstream water conditions. A win-win situation between improved land productivity and soil carbon content was observed for the *Jatropha* plantations. On the other hand, the results indicate that at the sub-basin scale, reductions in runoff generation as a result of large-scale conversion of wastelands to *Jatropha* cropping may pose problems to downstream water users and ecosystems. From a livelihoods perspective, *Jatropha* production was generally positive, creating a complementary source of income to the farmers, thus strengthening the resilience of the local community. In the future, the potential gain from *Jatropha* cropping is expected to become higher as cropping systems improve and growing biofuel markets result in better conditions for biofuel producers.

Keywords: Jatropha, biofuel, India, evapotranspiration, sedimentation, runoff, livelihoods, soil carbon, water balance, waste land

1. Introduction

In India, rapid urbanization coupled with industrialization and economic growth drives increasing energy demand and substantial import of crude petroleum oil[71]. Since beginning of the 1990s India's oil imports has increased more than five-fold and has considerable influence on the country's foreign exchange expenditures. The Indian economy is expected to continue to grow with resulting further increase in energy demand and rising oil imports, projected to reach 166 and 622 million tons by 2019 and 2047, respectively[71], which can be compared to the 110.85 million tons of crude oil that was imported in 2006-07[27].

As in many other countries, biofuels are in India considered an option for addressing the energy security concerns[2,28], while also responding to the challenges of climate change mitigation[51]. A Petrol blending program mandated 5% ethanol blending of petrol, initially for selected states and union territories, and in 2006 extended to the whole country (Ministry of Petroleum and Natural Gas 2009). Programs for stimulating complementary use of biodiesel to displace petroleum based diesel primarily focused on biodiesel production based on non-edible oil seeds produced on marginal or degraded lands. The Government of India approved the National Policy on Biofuels in year 2009 targeting a 20% blend of biofuels with gasoline and diesel by 2017[1].

1.1 Wastelands in India

The most recent governmental assessment in India classified slightly more than 50 million hectare (ha), or 16% of the Indian land area, as wasteland, including a range of different land types, e.g., degraded forest land, gullied, ravenous and bedrock-intruded land, land under shifting cultivation, degraded pasture and grazing land, degraded land under plantations and mining and industrial land[29]. Soil degradation processes have severely reduced the soil productivity and it has been estimated that, on average, wastelands have a biomass productivity less than 20% of the original potential[52].

Contributing causes include waterlogging, soil salinity/alkalinity, and a combination of low biomass productivity and excessive biomass removals reducing the soil organic carbon levels.

A substantial wasteland area consists of degraded lands that are deteriorating due to lack of appropriate soil and water management, or due to natural causes, and which can be brought into more productive use. Roughly 40% of the wasteland area has been estimated as available for forestation[58] and about 14 million ha is considered suitable for cultivating biofuel feedstocks, such as *Jatropha*[78]. The National Wastelands Development Board was established in 1986 with the objective of bringing five million ha of wasteland under fuel wood and fodder plantations every year. Establishment of biofuel plantations is considered an option for rehabilitating wastelands, enhancing energy security, and providing employment opportunities and better livelihoods in rural areas[2,51,65,76-78]. Considering that about 35% of India's inhabitants live below the poverty line and more than 70% of the poor are small/marginal farmers or landless labourers[66], it is essential that wasteland development provides these socioeconomic benefits.

1.2 *Jatropha*

Jatropha (*Jatropha curcas L.*), commonly known as "purging nut" or "physic nut", is a tropical, perennial deciduous, C3 plant belonging to the family *Euphorbiaceae*[14,70]. It adapted to perform best under conditions of warm temperatures and, as with many members of the family *Euphorbiaceae*, contains compounds that are highly toxic. *Jatropha* has its native distributional range in Mexico, C. America and part of S. America, but has today a pan tropical distribution[72]. Productivity of *Jatropha* depends on precipitation rates, soil moisture availability, soil characteristics including fertility[12,20,35,40], genetics[14,37,68], plant age[11] and various management factors like pruning, fertilization, and disease control[3,8,23,35,37]. Annual yield levels at 2-3 tons dry seeds has been proposed as achievable in semi-arid areas and on wastelands, while 5 tons ha^{-1} can be obtained with good management on good soils receiving 900-1200 mm average annual rainfall [11,19,20]. Jongschaap *et al.,*[36] reported potential *Jatropha* yields as high as 7.8 tons dry seed ha^{-1} yr^{-1}. The decorticated seeds yield about 28-40% oil[14], which can be transesterified and used for producing biodiesel[34,39]. *Jatropha* has not yet undergone breeding programs with selection and improvement. The productivity varies greatly from plant to plant and environmental factors are reported to have a dominating role over genetics in determining seed size, weight and oil content[37].

A global assessment of the ecological suitability for *Jatropha* cultivation under present and future climatic conditions indicates that high yields should be attainable in both tropical and hot temperate areas[72]. Climate change is estimated to reduce average global yield levels by about 10%, with higher variation at local scale[18,30,50]. Areas in Southern Africa (e.g. Zambia), South America (e.g. Argentina, Paraguay), and the northern part of South and East Asia (e.g., Northern India, Nepal and China) are expected to become more suitable for *Jatropha* cultivation in the future[72] due to expected reduced frequency of frost events and cold days and nights[33].

Jatropha is considered to be drought tolerant and possible to cultivate on degraded, sandy and saline soils with low nutrient content[60]. Nitrogen and phosphorous inputs may be required for high yields[13,31,36] but nutrient recirculates through the leaf fall reduces the need for fertilizer input[78]. It is estimated that three-year old *Jatropha* plants return about 21 kg N ha^{-1} back to the soil, although the quantity and nutrient content of the fallen leaves from the *Jatropha* plant vary with plant age and fertilizer application[78]. *Jatropha* can be grown in broad spectrum of rainfall regimes, from 300 to 3000 mm, either in the fields as a commercial crop or as hedges along the field boundaries to protect other plants from grazing animals and to prevent erosion[3,40]. There is limited knowledge about the actual water requirement of *Jatropha* in different agro-ecological regions. However minimum and optimum rainfall to produce harvestable *Jatropha* fruits is assessed as 500-600 and 1000-1500 mm yr^{-1} in arid and semi-arid tropics, respectively[3,12,72]. Furthermore, assessments of how downstream hydrological processes and sediment transport are affected by large-scale implementation at the meso-scale (10-10 000 km^2) are so far lacking.

Even so, from the perspective of water, *Jatropha* cultivation to provide feedstock for biodiesel production is in India considered an option for making productive use of wastelands while at least partly avoiding conflicts with downstream environmental flow requirements. It is proposed that additional beneficial effects might arise, such as less erosive storm floods and lower sediment loads in riverine ecosystems, and larger groundwater formation as a result of improved infiltrability. Using wastelands for cultivating *Jatropha* could also help strengthening local livelihoods and income diversification, given that this is set as a priority for land development[43].

1.3 Scope and aim of study

This article report results from a case study of *Jatropha* cultivation on wastelands in the state of Andhra Pradesh. The purpose of the *Jatropha* cultivation was to develop a model for improving the livelihoods of the poor, through promotion of plantations managed by user groups on common pool land resources. The aim of the study was to investigate opportunities and trade-offs of *Jatropha* cultivation on wastelands from a livelihoods and environmental perspective, with soil and water as the critical resources. Special emphasis was placed on water, and hydrological assessments were conducted using the ArcSWAT tool to analyse the impacts of three different land-use scenarios: (i) a wasteland state (barren land); (ii) biofuel cropping with *Jatropha*; (iii) and long-term biofuel cropping with *Jatropha* assuming changes in soil carbon content and soil physical conditions.

2. Study area and data

The state of Andhra Pradesh is located in the semi-arid tropics of Southern India and has some 4.52 million ha of land that is classified as wastelands. This equals 16.5% of the total geographic area of the state (GOI, 2010). Half the wasteland area consists of degraded forests, while the rest is covered with scrubs or forms a barren, rocky landscape. The effects of wasteland conversion to biofuel plantations on water flows and sedimentation losses are assessed for a formerly degraded wasteland belonging to the Velchal village, approximately 50 km outside of the city of Hyderabad, in the Manjeera sub-basin of the Godawari river basin, Andhra Pradesh, (**Fig. 1**). Due to over grazing by livestock, a large area of the Velchal watershed (17.28°N latitude, 77.52°E longitude, 645 meters AMSL) is classified as wastelands. This wasteland consists of hillock, which is relatively flat (2-3% slope) and with a sparse vegetation cover of some trees and grass, and a valley (10-25% slope) covered with various types of bushes and perennial trees. Soils have been classified as Vertisols with a very shallow soil depth between 10 and 50 cm as an effect of over grazing. The water holding capacity is medium to low, and the soil organic carbon content is between 0.60 to 1.2 %.

Demographic data of the Velchal watershed shows that more than 44% of the labourers in the watershed were classified as "land-less" in the year 2005. These people were largely dependent on casual agricultural labour work or on construction work. In addition, they often migrated to nearby cities and suburban areas to find work opportunities, where 70% of them were living in slum areas. The rest of the population in the community (56%) are so called "marginal farmers", cultivating rainfed crops on land-holdings less than 2 ha, and also working as intermittent agricultural labourers[65,75].

In the year 2005, the National Oilseeds and Vegetable Oils Development (NOVOD) together with the ICRISAT consortium, planted *Jatropha* on 160 ha common property land belonging to the Velchal village and classified as wasteland. *Jatropha* seedlings approximately 60 cm high were planted at 2m x 2m spacing at Velchal watershed. Plants were grown under rainfed conditions and no irrigation was applied. Soil and water conservation practices (e.g., bunding and trenches) were implemented to harvest more rainfall. Fertilization (30 kg N ha^{-1} and 12 kg P_2O_5 ha^{-1}) was applied during the *Jatropha* planting. Further fertilization (50 kg N ha^{-1} and 57 kg P_2O_5 ha^{-1}) was applied in year 2007. Growth parameters and seed yield of *Jatropha* crop was recorded. The plantations were mainly located in the hillock area, although some plantations are also found in the valley.

