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Efficacy of raised bed with furrow system in controlling runoff and soil loss in Alfisols

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ABSTRACT

Arid and semi-arid regions experience prolonged dry spells during the crop season, resulting in severe reduction of crop productivity. In-situ moisture conservation could be a viable solution to withstand the intermittent dry spells of short duration ranging from 7-10 days during crop season. Adoption of in-situ moisture conservation interventions like raised bed and furrow, BBF, mulching, conservation furrows etc. conserves moisture in the soil, controls runoff and reduces soil erosion. In this study, the effectiveness of in-situ moisture conservation using raised bed and furrow system in controlling runoff and soil loss was evaluated for the period 1951 to 2023 and 2050s using SCS-CN method and RUSLE. It was found that raised bed treatment has reduced the runoff to 7.14% of seasonal rainfall compared to 9.71% in the control in a normal year (2022). Similarly, the runoff was 2.89% of seasonal rainfall in drought year compared to 4.35% in the control (2023). Raised bed with furrow system has reduced the soil loss to 2.94 t $ha^{-1}y^{-1}$ compared to 4.97 t $ha^{-1}y^{-1}$ in control during normal year (2022) and 0.97 t $ha^{-1}y^{-1}$ compared to 1.62 t $ha^{-1}y^{-1}$ in control during drought year (2023). The mean seasonal runoff during 1951-2021 from raised bed treatment was 6.79% and 8.85% of mean seasonal rainfall in control whereas the mean seasonal soil loss was 2.23 t $ha^{-1}y^{-1}$ in raised bed and furrow system compared to 3.72 t $ha^{-1}y^{-1}$ in control. The expected rainfall in the study area by the 2050s is more than the mean seasonal rainfall, and hence, there is more scope for rainwater harvesting in the near future. The mean seasonal runoff expected by the 2050s (under RCP 4.5) in control is 9.9% whereas with interventions it can be reduced to 6.0% of seasonal rainfall. Similarly, the expected mean seasonal soil loss from control is 4.4 t $ha^{-1}y^{-1}$ which can be reduced to 2.20 t $ha^{-1}y^{-1}$ with interventions. Similar trend was observed in case of mean annual runoff and mean annual soil loss. Based on the long-term data analysis, it was found that in semi-arid regions, in-situ moisture conservation plays a pivotal role in controlling runoff and soil loss and needs to be adopted as a compulsory component while sowing the field crops or planting tree crops.

Keywords: *Alfisols, climate change, curve number, raised bed and furrow system, runoff, RUSLE, soil loss.*

Introduction

In low-input rainfed systems, especially in lower-income countries, the changing temperatures and rainfall patterns, combined with poor soil and water management, results in soil erosion and reduces soil organic matter content, limits crop production capacity, affects farmers' incomes, food and nutritional security [1]. Climate change is predicted to increase the average surface temperature, dry spells, decrease the number of rainy days, and increase the high-intensity rains in many parts of the world, including drylands [2,3]. In semi-arid regions of India, the mean annual rainfall ranges between 400 to 1000 mm, and is unevenly distributed, highly uncertain, and erratic [4]. As a result of low and erratic rainfall, prolonged dry spells are very common in drylands, causing a reduction in crop yield or even crop failure, which in turn affects farmers' income [5]. The impact of climate change is more in semi-arid regions and these regions are subjected to medium to high soil erosion which carries away the fertile top soil and further reduces the crop productivity [6]. It is estimated that nearly 75 billion tons of soil is lost annually @ 13 to 40 t ha^{-1} y^{-1} from agricultural lands across the globe, with erosion rates @ 13-40 times faster than the rate of natural soil formation in many regions [7]. In India, the annual average rate of soil erosion is 16.0 t $ha^{-1}y^{-1}$ [8]. Indian agriculture is highly vulnerable to climate change since 60% of agricultural land is rainfed and 80% of farmers are small to marginal holders and are highly susceptible to climate change and soil erosion [9].