Before the initiation of the project, landless and marginal farmers were called to a planning meeting along with the village institutional body (known as Gram Sabha). The objective of the proposed project, the work protocol, and potential local benefits were discussed. Self-help groups were formed based on the voluntary interest of poor people in need of livelihood opportunities. The group members were trained in various activities such as nursery raising, planting, harvesting and oil extraction.

Data on crop characteristics to estimate crop water uptake was collected at the ICRISAT experimental site, a micro-watershed located at the ICRISAT campus in Hyderabad (17.53ºN latitude and 78.27ºE longitude) where *Jatropha* seedlings (3m x 2m spacing) were planted on 4 ha of land in 2004. Since then, the *Jatropha* has been cultivated under good management practices, including fertilization (90 kg N and 40 kg P_2O_5 ha^{-1} $year^{-1}$) and various agronomic measurements. Seed yield and oil content has been monitored.

The monitored site is characterized by similar climate and rainfall patterns as the degraded wasteland that was planted with *Jatropha* in the Velchal watershed. The topography of the landscape is relatively flat (1-2 % slope). The Vertisol soil that covers the site has low permeability and a soil depth at approximately 2-3 meters. Rainfall is highly erratic, both in terms of total amount and distribution over time. The mean annual rainfall equal to 860 mm, of which 85 % is distributed between June and October. Pictures in **Fig. 2** show *Jatropha* plantation and its fruiting stage at Velchal and ICRISAT watershed during year 2010.

3. Material and Methods

Fig. 3 shows a conceptual representation of the hydrological cycle at watershed scale. Rainfall is partitioned into various hydrological components as defined by mass balance equation: Rainfall = Out flow from the watershed boundary (Surface runoff + base flow) + Groundwater recharge + Evapotranspiration (Evaporation + Transpiration) + Change in soil moisture storages. Where fraction of rainfall stored into Vadoze zone is known as green water; and water available into groundwater aquifer and amount of water reached at river stream is known as blue water[16].

A GIS based hydrological model, ArcSWAT (the Soil and Water Assessment Tool), was used to assess the hydrological processes and yields for the Velchal watershed, for scenarios with and without biofuel plantations. Since ArcSWAT does not differentiate between transpiration and soil evaporation, a one dimensional, Richards' based model, HYDRUS1D, was used to estimate root water uptake under *Jatropha* cultivation using data from the ICRISAT BL3 watershed. **Fig. 4** shows a flow diagram of the adopted modeling methodology. ArcSWAT divides rainfall into different hydrological components based on topography, soil and management practices. Therefore, the ArcSWAT simulation of the Velchal watershed area results in a partitioning of rainwater at the soil surface between runoff and infiltration.

To further analyse the division between transpiration and evaporation, the HYDRUS1D model is used. First, HYDRUS1D was parameterized and calibrated using soil and crop data from the ICRISAT field experimental station. Secondly, the soil properties were changed to represent the Velchal watershed, but without changing the crop water uptake parameterization. The amount of infiltrated water from the ArcSWAT simulation was then used as input to the HYDRUS1D model, and HYDRUS1D then computed soil evaporation, transpiration and deep percolation for the Velchal watershed. Both ArcSWAT and HYDRUS1D assume a second water partitioning point in the soil between deep percolation to lower soil layers and evaporative flows. This could potentially cause inconsistencies if the estimates of the water partitioning from the two models of the Velchal watershed differed substantially. It was however found that the difference between the models was less than 10%, and the approach combining the two models was therefore considered as giving a sufficiently accurate representation of the Velchal watershed.

3.1 ArcSWAT description and inputs

ArcSWAT is a semi-process based hydrological model for analyzing impacts of land management practices on water flows and sediment loss in complex watersheds[5,22]. The model integrates the principal hydrological processes, soil and nutrient transport, and vegetative growth on a spatial and temporal frame, using a daily to an annual time scale. Surface runoff from daily rainfall is estimated using a modification of the Soil Conservation Service curve number (CN) method from United States Department of Agriculture-Soil Conservation Service[4,47] and peak runoff rates are estimated using a modified rational method[47]. SWAT simulates plant growth by using the generic crop growth module from the EPIC (Erosion Productivity Impact Calculator) model[47]. The crop growth module first calculates the plant growth under optimal conditions, and then computes the actual growth under stress inferred by water, temperature, nitrogen, and phosphorous deficiency[42]. Sediment yield is estimated using the Modified Universal Soil Loss Equation (MUSLE)[81]. A detailed description of this model is given by Neitsch *et al.*[47]

ArcSWAT requires three basic files for delineating the watershed into sub-watersheds: a Digital Elevation Model (DEM), a Soil map and a Land Use/Land Cover (LULC) map. The DEM for the Velchal watershed was generated from ASTER 30 m remote sensing data. Only the area marked as "plantation" in **Fig. 1** was included in the model set-up. A soil map of the watershed was prepared by collecting soil samples on a grid structure of approximately 200 m (**Fig. 1**). Undisturbed soil cores (34 cores) were taken for measuring bulk density. Other physical properties such as texture, gravel content, organic carbon, field capacity and permanent wilting point were estimated in the laboratory. **Table 1a** summarizes details of soil physical properties of the Velchal watershed.

A rainfall station (**Fig. 1**) was installed in the Velchal watershed in the year 2010. In addition, ICRISAT data of daily rainfall, wind speed, relative humidity, solar radiation and air temperature were used as meteorological input to the model. Locations of check-dam storage structures were obtained from GPS readings and their surface area and storage volume were measured. All together 6 reservoirs were created (**Fig. 1**); their year of construction and other salient features (i.e., surface area and total storage capacity) were provided as inputs into model. Rainfed *Jatropha* is planted in the whole area included in the analysis. Moreover, some of the parameters values (e.g. soil loss parameters) were based on a previous study[21] of a nearby watershed, Kothapally (**Fig. 1**), located in the Musi catchment (**Table 1a**).

ArcSWAT was subsequently calibrated based on reservoir-volume data. The water level in two reservoirs (Check dam 1 and Check dam 2 in **Fig. 1**) were monitored daily between September and November, 2010, and translated into water volumes of the reservoirs based on information on the area of the dams. These check dams are the largest dams in the study area and have a storage capacity in the range 3000-5000 m^3. The check dams are not related to the biofuel plantations project *per se*, but were constructed for the purpose of flood prevention and improved groundwater storage. Calibrated parameters were related to surface runoff processes (CN) and base flow (REVAP_MN, GWQMN) (**Table 1a**). Important parameters required for simulating crop growth were taken from agronomical measurements and chemical analyses[78] at the BL3 ICRISAT experimental site (**Table 1a**) and from past studies[3,6]. Seed yield data for *Jatropha* was collected for a three year period from year 2008 and 2010 in Velchal, and used to validate simulated results.

3.2 HYDRUS1D description and inputs

HYDRUS1D is a one-dimensional hydrological model for simulating movement of water, heat, and multiple solutes in variable saturated media[63]. This model numerically solves the Richards' equation for saturated-unsaturated water flow, and the Van Genuchten-Mualem, single porosity hydraulic module was selected for simulating water flows. Related soil hydraulic parameters (i.e. θ_r, θ_s, n, α and K_s) were estimated from neural network prediction (inbuilt in the public domain model HYDRUS1D, version 4.14) using basic soil physical properties like texture, bulk density, soil moisture content at field capacity and permanent wilting point[59] for different soil layers, which had been measured in the field (**Table 1b**). The parameters θ_r, θ_s are the moisture content at residual and saturated level, n and α are the shape parameters of the soil water retention curve and K_s is the saturated hydraulic conductivity of the soil profile, respectively. A soil profile of 220 cm was defined in the simulation environment and divided into four layers system based on measured soil physical properties. Upper boundary conditions (rainfall, potential evapotranspiration and leaf area index) had been measured in the field for the simulation period, and were provided to the model on a daily time-step. Free drainage conditions were assumed as the lower boundary condition. A root water uptake module developed by Feddes[17] was selected in present study. The model was run for the period October 2005 to October 2008.

Soil moisture data at different soil depths had been collected using a neutron probe at 10 locations in the BL3 watershed with a 15 day interval since Oct 2005 onwards and was used to calibrate the model. Initially, parameters governing root water uptake of *Jatropha* was assigned from the default dataset of HYDRUS1D for pasture growth (**Table 1b**), but were subsequently modified by comparing observed soil moisture with observed data at different soil layers (22, 37, 52, 82, 112 and 142 cm) during manual calibration. After calibration, the plant water uptake parameters were maintained, while the soil characteristics were changed to represent the Velchal watershed instead (**Table 1b**). Thereafter the re-parameterised model was run with the simulated infiltration amounts from the ArcSWAT simulation of the Velchal watershed as soil water inputs at the soil surface.

3.3 Model Performance

The simulated reservoir volume was similar to measured volumes (correlation coefficient = 0.97) after calibration (**Fig. 5a**). The Root Mean Square Error (RMSE) of prediction is about 350 m^3, which is less than 8% of total storage capacity of the check dams, indicating good model performance. Simulated *Jatropha* yields (dry seed) ranged from 0.4 tons ha^{-1} to 0.75 tons ha^{-1}, and correspond well to what was harvested at selected locations of the Velchal biofuel plantation. Moreover, the calibration results obtained from HYDRUS1D for the BL3 ICRISAT watershed show good correlation between simulated and observed data (**Fig. 5b**). The overall RMSE of soil moisture was 0.04 cm^3 cm^{-3}, while the correlation coefficient ranged between 0.64 and 0.85.

3.4 Scenario development and simulation protocol

The calibrated SWAT set-up was run for a 10 year time period (2001 to 2010). Results are presented for dry, normal and wet years according to the following classification (Indian Meteorological Department, Pune, India; http://www.imdpune.gov.in):

- Rainfall less than 20% of the long term average = dry;
- Rainfall between -20% to +20% of the long term average = normal;
- Rainfall greater than 20% of long term average = wet.

The annual average rainfall of the study area is 910 mm between period from year 2001 and 2010. Three scenarios were analyzed in the study:

i) The "*Wasteland*" scenario represents the situation where the landscape is in a degraded stage. Soils are highly eroded and poor in organic matter and have poor water holding capacity. Bushes and seasonal grasses dominate the landscape, which is used for grazing.

ii) The "*Current Jatropha*" scenario represents the situation where *Jatropha* is cultivated and some soil and water conservation measures (insitu interventions) are implemented. Leaf fall, stem and other bush/tree biomass is being added to the soil mainly at dormancy period. *Jatropha* seeds are harvested by the local community.

iii) The "*Long-term Jatropha*" scenario represents a thought situation where the conditions in the "Current *Jatropha*" scenario have been maintained for long period of time, leading to increased soil organic matter and changed soil characteristics what regards, e.g., infiltrability and soil water holding capacity[78].

The Wasteland scenario was created by removing the current vegetation cover in the ArcSWAT parameterization, while the parameterization procedure of the *Current Jatropha* scenario was done as described above[21]. Finally, the *Long-term Jatropha* scenario was parameterized based on modifying selected parameters as described in **Table 1c**: a) 20% increase in soil carbon content (same as for the long-term biofuel plantations at the ICRISAT experimental station); and b) changed soil characteristics (parameterisation taken from the *in-situ* soil water management scenario in the nearby Kothapally watershed, as described in Garg *et al*.[21]

4. Results

4.1 Impact of *Jatropha* plantation on water balance

The water balance for the area under study differs substantially depending on land use and amount of annual average rainfall (**Fig. 6a**). In general, a larger share of the total rainfall forms runoff during wetter years compared with drier years. For the Wasteland scenario, runoff constituted 40-60% of total rainfall amount, while for the Long-term *Jatropha* scenario, the corresponding figure is 20-40%. Between 4 and 17% of total rainfall was going to groundwater recharge, while the remainder was transferred to the atmosphere through evaporation or evapotranspiration.

A comparison of the different land management scenarios shows that more than 50% of the non-productive soil evaporation in the Wasteland scenario is shifted into productive transpiration in the two *Jatropha* plantation scenarios (**Fig. 6a**), while the total amount of evapotranspiration (ET) is relatively similar in all three scenarios, except during dry seasons when ET is higher in the *Jatropha* scenarios, and even higher under improved soil conditions. Groundwater recharges doubles in the *Jatropha* scenario and quadruples in the Long-term *Jatropha* scenario, compared with the Wasteland scenario (**Fig. 6a**). As a result of higher ET and groundwater formation, runoff formation decreases in the *Jatropha* scenarios, in particular during dry years. In the Wasteland scenario, runoff constitutes around 40% of the total rainfall during dry years while the corresponding figure for the Current *Jatropha* scenario is around 30%, and even lower (down to 20%) for the Long-term *Jatropha* scenario. Such a large reduction in outflows from the watershed at a time when the average rainfall amount is low might have negative impacts on downstream ecosystems and water users.

The distribution of the water balance components over the year also varies with land-use (**Fig. 6b**). While the total ET is lower for the two *Jatropha* plantation scenarios during the dry season (December-March), it becomes higher during the wetter parts of the year. This means that the annual fluctuations in runoff and groundwater generation are smaller in the *Jatropha* plantation scenarios, compared with the wasteland scenario.

Runoff generated from the watershed consists of two components: i) surface runoff and ii) base flow generation. It was found that even though the total runoff was significantly lower with *Jatropha* plantations compared with the waste-land condition, base flow was in fact higher with *Jatropha* plantations (**Fig. 6c**). On an average, the total amount of base flow generation in the Wasteland scenario was only 70% of the base flow in the *Jatropha* scenarios; however, total runoff was 40% larger for the wasteland state compared with the long-term *Jatropha* scenario.

Land management also affects runoff intensity. In general, higher runoff intensities were predicted for the wasteland state, compared with *Jatropha* plantations (**Fig. 6d**). The results show that the average daily run-off intensity decreased by 12 % for the current *Jatropha* plantation, compared with the wasteland condition, and is likely to decrease even further with continued *Jatropha* cropping (the Long-term *Jatropha* scenario had 39 % lower runoff intensity than the Wasteland scenario).

4.2 A comparison of water balance among BL3 ICRISAT and Velchal watershed

A comparison of water balance components between the well managed ICRISAT BL3 watershed and the Velchal community site ("current *Jatropha*" scenario) shows (**Table 2**) that a larger part of the rainfall formed green water flows (i.e. evapotranspiration) at the well managed site (80-90% compared with 40-60% respectively). This means that only a small fraction (10-20%) of the total rainfall generated blue water flows (runoff and groundwater recharge) at the ICRISAT BL3 location. During dry years, blue water generation was lower than green water generation at both sites. The division between green and blue water components for *Jatropha* at the well managed site corresponds well with those observed for many water demanding cereal crops[53].

4.3 Sediment transport and soil loss

Currently, the estimated average soil loss in the Velchal watershed is between 10-15 tons $ha^{-1}yr^{-1}$. Because the soil depth is low and the available water holding capacity is poor in the watershed, large runoff is commonly generated during rain, with the capacity to carry large amounts of sediments. Soil loss was found to increase exponentially with rainfall intensity, and varied with land-use (**Fig. 7a**), so that the highest soil loss occurred at high rainfall intensities under wasteland conditions. Cumulative soil loss generated at the watershed outlet over a ten year period showed that *Jatropha* cultivation resulted in a reduction of the total soil loss amount of nearly 50% compared to the wasteland state

(**Fig. 7b**). With improved soil condition (Long-term *Jatropha* scenario), soil loss decreased even further.

4.4 *Jatropha* Growth and crop yield

Crop growth parameters measured at ICRISAT and Velchal during year 2008 are presented in **Table 3**. *Jatropha* seed yields are found below 0.5 tons ha^{-1} within the three years of plantation at ICRISAT but afterwards increased substantially. *Jatropha* seed yields in the Velchal watershed after year three and onwards varied (0.3-0.8 tons ha^{-1} yr^{-1}) depending on rainfall variability[78]. At the ICRISAT BL3 site, the corresponding figure is 1.0-2.7 tons $ha^{-1}yr^{-1}$. The relatively poor seed yield in Velchal is due to water and nutrient stress, as confirmed by model simulations (data not shown). **Table 2** shows difference in soil physical and land management conditions of two experimental sites. *Jatropha* plants at the ICRISAT micro-watershed could utilize more green water compared to *Jatropha* plants at the Velchal watershed. Moreover**,** three year old plantations recycled 20.8 Kg N, 2.0 Kg P and 23 Kg K ha^{-1} through leaf fall (**Table 3**). This nutrient recycling has an important role in sustaining the productivity of the landscape and building carbon stocks[2,78].

5. Discussion

5.1 Soil and water related impacts

Wastelands are characterized by sparse vegetation cover, exposing soils to both rainfall and solar radiation. Large soil losses occur during instances of intensive rainfall, and the non-productive soil evaporation can be very large due to the lack of vegetative cover. The results show that under favorable soil management and with a good water supply, the water uptake of *Jatropha* is similar to that of many water demanding cereal crops. However, on wastelands where crop management is quite difficult, *Jatropha* plantations might be a better option for enhancing productive water flows and at the same time protect these areas from further degradation[1].

The results from this study confirm the hypothesis that *Jatropha* plantations on waste lands can have several positive effects in relation to soil and water:

- Reduced soil losses due to lower erosion rates when the soils are better protected by vegetation and roots. Besides the on-site benefits this also has the benefit that sedimentation loads on rivers and other water bodies are reduced;
- Increased soil carbon content, which changes the soil physical characteristics so that both water infiltrability and soil water holding capacity increase. The soil carbon increases also enhances the climate change mitigation benefit by withdrawing CO_2 from the atmosphere;
- Redirection of non-productive soil evaporation into productive transpiration, which improves the field level water productivity;
- Increased groundwater recharge.

A potential risk with *Jatropha* plantations is reductions in runoff generation resulting in reduced downstream water availability. In this study, the total runoff amount was modeled to be 40% larger for the wasteland condition, but despite of this, base flows were higher when *Jatropha* was grown and runoff intensities were at the same time lower, which is generally positive, since it reduces the risks of flooding of cultivated areas. Higher base flow results in lower differences between high and low flows in rivers, which again is beneficial from a flood risk perspective. Most likely this is also positive for the riverine ecosystems, since rivers in this region are perennial and thus requires a certain amount of base flow to sustain key processes and functions.

Thus, under the conditions existing in the Velchal watershed the establishment of *Jatropha* plantations appear to be an attractive option. A larger share of the precipitation was channeled to productive transpiration and groundwater recharge, and a more stable (less erosive) runoff improved the downstream water conditions. On the other hand, maintaining a certain amount of total annual runoff is crucial for the Manjeera dam located downstream of the watershed **(Fig. 1)**, which is one of the drinking water supplies for the rapidly growing city of Hyderabad. If *Jatropha* plantations were implemented at a large scale upstream, resulting in higher consumptive water use, the concurrent reductions in runoff, in particular during dry seasons, might result in trade-offs between upstream and downstream water users, and potentially also impact riverine ecosystems.

Downstream water availability is likely to be least affected in good years or high and moderate rainfall zones but could be an important constraint in dry years or low rainfall zones of semi-arid tropics[9,38,69]. Again, this should be weighed against the positive effects of reduced sedimentation in the rivers and the dam due to the reduced soil loss from *Jatropha* plantations. In order to analyze effects of different upstream land-use alternatives on the various stakeholders in the sub-basin, an integrated assessment of various land-use and management options for the whole sub-basin area has to be made.