The prolonged dry spells exceeding 7-10 days during the crop growing season can result in yield loss or even crop failure [10]. Many studies reported yield loss ranging from 30-50% in drylands due to water stress, highlighting the need for adoption of water conservation strategies [11]. In recent years, various in-situ moisture conservation practices, including raised bed planting systems, conservation tillage, and micro-catchment techniques, etc., have been promoted for controlling soil erosion and enhancing crop productivity [12]. Studies from diverse agroecological zones reported that raised bed systems enhanced water use efficiency, reduced soil erosion, and improved crop yields by 15-20% over conventional flat bed planting [13,14]. In developing countries like India, the availability of gauging stations to record runoff and soil erosion

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data is very limited. Hence, runoff and soil loss are quantitatively estimated using hydrological and other erosion estimation models. The most widely used methods are the Soil Conservation Service Curve Number (SCS-CN) method for runoff estimation and the Revised Universal. Soil Loss Equation (RUSLE) for soil erosion estimation [15,16]. Long-term rainfall data analysis, along with future climate data sets (RCPs) can help in the evaluation of conservation practices and provide valuable insights for planning interventions [17].

Despite the performance of in-situ moisture conservation, there is a critical knowledge gap with respect to the long-term performance of these conservation practices, like raised bed systems, in controlling runoff and soil erosion under both existing scenarios as well as future scenarios. Furthermore, there is limited data on the effectiveness of these interventions during normal and drought years, which is essential for designing location-specific water harvesting interventions and supplementary irrigation systems in the semi-arid regions. Hence, this study was attempted to evaluate the performance of raised bed and furrow (RB&F) systems in reducing runoff and soil loss over a 70-year historical period (1951-2021) as well as under future climate scenarios (2050s). The findings of this study will provide evidence-based insights for promoting climate-resilient agricultural practices in semi-arid regions for policy decisions regarding rainwater harvesting and soil conservation strategies.

Methodology

Rainfall analysis

Daily rainfall and temperature data collected from the experimental station were used for the period 2022-2023, and India Meteorological Department (IMD) data was used for the long term data analysis for the period 1951-2021. For future scenarios, ENSEMBLE data of CMIP 5 (Source: ICAR HQ) of RCPs 2.6, 4.5, 6.0 and 8.5 pertaining to 2050's was used for the analysis. The annual runoffs occurring in an area during normal and drought years are essential for planning the soil and water conservation interventions and water harvesting structures. Hence, the annual rainfall during 1951-2023 was categorized into normal and drought years based on IMD criteria. The years with mean annual rainfall >-19% deviation was classified as normal year, and <−19% as drought year [18].

Effective rainfall

The effective rainfall (R_e) was estimated from 10 day rainfall using empirical *Eqns (1&2)* developed at ICAR-CRIDA [19].

$$R_e = P(41.7 - 0.2P)/41.7 \quad for\ P \leq 83 \qquad (1)$$

$$R_e = 41.7 + 0.1P \quad for\ P > 83 \qquad (2)$$

where R_e= 10 days effective rainfall (mm) and P = 10 days rainfall (mm)

In this study, effective rainfall was determined for 1951 to 2023 and 2050s to analyse its variability over the years.

Environmental implications

Conserving rainfall through raised bed and furrow system (RB&F) has positive environmental implications, such as controlling soil erosion, reducing runoff, preserves the valuable topsoil, enhances the soil moisture content and nutrient status of the soil which in turn prevents soil degradation and maintains soil fertility thereby contributing to long-term agricultural sustainability.

Therefore, runoff and soil loss are estimated from data recorded using tipping bucket and its accessories for the period 2022 and 2023 for treatments with and without raised bed and furrow system and was validated. From the recorded values of the runoff during the experiment, curve number (CN) values were derived for both cases and was used for estimating runoff for the period 1951 to 2021 and 2050s using Soil conservation service-curve number (SCS-CN) method [18].

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \text{for P > 0.2 S} \qquad (3)$$

$$Q = 0 \text{ for P} \leq 0.2\text{ S} \qquad (4)$$

where P = total precipitation (mm); Q = surface runoff (mm); and S = potential maximum retention or infiltration (mm). The value of S is given as

$$S = \frac{25400}{CN} - 254 \quad (5)$$

The potential maximum retention storage (S) is related to a curve number (CN), which is a function of land use, land treatments, soil type, and antecedent moisture condition of the area. Curve number varies from 0 to 100 and can be obtained from a standard table; however, CN is estimated in this study based on runoff data recorded from raised bed and control plots. Based on soil characteristics, the soil comes under hydrologic soil group C (moderately high runoff potential). The three levels of antecedent moisture condition (AMC) used were AMC I, AMC II, and AMC III [20]. Hence, the curve number values corresponding to three AMC conditions, namely, CN_1, $CN_2$and $CN_3$was used.