Soil loss and soil degradation might become an increasingly important factor to account for in the future[62,74]. It is apparent that soil loss from the fields at rainfall intensities above 30-50 mm day^{-1} is significant[21], in particular for wastelands. Due to climate change, high rainfall intensities are projected to become more common in different parts of India[46,49,83] and elsewhere in the World[7,10,84]. Soil loss from the fields can therefore be expected to increase[61,80,85]. Once land degradation has begun, the process may eventually become difficult to halt since the lack of vegetation causing high soil loss makes rehabilitation more difficult[41,48,73,82]. Hence, a vicious circle may become established, which is difficult to interrupt due to the negative feedback mechanisms between canopy coverage, runoff generation and soil loss. Other studies have shown that *Jatropha* has the potential to rehabilitate landscapes that have been badly degraded[3,51] and can also induce carbon sequestering in soils[32]. For Indian wastelands, an average annual carbon sequestration rate as 2.25 CO_2 tons ha^{-1} $year^{-1}$ has been reported for the case of *Jatropha*[20].

5.2 Contributions to improved livelihood conditions

There are several negative consequences of *Jatropha* has also been assessed at larger scale of implementation[24-26,57]. It is not found socially and economically viable to switch agricultural land into bio-fuel plantation[15,44]. Conversion of agricultural land to *Jatropha* is not found remunerative both in rainfed and irrigated lands in private farms at Tamil Nadu, India and its potential variability is strongly determined by water access. Unrealistic claims on yield predictions mainly in low input regions by various development agencies led to serious conflicts between the state and the farmers, between socio-economic classes and even within households[45].

The present study supports the view of above study that does not address to convert agricultural land into *Jatropha* land. However, wastelands or degraded lands where crop cultivation is not feasible, provides an opportunity to cultivate *Jatropha* through collective community participation. In current case study, *Jatropha* cropping has provided the local community in the Velchal watershed with an additional source of income, which strengthens the resilience of the village by enabling farmers to operate on different markets (food and energy). Currently the income from the biofuel plantation is small in relation to total household budgets. Harvested *Jatropha* seeds generate an income of approximately 100 US$ ha^{-1} $year^{-1}$ (considering seed yield between 0.5 and 1.0 tons ha^{-1} after the fourth year and onwards[65,78] and *Jatropha* seed cost as 0.22US$ kg^{-1} (10 INR kg^{-1})[45,78], which can be compared with incomes from agricultural crops grown in the area at around 400-500 US$ ha^{-1} $year^{-1}$ (assuming a cropping intensity of 150 % and average crop yields at 1-2 tons ha^{-1} in arid and semi-arid tropics under rainfed conditions[55,64,79]). However, the economic returns from the biofuel plantations will be higher if the biofuel prices increase in the future. Moreover, the present seed yields are less than half of the potential yields, which are estimated to be about 2.5 tons ha^{-1} under rainfed conditions[78]. This indicates substantial scope for further yield improvements through better management practices such as nutrient application coupled with improved soil and water conservation, and subsequently higher economic returns.

The beneficiaries of the *Jatropha* plantations on former wastelands in the Velchal watershed are mainly landless labourers and marginal farmers. There are plans to put an oil expeller unit for oil extraction and a power-generator unit for electricity production in the Velchal village[65]. The electricity generated from this setup is intended to be sold for commercial purposes in the village itself, thus providing an additional income. Moreover, this program has also helped to generate other employment opportunities to some of the women groups by starting plant nurseries and supplying quality seedlings[78]. At the same time the former land-use practice, *i.e.* grazing, has continued as before in the *Jatropha* plantation, but the risk for further degradation is now gone. This means that nobody in the village lost their customary right due to the *Jatropha* plantations. Grazing in *Jatropha* plantations may raises concerns about the potential intoxication of livestock. Toxicity in *Jatropha* is due to presence of toxalbumin of nomecurcin (toxin protein) which irritates to the gastrointestine mucosa and also hemoagglutinating and cause nausea, vomiting, intense abdominal pain and diarrhea with bloody stool[54], however such incidence in study village has not been reported till date. An additional benefit to the community is higher groundwater tables, which improves access to water for domestic and agricultural use. Achten *et al*.[1] thoroughly discussed the benefits of *Jatropha* cultivation in wastelands at local scale. After oil extraction seed cake, however, could not be used for animal feed due to its toxic content but it could potentially be used as fertilizer that also serves as biopesticides/insecticide and molluscicide simultaneously[56]. Moreover seed cake could be used for biogas production through anaerobic digestion before using it as a soil amendment[67].

5.3 Model and data uncertainties

The approach to combine the two modeling tools ArcSWAT and HYDRUS1D causes a risk for small discrepancies in the estimations of the division between deep percolation and evapotranspiration. Ideally, both soil evaporation and transpiration should be calculated explicitly in ArcSWAT, but this was not possible in the current model version. The parameterization of the different land management scenarios for Velchal was based on analyses from Kothapally, which is located at a nearby watershed in the Osman Sagar catchment area as shown in **Fig 1**[21]. This may lead to some uncertainty in results and additional validation to support the model parameterization may further improve the confidence of the modeling results. Even so, the data quality and overall model performance is judged to be satisfactory for the purposes of this study, and for supporting the conclusions made.

6. Conclusion

Overall, changes arising from the conversion of wastelands into *Jatropha* plantations were desirable from an ecosystem's perspective at the watershed scale. Non-productive soil evaporation was shifted to productive transpiration, groundwater recharge improved and soil loss from the fields was reduced. Moreover, it was found that the soil carbon content increased in the *Jatropha* plantations over time creating a win-win situation between land productivity and climate change mitigation.

The results from this study indicate that at the sub-basin scale, reductions in runoff generation as a result of converting wastelands to *Jatropha* plantations may pose problems for downstream ecosystems and water users if implemented on a large area; however base flow actually improved with *Jatropha* cropping while storm flows and sedimentation loads were lower. The net impact of these changes depends on the characteristics of downstream water users and ecosystems.

At the community level, *Jatropha* production was generally positive from a livelihoods perspective. The previous land-use, in this case grazing, could continue in the *Jatropha* plantations, which provided a new source of income, thus strengthening the resilience of the farmers. In the future, the potential gain from *Jatropha* cropping may become a lot higher compared with today, as plantation yields increase and demand for petroleum substitutes such as *Jatropha* biodiesel grows.

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Table 1a. ArcSWAT parameterization.

Variable (unit)	*Parameter name*	*Parameter Value*	*Source*
Sand content (%)	SAND	43 (35-50)*	Measured
Silt content (%)	SILT	17 (15-19)	Measured
Clay content (%)	CLAY	40 (34-47)	Measured
Gravel fraction (%)	ROCK	64 (49-90)	Measured
Bulk Density (g cm^{-3})	SOL_BD	1.55 (1.4-1.7)	Measured
Available Water Content (mm H_2O/mm soil)	SOL_AWC	0.07 (0.03-0.10)	Measured
Organic carbon (%)	SOL_CBN	0.91 (0.6-1.2)	Measured
Soil Depth (mm)	SOL_Z	350 (120-500)	Surveyed
Saturated Hydraulic conductivity (mm/hr)	SOL_K	1.7-5.9	Estimated by Pedo-transfer func.[59]
Curve number (-)	CN	86	Calibrated
Hydraulic conductivity of the reservoir bottom (mm/hr)	RES_K	8.0	Measured
Groundwater revap coeff(-)	GW_REVAP	0.1	From Garg *et al.*[21]
Threshold depth of water for revap in shallow aquifer (mm H_2O)	REVAP_MN	10	Calibrated
Threshold depth of water in the shallow aquifer required to return flow (mm H_2O)	GWQMN	20	Calibrated
Groundwater delay time (days)	GW_DELAY	2	From Garg *et al.*[21]
Channel erodibility factor(-)	CH_EROD	0.5	From Garg *et al.*[21]
Channel cover factor (-)	CH_COV	0.5	From Garg *et al.*[21]
USLE eq. support practice factor (-)	USLE_P	0.5	From Garg *et al.*[21]
Peak rate adjust factor for sediment routing in the sub basin (-)	ADJ_PKR	0.5	From Garg *et al.*[21]
Linear parameters for cal. of max. amount of sediment to be re-entrained during channel sediment routing	SPCON	0.005	From Garg *et al.*[21]
Normal fraction of Nitrogen in (seed) yield (kg N/kg yield)	CNYLD	0.022	Measured at BL3 ICRISAT site[78]
Normal fraction of Phosphorus in (seed) yield (kg P/kg yield)	CPYLD	0.0048	Measured at BL3 ICRISAT site[78]
Normal fraction of Nitrogen in plant biomass at maturity (Kg N/Kg yield)	PLTNFR	0.013	Measured at BL3 ICRISAT site[78]
Normal fraction of Phosphorus in plant biomass at maturity (Kg P/Kg yield)	PLTPFR	0.0015	Measured at BL3 ICRISAT site[78]

Variable (unit)	*Parameter name*	*Parameter Value*	*Source*
Fraction of tree biomass accumulated each year that is converted to residue during dormancy (-)	BIO_LEAF	0.70	Measured at BL3 ICRISAT site[78]
Number of years required for tree species to full development (Years)	MAT_YRS	4	Achten *et al.*[3]; Bailis and McCarthy[6]
Maximum biomass for a forest (tons ha^{-1})	BMX_TREES	10	Achten *et al.*[3]; Bailis and McCarthy[6]

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

Table 1b HYDRUS1D parameterization.

Soil Physical Properties of Velchal watershed				
Variable (unit)	*Parameter name*	*Parameter Value, Velchal*	*Parameter Value, ICRISAT, BL3*	*Source*
Sand content (%)	SAND	43	45.1	Measured
Silt content (%)	SILT	17	16.0	Measured
Clay content (%)	CLAY	40	39.1	Measured
Bulk Density (g cm^{-3})	BD	1.55	1.4	Measured
Moisture at Field capacity (cm^3 cm^{-3})	TH33	0.22	0.34	Measured
Moisture at permanent wilting point (cm^3 cm^{-3})	TH1500	0.16	0.21	Measured
Depth of soil profile (mm)	SOL_Z	350	2500	Surveyed

Root Water Uptake parameters, estimated from ICRISAT, BL3 watershed			
Variable (unit)	*Parameter name*	*Parameters Value*	*Source*
Value of the pressure head below which roots start to extract water from the soil (cm)	P0	-10	Default
Value of the pressure head (cm) below which roots extract water at the max possible rate.	POpt	-25	Default
Value of the limiting pressure head (cm), below which roots cannot longer extract water at the max rate	P2H	-800	Calibrated
As above, but for a potential transpiration rate of *r2L*. (cm)	P2L	-1500	Calibrated
Value of the pressure head (cm), below which root water uptake ceases (usually wilting point).	P3	-16000	Calibrated

Table 1c: SWAT parameters modified from current setup to represent improved organic condition

Variable (unit)	*Parameter in ArcSWAT*	*Parameter Value: current Jatropha scenario*	*Parameters Value: long-term Jatropha scenario*
Available Water Content (mm H_2O/mm soil)	SOL_AWC	0.07 (0.03-0.10)	0.08 (0.03-0.13)
Organic carbon (%)	SOL_CBN	0.91 (0.6-1.2)	1.1 (0.75-1.5)
Curve number (-)	CN	86	80
Groundwater revap coeff(-)	GW_REVAP	0.1	0.15
Threshold depth of water for revap in shallow aquifer (mm H_2O)	REVAP_MN	10	2
Threshold depth of water in the shallow aquifer required to return flow (mm H_2O)	GWQMN	20	120
Channel erodibility factor(-)	CH_EROD	0.5	0.4
Channel cover factor (-)	CH_COV	0.5	0.6
USLE equation support practice factor (-)	USLE_P	0.5	0.6

Table 2: Comparison of different hydrological components and crop yields between the ICRISAT BL3 watershed, and the Velchal watershed ("current *Jatropha*" scenario).

Variable (unit)	*Dry Year (Year 2007)*		*Wet Year (Year 2008)*	
	ICRISAT watershed, BL3	*Velchal watershed*	*ICRISAT watershed, BL3*	*Velchal watershed*
Inputs				
Available water ($cm^3\ cm^{-3}$) (soil moisture at FC-PWP)	0.13	0.07	0.13	0.07
Soil depth (cm)	300	35	300	35
Annual average rainfall (mm)	707	707	1105	1105
Outputs				
Evaporation (mm)	251 (36%)	188 (27%)	265 (24%)	180 (16%)
Transpiration (mm)	400 (57%)	263 (37%)	606 (55%)	262 (24%)
Outflow (mm)	ND	162 (23%)	ND	550 (50%)
GW recharge/ Deep percolation (mm)	ND	95 (13%)	ND	111 (10%)
Jatropha seed yield (tons ha^{-1})	0.9	0.5	1.1	0.5

FC = field capacity; PWP = permanent wilting point; ND = not determined

Table 3: Growth parameters of *Jatropha* crop and nutrient content in fallen leafs and *Jatropha* seeds measured from the experimental sites (Data collected in year 2008, Sreedevi *et al.*[65]; Wani *et al.*[78])

Variable (unit)	*ICRISAT BL3 watershed*	*Velchal watershed*
Jatropha Tree age (years)	3	2
Plant spacing	3 m x 2 m	2 m x 2 m
Plant Height (cm)	120 (64-196)*	86 (50-114)
Branches per Plant (-)	8 (1-38)	5 (2-7)
Stem girth at 10 cm height (cm)	21 (6-44)	15.6 (9.2-20.3)
Crown Area (m^2)	0.9 (0.5-4.1)	-
No. of flowering branches (-)	3 (1-7)	-
No of inflorences per plant (-)	3 (1-8)	-
Female-male flower ratio (-)	(4-17)	-
No. of Female flowers (-)	(2-45)	-
Pod bunches per plant	(1-7)	-
No of pods per plant	(3-90)	-
Seed yield per plant (g)	(28-280)	-
100 seed weight (g)	(44-72)	-
Total seed yield (tons ha^{-1})	(0.2 -0.5)	0.1
Total oil content (%)	34 (27-38)	-
Nitrogen content in Seed (g kg^{-1})	22.2	-
Phosphors content in Seed (g kg^{-1})	4.8	-
Potassium content in Seed (g kg^{-1})	8.1	-
Sulphur content in Seed (g kg^{-1})	1.4	-
Boron content in Seed (g kg^{-1})	0.015	-
Zinc content in Seed (g kg^{-1})	0.017	-
N content in fallen Leaves (g kg^{-1})	9.5	-
P content in fallen Leaves (g kg^{-1})	0.7	-
K content in fallen Leaves (g kg^{-1})	10	-
S content in fallen Leaves (g kg^{-1})	0.94	-
B content in fallen Leaves (g kg^{-1})	0.034	-
Zn content in fallen Leaves (g kg^{-1})	0.024	-
Seed Yield measured from the fourth year onwards (tons ha^{-1})	1.0-2.7	0.3-0.8

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

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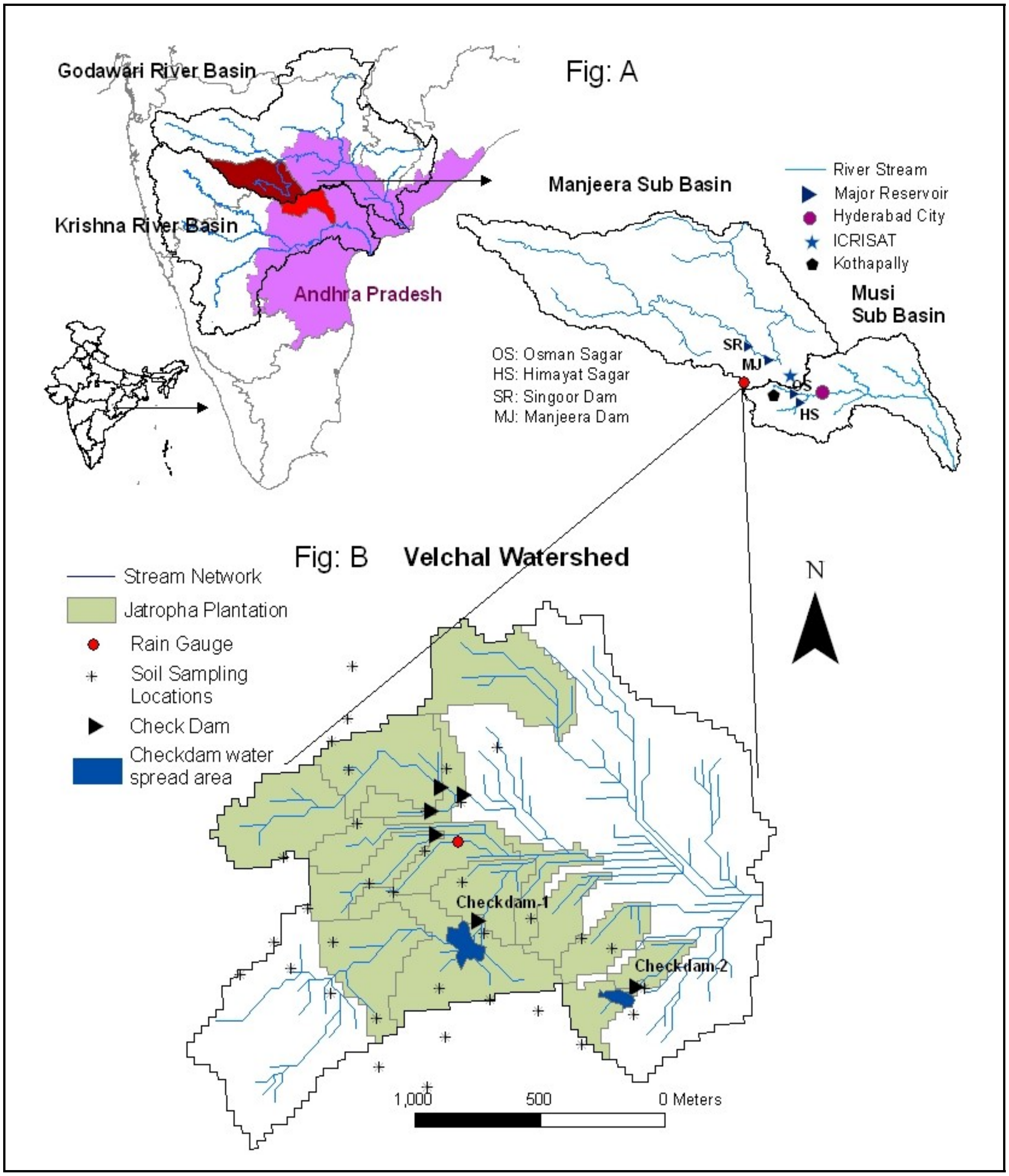