Similarly, conservation practice factor (C) was derived from the soil loss values recorded during the experimental period. By utilizing the derived C factor, soil loss pertaining to both the cases was estimated for the 70-year period and 2050s using the Revised Universal Soil Loss Equation (RUSLE) as given below:

$$A = R\,K\,L\,S\,C\,P \qquad (6)$$

where A= average annual soil loss (t ha^{-1} y^{-1}); *R* is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} y^{-1}) *(Eqn.2)*; *K* is the soil erodability factor (t ha h ha^{-1} MJ^{-1} mm^{-1}); *LS* is the slope length - steepness factor (dimensionless); *C* is the cover management factor (dimensionless); and *P* is the conservation practices factor (dimensionless).

The erosivity (R) factor was estimated using the equations utilizing daily rainfall values developed at ICAR-CRIDA [21].

$$R = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} EI_{30}}{n} x1000/200.6 \qquad (7)$$

where R= average annual erosion index (MJ mm ha^{-1} h^{-1} y^{-1}); i= number of years; j= number of days per year, i; EI_{30} = rainfall erosivity at 30 minutes per day (hundreds t cm ha^{-1} h^{-1})

$$EI_{30} = 34.065\,EI_{1440} - 0.2695 \ (R^2=0.83) \qquad (8)$$

where, EI_{1440} = erosion index per day (hundreds t cm $ha^{-1}h^{-1}$)

$$EI_{1440} = 3.856\,PI_{1440} - 0.0048 \ (R^2= 0.89) \qquad (9)$$

where, PI_{1440} = daily precipitation index, cm^2h^{-1}

$$PI_{1440} = (\text{Rainfall})^2/24 \qquad (10)$$

where rainfall is in cm.

The daily R value obtained was then converted to monthly and annual values and the mean annual erosivity was determined. In addition to this, the performance of treatments with and without raised bed and furrow system was evaluated in normal and drought years, and also assessed the effectiveness of RB&F systems under projected future rainfall scenarios. In this study, both the raised bed and control plots are of the same size and have the same slope. Hence, LS is same for both treatments.

Similarly, R, K, and C factors are also the same for both treatments. K value depends on soil properties and in this study, the value of K factor for the selected area was 0.02, LS was 0.2 and C was 0.4.Therefore, P is the only factor varying in raised bed and control treatments and is derived in this study. Using these parameters, runoff and soil loss was estimated seasonally and annually.

Results and Discussion

Variability in rainfall and temperature

The rainfall analysis at Hayathnagar Research Farm was carried out for the period 1951 to 2023 and 2050s to study the trends in rainfall pattern like dry spells, normal years and drought years. The mean seasonal rainfall during 1951-2020 was 693.4 mm, the effective rainfall (seasonal) was 427.8 mm Similarly, during the normal year 2021 and 2022, the seasonal effective rainfall was 530.6 and 558.8 mm respectively.

Table 1: Seasonal rainfall, effective rainfall, under current scenario, past and 2050s

Year	Rainfall -crop season (mm)	Effective rainfall - crop season (mm)	T max	T min
1951-2020 (mean)	693.4	427.8	31.3	20.9
2021 (normal year)	1001.7	530.6	30.9	21.3
2022 (normal year)	936.6	555.8	31.0	21.0
2023 (drought year)	442.6	300.1	31.9	21.0
Baseline	635.5	454.5	31.4	21.0
2050s-RCP 2.6	791.0	467.0	32.4	22.7
2050s-RCP 4.5	797.5	469.8	32.7	23.1
2050s-RCP 6.0	772.0	461.0	33.2	23.2
2050s-RCP 8.5	817.2	476.2	33.2	23.8

However, during the drought year, 2023, the seasonal rainfall was 442.6 mm, and the effective rainfall was only 300.1 mm. Under changing climatic scenarios, an increase in rainfall, maximum and minimum temperature is predicted by 2050s under RCP 2.6, 4.5, 6.0 and 8.5. Similarly, under all RCPs, an increase in rainfall and effective rainfall is predicted.