Fig. 1: Location of Study area

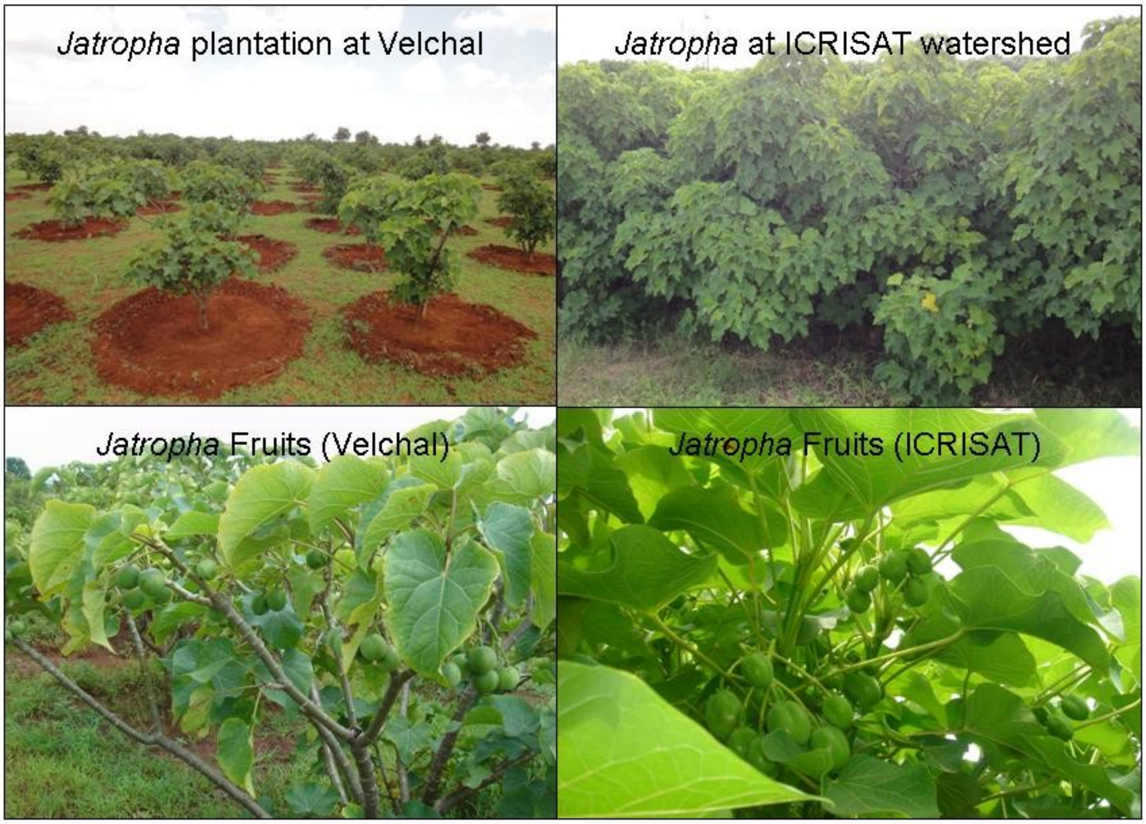


Fig. 2: Picture showing *Jatropha* crop and its fruiting stage at Velchal and ICRISAT watershed during year 2010.

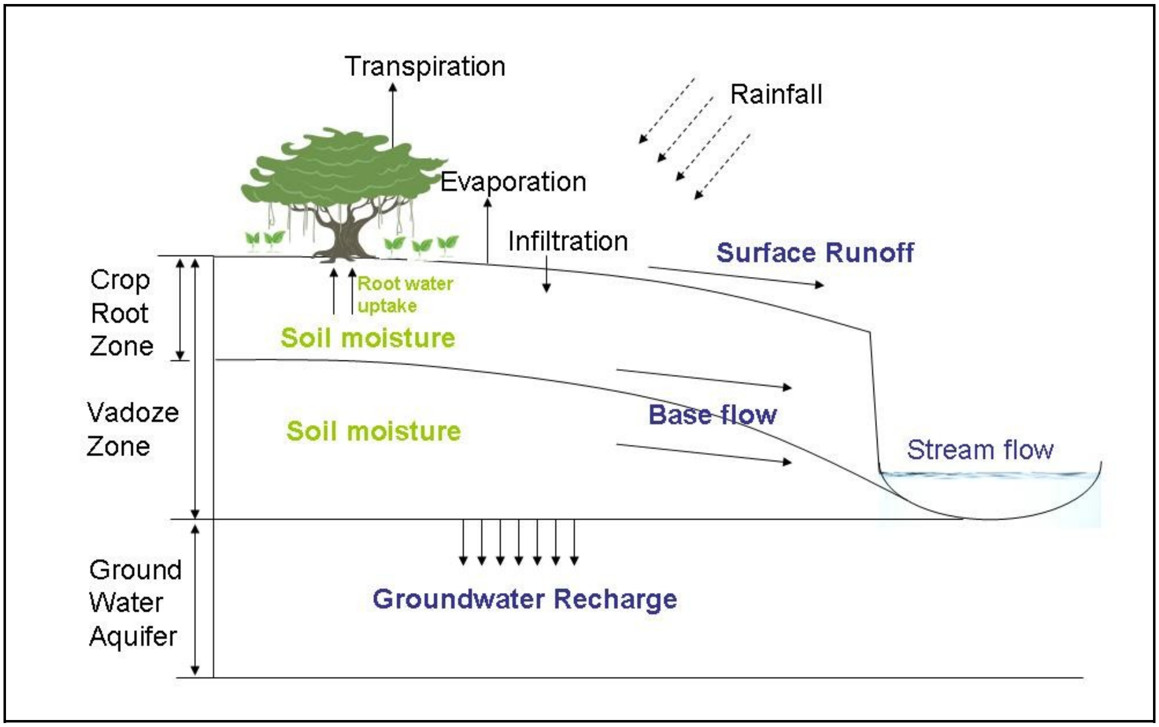
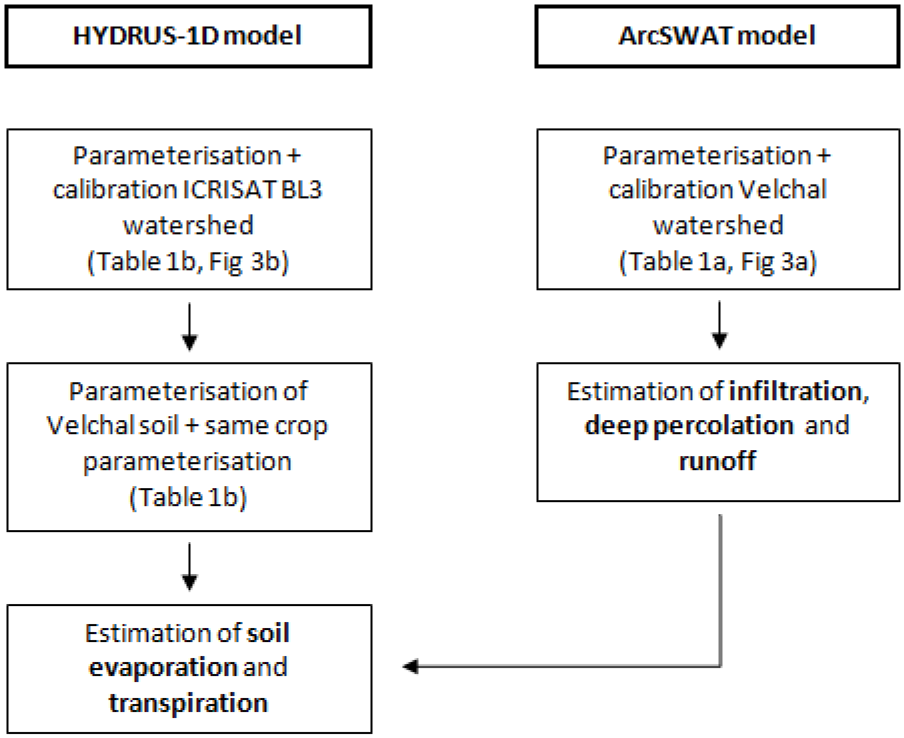


Fig. 3: Conceptual representation of hydrological cycle and different hydrological components at watershed scale.



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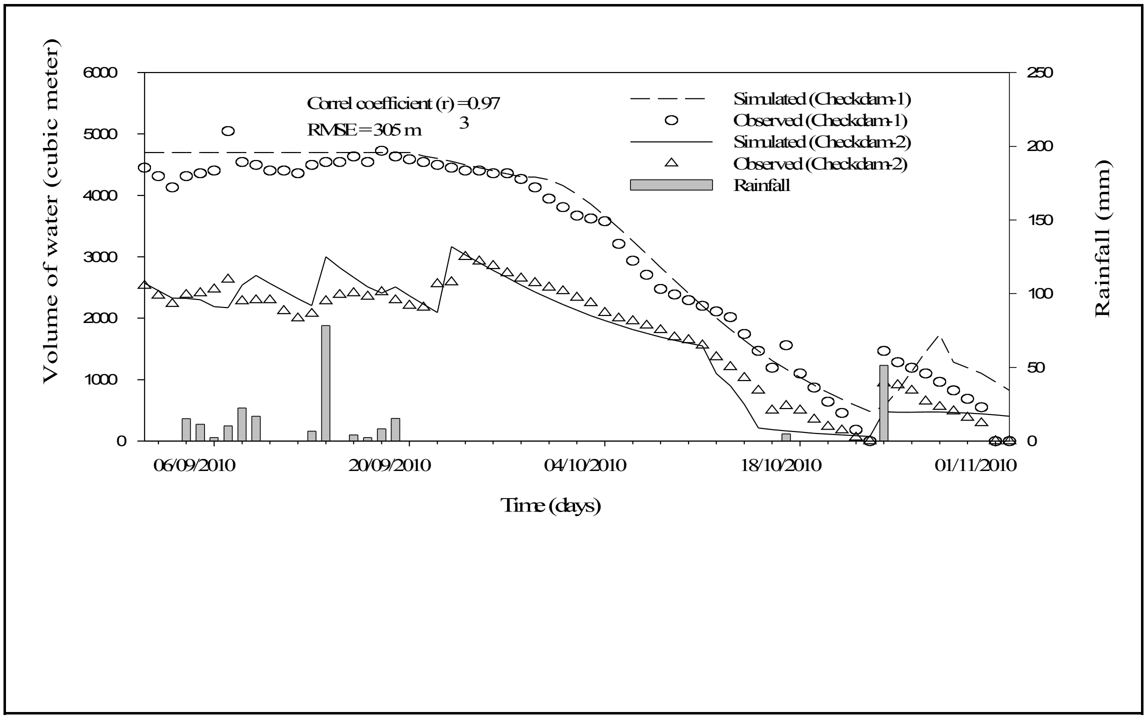


Fig. 5a: Observed and simulated water volume in check-dams between period Sept and Nov 2010.