Effect of RB & F on runoff and soil loss

Using the derived CN values, runoff was estimated for the period 1951 to 2021 and 2050s using SCS-CN method and by utilizing the derived P factor, soil loss pertaining to different treatments was also estimated for the 71-year period as well as 2050s using the RUSLE for analyzing long term variation in soil loss. It was found that raised bed treatment has reduced the seasonal runoff to 7.14% of seasonal rainfall compared to 9.71% in control during normal year (2022). Similarly, the seasonal runoff was 2.89% of seasonal rainfall in drought year compared to 4.35% in the control (2023). Raised bed with furrow system has reduced the seasonal soil loss to 2.94 $tha^{-1}y^{-1}$ compared to 4.97 $tha^{-1}y^{-1}$ in control during normal year (2022) and 0.97 $tha^{-1}y^{-1}$ compared to 1.62 $tha^{-1}y^{-1}$ in control during drought year (2023). The mean seasonal runoff during 1951-2021 from raised bed treatment was 6.79% of mean seasonal rainfall and 8.85% of mean seasonal rainfall in the control. The mean seasonal soil loss during 1951-2021 was estimated as 2.23 in RB&F treatment and 3.72 t $ha^{-1}y^{-1}$ in control. The expected rainfall in the study area by 2050s is more than the mean seasonal rainfall and hence, there is more scope for rainwater harvesting in near future. The seasonal runoff expected by 2050s (under RCP 4.5) in control is 9.9% whereas with interventions it can be reduced to 6.0% of seasonal rainfall. Similarly, the expected seasonal soil loss from control is 4.4 $tha^{-1}y^{-1}$ which can be reduced to 2.20 $tha^{-1}y^{-1}$ with interventions (Figure 1a & b).

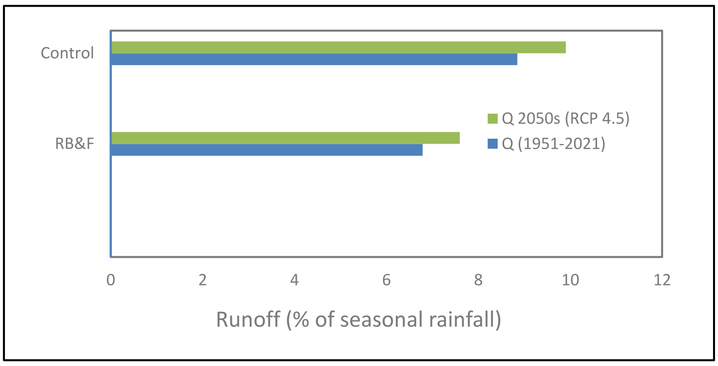

Figure 1a: Effect of RB&F on mean seasonal runoff during 1951-2021 and 2050s

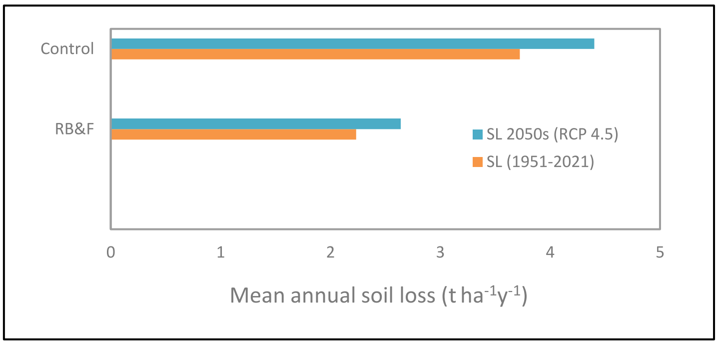

Figure 1b: Effect of RB&F on mean seasonal soil loss during 1951-2021 and 2050s

Table 2: Mean annual rainfall, runoff and soil loss under current scenario and 2050s

Year	Mean annual rainfall (mm)	Mean annual runoff in control (% of annual rainfall)	Mean annual runoff in RB&F (% of annual rainfall)	Mean annual soil loss in control (t $ha^{-1}y^{-1}$)	Mean annual soil loss in RB&F (t $ha^{-1}y^{-1}$)
1951-2023 (mean)	770.3	12.47	9.96	4.36	2.61
Baseline (1986 – 2005)	696.8	10.20	6.01	3.40	2.04
2050s-RCP 2.6	875.2	12.62	8.46	4.96	2.97
2050s-RCP 4.5	877.4	12.97	8.73	5.08	3.05
2050s-RCP 6.0	858.0	12.62	8.41	4.97	2.98
2050s-RCP 8.5	902.6	13.55	9.29	5.42	3.25

The mean annual rainfall, runoff and soil loss under current scenario and 2050s showed considerable increase in rainfall under 2050s under all the four RCPs. The annual runoff and soil loss predicted under RCP 8.5 is considerably high compared to RCP 2.6, 4.5 and 6.0 due to the higher rainfall (Table 2). With interventions, the annual runoff can be reduced by nearly 4% of the annual rainfall and annual soil loss can be reduced by nearly 2 t $ha^{-1}y^{-1}$.

Long term variability in seasonal rainfall, runoff potential and soil loss

Considerable variability in seasonal rainfall, runoff potential and soil loss were observed over the years in normal as well as drought years for the period 1951-2023 (Table 3). Out of 73 years, 51 years were normal and 22 were drought years. Even though the seasonal rainfall in normal year ranged from 602 to 1530 mm, but the effective rainfall was only 310 to 688 mm. In drought years, the seasonal rainfall ranged from 312 to 560 mm, but the effective rainfall was 246 to 407 mm. In the normal year, runoff ranged from 2.5 to 17.0 % of the seasonal rainfall and the soil loss ranged from 1.7 to 8.7 t $ha^{-1}y^{-1}$ in control. With the adoption of RB&F system, the runoff can be reduced to1.6 to 14.7 % of seasonal rainfall and soil loss can be reduced to 1.0 to 6.9 t $ha^{-1}y^{-1}$. In case of drought years, runoff ranged from 0.4–10.1 % of the seasonal rainfall and the soil loss ranged from 0.9 to 3.1 t $ha^{-1}y^{-1}$ in control whereas RB&F reduced the runoff to 0.2 - 8.7 % of the seasonal rainfall and the soil loss to 0.6 to 1.8 t $ha^{-1}y^{-1}$.

Table 3: Variability in seasonal rainfall, runoff potential and soil loss in normal and drought years for the period 1951-2023

Parameters during 1951-2023	Normal year	Drought year
For the period 1951-2023 (73 years)	51	22
Seasonal rainfall, mm	602-1530	312 to 560
Effective rainfall, mm	310-688	246-407
Runoff (RB&F) %	1.6 to 14.7	0.2 - 8.7
Runoff (Control) %	2.5 to 17.0	0.4 - 10.1
Soil loss (RB&F) t $ha^{-1}y^{-1}$	1.0 to 6.9	0.6 to 1.8
Soil loss (Control) t $ha^{-1}y^{-1}$	1.7 to 8.7	0.9 to 3.1

Conclusions

In-situ moisture conservation is one of the effective ways to control runoff and soil loss from agricultural fields. In semi-arid regions with Alfisols, raised bed with furrow system is found to be very effective in controlling soil erosion. It was found that raised bed and furrow system has reduced the mean seasonal runoff (1951-2021) from 8.85% to 6.79% of mean seasonal rainfall and the soil loss from 3.72 t $ha^{-1}y^{-1}$ to 2.23 t $ha^{-1}y^{-1}$. The expected rainfall in the study area by 2050s is more than the mean seasonal rainfall and hence, there is more scope for rainwater harvesting in near future. The seasonal runoff expected by 2050s (under RCP 4.5) in control is 9.9% whereas with interventions it can be reduced to 6.0% of seasonal rainfall. Similarly, the expected seasonal soil loss from control is 4.4 t $ha^{-1}y^{-1}$ which can be reduced to 2.20 t $ha^{-1}y^{-1}$ with interventions. Similarly, annual runoff and soil loss was also analyzed. These findings will provide evidence-based insights for promoting in-situ moisture conservation practices in semi-arid regions and inform policy decisions regarding the adoption of soil conservation strategies to maintain the soil health.

Future scope of the study

The output of this study will help to develop climate-resilient adaptation strategies for ensuring long-term agricultural sustainability and environmental health. Advanced tools like the Soil and Water Assessment Tool (SWAT), Geographic Information Systems (GIS), and remote sensing data could be utilized to predict changes in runoff and soil erosion spatially under climate change scenarios.

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Conflict of interest

The authors have no conflict of interest.

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