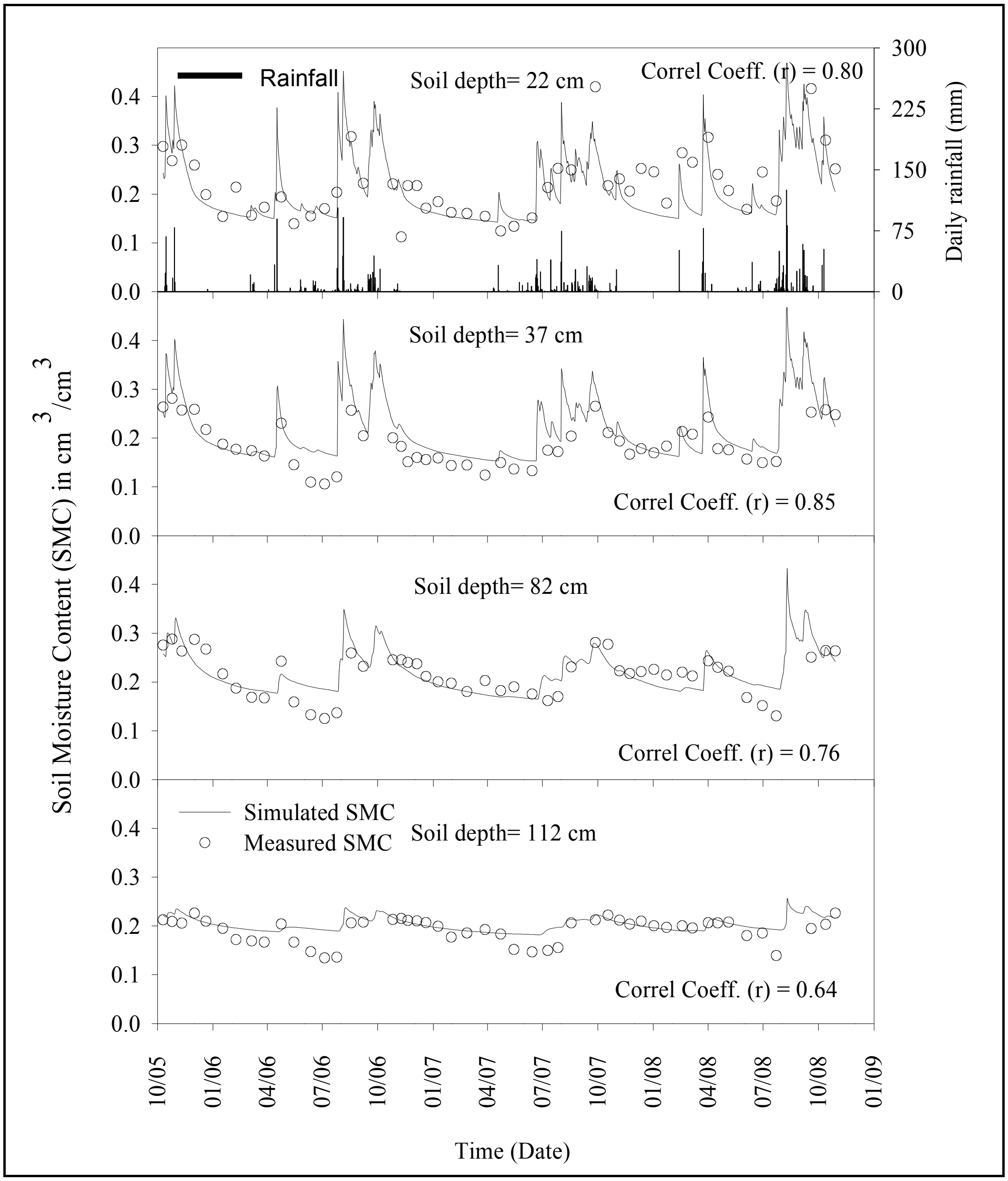


Fig. 5b: Observed and simulated soil moisture content at different soil depth in *Jatropha* planted area of ICRISAT BL3 watershed from period Oct 2005 to Oct 2009

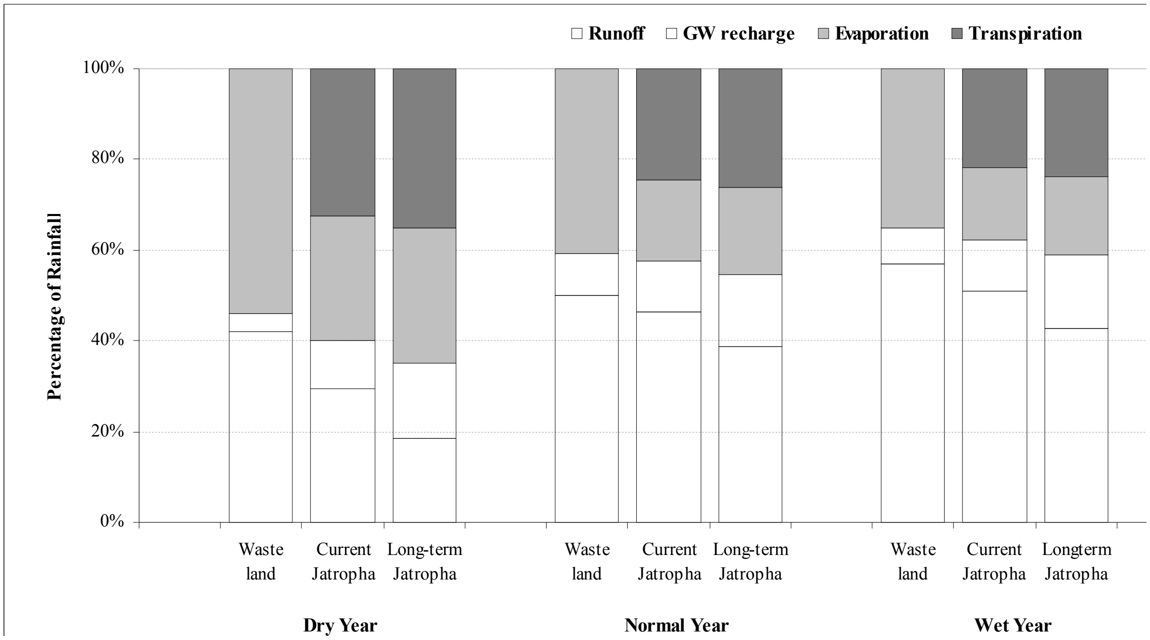


Fig. 6a: Water balance components of different land management scenarios during dry, normal and wet (data from 2001 to 2010).

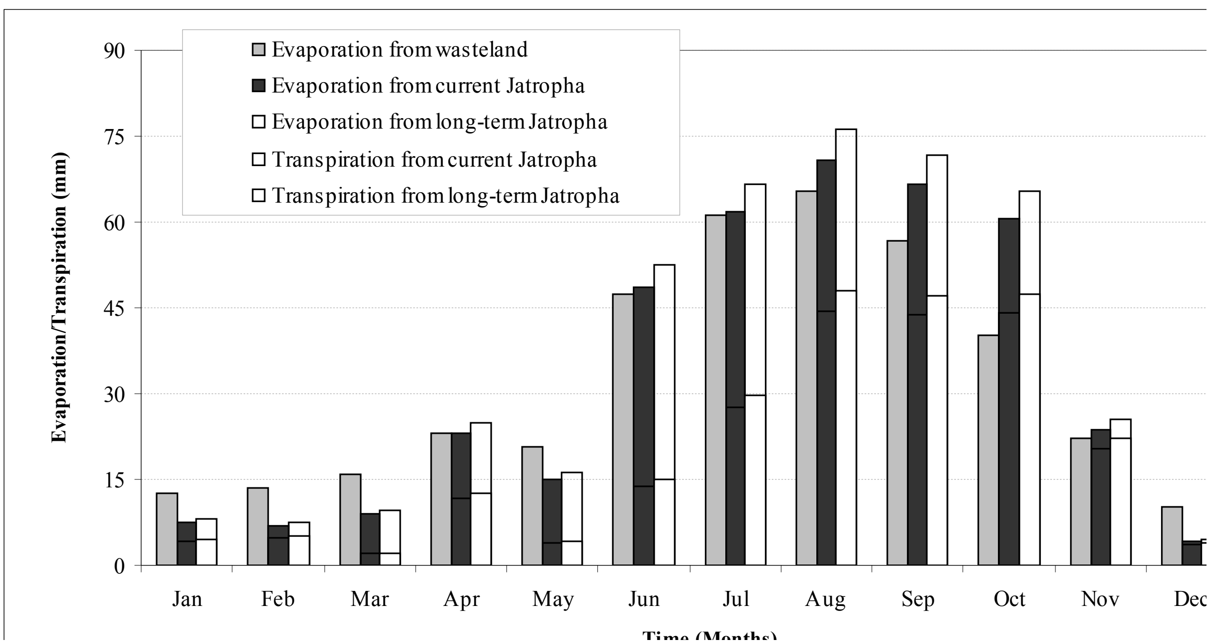


Fig. 6b: Monthly soil evaporation and transpiration for three different land management scenarios in Velchal watershed.

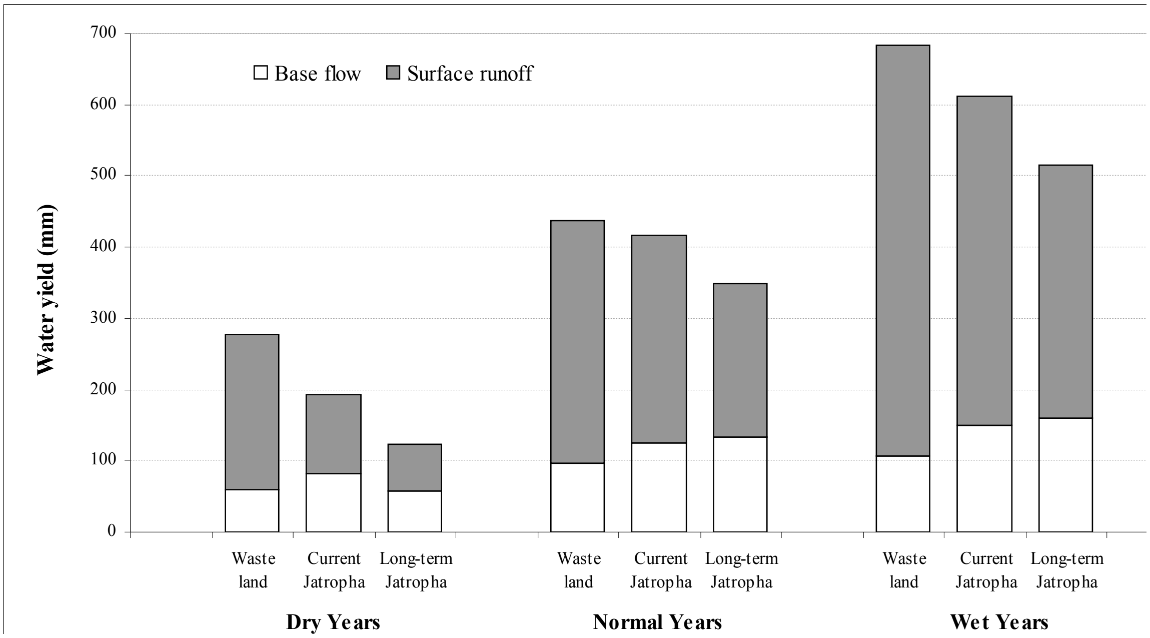
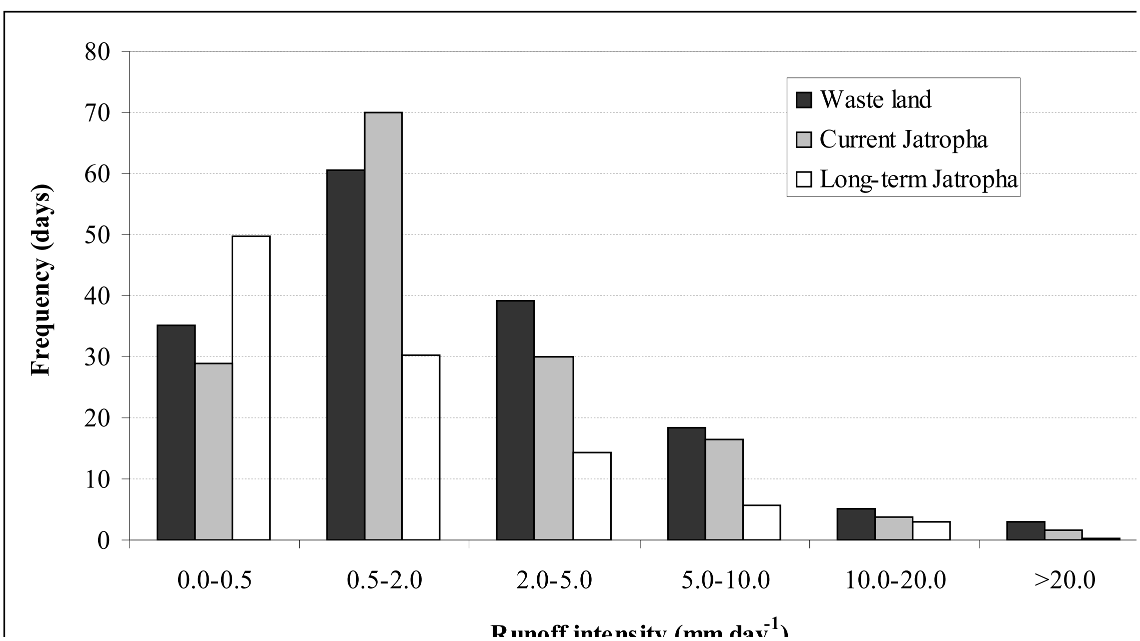


Fig. 6c: Total runoff generation from the watershed, divided up into base flow and surface runoff, for three different land management scenarios during dry, normal and wet years (data from 2001 to 2010).



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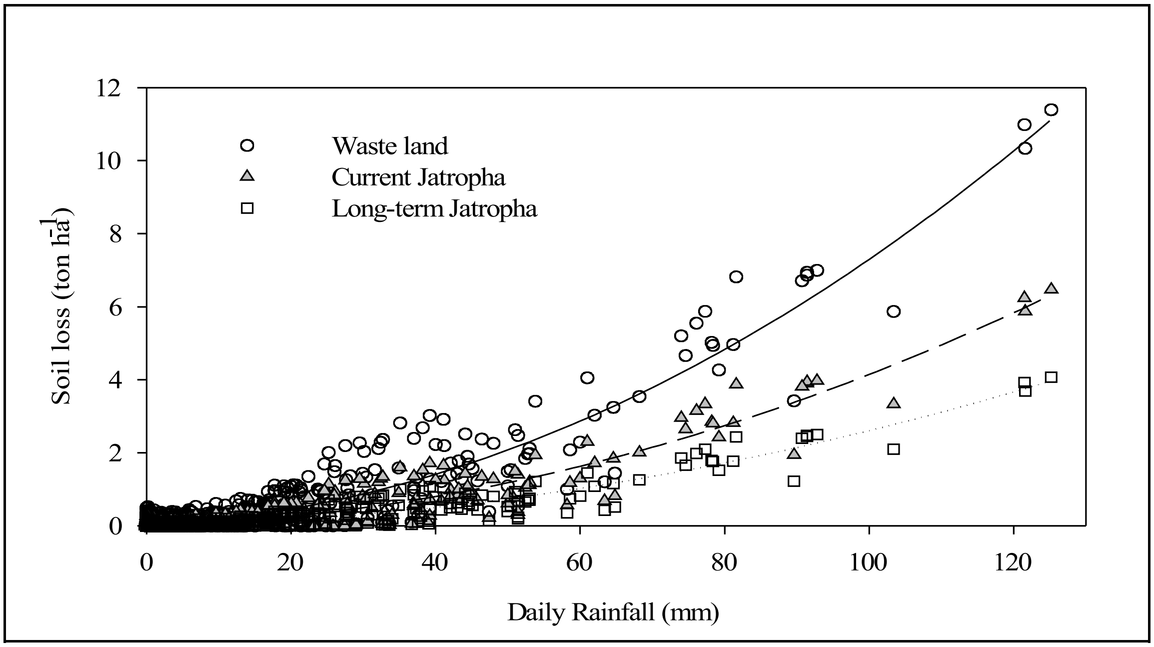
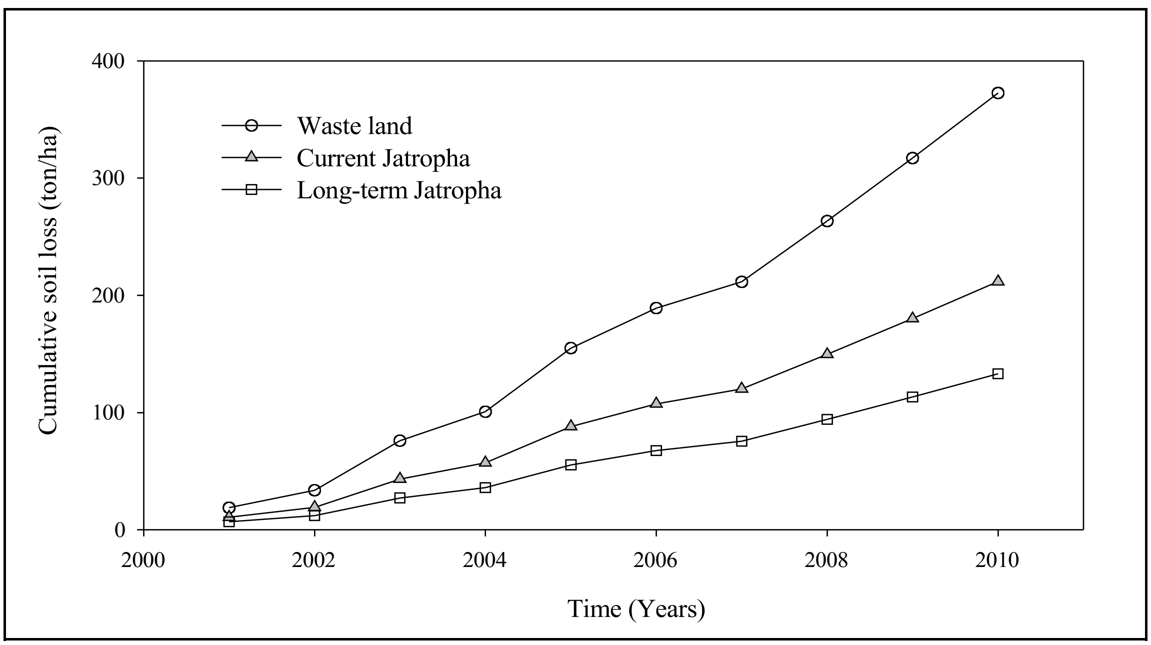


Fig. 7a Impact of land management practices on sediment transport under different land management conditions (data from year 2001 to 2010).



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